University of Strathclyde
Department of Civil and Environmental Engineering
Glasgow

How best to plan for dispersed energy?
UK shale gas as a case study.

by

Christopher Derek Ford

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Declaration

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Signed:

Date: 15 October 2022

Dedication

To Angela and Michael, Katie, Rhona and Kelsie.

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Abstract

The energy transition requires new sustainable forms of energy production to replace fossil-fuels. This new energy often requires substantial land areas or is tied to the resource location or both. UK data, in 2020, shows traditional, locationally flexible, power generation produced 1,715 MWe per square kilometre of land used, while locationally tied wind energy provides only 3.8 MWe/km^2 onshore or 2.8 MWe/km^2 offshore.

Substantial dispersal of energy development is likely to lead to increased local environmental effects and social acceptance issues. Exacerbated by an implementation gulf between the domains of energy policy and planning practice, this leads to insufficient provision to meet projected demand.

This thesis explores this gap by asking how best to plan for dispersed energy, by investigating whether dispersed energy can be provided without undue local environmental effects? This is examined via a case study which develops a plan modelling dispersed shale gas development across Northern England. It observes the institutional gulf, also evident in published research, in dispersed energy provision in the UK, due to insufficiently scoped regional energy strategies and impotent statutory planning for dispersed energy.

The research demonstrates that local environmental effects of dispersed energy can be avoided or minimised by deploying a positive planning approach. This should include: a whole-system perspective including technical understanding; covers both energy production and transportation; and assesses overall and cumulative effects in holistic positive planning rather than serial project-level decision-making. Strategic positive planning is aided by evaluating alternative scenarios and integrating planning and environmental assessment techniques, rather than the detached support tool of environmental assessment. Importantly, rather than seeking public views on inappropriately sited, developer identified proposals, positive planning applies criteria-based site selection which seeks to avoid effects on environmental and social receptors. However, implementing this planning approach requires institutional change to bridge the policy/planning gap.

Ethics, Privacy and Data Protection

Elements of the research conducted here involve gathering and holding personal information. Ethical clearance on the collection, use and storage of data was provided under the University of Strathclyde's ethical research provisions in compliance of the University's research code of practice. All personal data has been anonymised.

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Acronyms

AM	Adaptive Management (not Section 3.5)
AM	Altcar Moss (proposed shale gas site) (Section 3.5 only)
AONB	Area of Outstanding Natural Beauty
AP	access point
BGS	British Geological Survey
BSI	British Standards Institute
CAS	Compressed Air Storage
CC	County Council
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Use and Storage
CEA	Cumulative Effects Assessment
CEAM	Cumulative Effects Assessment and Management
csv	comma separated value (file format)
DECC	Department of Energy and Climate Change
DToLR	Distance Travelled on Local Roads
DUKES	Digest of UK Energy Statistics
EA	Environment Agency
EC	European Community
EIA	Environmental Impact Assessment
ENGO	Environmental Non-Governmental Organisation
E-NPS	Energy National Policy Statement
fPP	Final Pad Point
GHG	Greenhouse Gas
GIS	Geographic Information System
gpkg	geopackage (gis file format)
GW	Gigawatts
GWh	Gigawatt hours
GWp	Gigawatts peak (used for peak solar power output)
Ha	Hectares
HCLG	Ministry of Housing, Communities and Local Government
HCWS	House of Commons Written Statement
HF	Hydraulic Fracturing
HFC	Hydraulic Fracturing Consent
HDV	Heavy-duty vehicle (or HGV)
HGV	Heavy Goods Vehicle
Hh	Harthill (proposed shale gas site)
HM Government	Her Majesty's Government, also known as the Government of the United Kingdom of Great Britain and Northern Ireland, or the UK Government
HSE	Health & Safety Executive
HVDC	High Voltage Direct Current transmission cable
IEMA	Institute of Environmental Management & Assessment
Info	Information
IPIECA	International Petroleum Industry Environmental Conservation Association
JSON	JavaScript Object Notation (file format)

K	Thousand
kV	kilovolts
KM	Kirby Misperton (proposed shale gas site)
km	Kilometres
km^2	Square Kilometres
LNG	Liquified Natural Gas
LPA	Local Planning Authority
LR	local road
LU	land use
MBC	Metropolitan Borough Council
MER	Maximising Economic Return
Mi	Misson (proposed shale gas site)
M_L	Local Magnitude (Richter Scale)
ML	Marsh Lane (proposed shale gas site)
m	Metres
m/s	Metres per second
$MtCO_2e$	Million metric tons of Carbon Dioxide Equivalent
MW	Megawatts
MWe	Megawatts electricity
MWh	Megawatt hours
MWp	Megawatts peak output (used for peak solar power output)
n/a	Not applicable
NGO	Non-Governmental Organisation
NIMBY	not in my back yard
nPP	Notional Pad Point
NSIP	National Significant Infrastructure Project
No	Number
NORM	Naturally Occurring Radioactive Materials
NP	National Park
NPPF	National Planning Policy Framework
OGA	Oil and Gas Authority
OS	Ordnance Survey
OSGB	Ordnance Survey National Grid for Great Britain
OSM	Open Street Maps
PA	Planning Authority(ies)
PHE	Public Health England
PINS	Planning Inspectorate (England & Wales)
PNR	Preston New Road (shale gas site)
ppb	Pads per Block (Blocks are 10km by 10km = $100km^2$)
PPG	Planning Practice Guidance
PTL	point-to-layer (GIS tool)
QGIS	Quantum GIS (gis software)
RAE	Royal Academy of Engineers
ROC	Renewables Obligation Certificate
RoSPA	Royal Society for the Protection of Accidents
RS	Royal Society
RW	Roseacre Wood (proposed shale gas site)
SEA	Strategic Environmental Assessment
SGD	Shale gas development
S_{Hmax}	Maximum Horizontal In-Situ Stress
SIA	Social Impact Assessment
SLO	Social License to Operate
SPE	Society of Petroleum Engineers

tcf	trillion cubic feet of standard gas
tcm	trillion cubic metres of standard gas
TWh	Terawatts hours
TL	Tinkers Lane (proposed shale gas site)
TOC	Total Organic Carbon
U/C	Under consideration
UKCS	United Kingdom Continental Shelf
UKOOG	UK Onshore Oil & Gas (trade body)
vol	volume
WS	Woodsetts (proposed shale gas site)

1. Introduction

The energy transition requires a major move towards new sources of energy, which are both sustainable and pollution free. Compared with traditional power production, such as gas or coalfired power stations, these new energy sources are likely to be considerably more dispersed. Harnessing resources, such as wind or solar energy, requires more extensive spatial coverage for equivalent energy output. This dispersed energy, spread across wide areas, presents new and sometimes greater challenges for the local environment. It may also give rise to issues of social acceptance. Essentially, this is a problem of implementing energy policy, provisioning and planning. To meet society's energy needs, planning for dispersed energy should minimise adverse local environmental effects whilst maximising resource recovery. This thesis examines if the UK planning system is fit for the purpose of developing the necessary dispersed energy. It does this by considering the development of shale gas as a case study. Whilst the use of gas gives rise to greenhouse gas emissions the extraction of shale gas is emblematic of the challenge of planning for dispersed energy.

This thesis seeks to examine the question of whether we can make adequate provision for dispersed energy. It examines the track record of dispersed energy provision, showing that this is problematic. The current arrangements result in inadequate levels of dispersed energy provision or inappropriate and unbalanced local environmental effects. The question therefore arises how to minimise the local environmental effects whilst maximising these resources? Given the apparent obstacles, can we in fact plan and make adequate provision for dispersed energy? If so, how could this be done?

This introductory chapter sets out the challenge of the need for dispersed energy, the problems of onshore decision making and the related policy and research gaps between energy policy and local planning for dispersed energy. The remainder of the chapter sets out the research aims and objectives together with outlining the methodology adopted in this thesis. The closing section lays out how the remainder of the thesis is structured.

1.1 The Challenge of Dispersed Energy

Traditionally power generation was concentrated in large-scale single point plants. In 1989 Great Britain had an installed electricity generation capacity of 75GW, provided by only 163 generating stations (DUKES 2013). This equates to an average station size of 460MW, although most power was produced by larger stations of 1,900MW and more (Hannah 1982). As with much of the developed world, UK power was supplied by large thermal stations, fuelled either by coal, gas or nuclear. Typically, nuclear power stations produce around 5.7GW of power generation capacity per square kilometre of land used, coal fired power stations, built between 1966 and 1986, produce 1.7GW per square kilometre, whilst newer gas fired power station produce 13GW per square kilometre (Table 1.1). This intensive use required relatively little land area to produce sufficient power to meet UK energy needs. The land area needed for the UK's 75GW power demand equates to only 43.7 km^2 for coal, or 13.4 for km^2 for nuclear, or just 5.7 km^2 for gas. Electricity generation is supported by a high voltage national grid to transmit the electricity from the generation points to the large population centres and throughout the country. England and Wales have a high voltage network of 8,094 km.

The largest operational onshore wind farm in the UK is 322MW. The average turbine size of the operational fleet for onshore wind farms (with more than 3 turbines) is 2MW (Renewables UK 2020). In Great Britain, onshore wind farm development has mostly taken place in Scotland, with 95.5% of British operational transmission grid connected onshore wind power there (National Grid 2020a). Operational wind farms in the Scottish Borders have a mean energy density of 9.8MW per square kilometre. These range between 23MW and 1.5MW per square kilometre (Scottish Borders Council 2020). Much new wind energy development is taking place offshore. The largest operational turbine offshore currently is 8.4MW with an average wind farm size of 4.4MW (Renewable UK 2020). Wind turbines are steadily growing in size. It is planned to deploy 14MW turbines offshore within 5 years. The Sofia Offshore Wind Farm is expected to use 125 of these turbines. Despite the increase in turbine size, the area of sea covered is large at 593 km^2 (RWE 2020). This implies a constructed power energy density of 3MW per square kilometre.

For comparison with traditional generating plant, however, adjustments need to be made for the energy produced after allowing for the intermittency of wind energy. For example, the 14MW Sofia turbine manufacturer claims a potential 61% load factor (GE 2021). Typical current load factor results for current operating offshore and onshore wind farms are 47% and 26%, respectively (Energy Numbers 2021, Renewables UK 2021). Adjusting for this load factor provides a net power generation capacity of 2.8MW and 3.8MW per square kilometre for offshore and onshore wind, respectively (Table 1.1). This is three orders of magnitude below the 1,715MW (1.7GW) per square kilometre of traditional coal thermal power generation and four orders below nuclear (5.7GW/km^2) and gas power generation (13GW/km^2). Table 1.1 compares the land area required for traditional and new sources of energy in the UK.

Wind and solar energy require substantially more land than traditional conventional power generation, for equivalent power production capacity. Both of these new energy types require to be dispersed to harness the resource. To provide for Great Britain's 75GW power requirement, at the current rates of development spread, would require 19,737 square kilometres onshore or 26,786 km^2 offshore wind energy. *This equates to 8.1% of Great Britain's land and 3.5% of its sea area.* By any measure these figures are substantial. Other energy types, such as geothermal, CCUS, hydropower, compressed air and shale, need similarly extensively dispersal within a specific geographical resource location. Unavoidably these new energy developments require greater dispersion than traditional power production.

Dispersed energy is also often tied to the resource location. These locations are often not convenient to the legacy power transmission system. Potential future energy developments will therefore also require reorganised and new power transmission infrastructure, not only to collect the dispersed energy but to transmit it to the population centres and throughout the country. If not suitably located within the transmission network, dispersed energy can

Table 1.1: Land Energy Density for Traditional and Dispersed Energy in the UK

Group	Energy Type	Plant Name	Open	Close	Net Power -MW	Site Area -km^2	Energy Density-MW/km^2	Type Average Density-MW/km^2	Group Average Density-MW/km^2
Nuclear	Existing	Dungeness	1983		1,320	0.2	6,600	6,288	5,698
		Torness	1988		1,364	0.2	6,820		
		Sizewell B	1995		1,198	0.22	5,445		
	New	Hinkley C	2025		3,260	0.83	3,928	3,928	
Fossil Fuel	Coal	Ferrybridge	1966	2016	2,034	1.64	1,240	1,715	7,390
		Ratcliffe	1968	2024	2,116	1.18	1,793		
		Eggborough	1970	2018	1,960	1.64	1,195		
		Fiddlers Ferry	1971	2020	1,989	1.03	1,931		
		Drax	1986	2021	3,960	1.64	2,415		
	Gas CCGT	Humber Bank	1994		1,365	0.1	13,650	13,066	
		Keadby	1996		734	0.05	14,680		
		Little Barford	1996		732	0.06	12,200		
		Seabank	2000		1,140	0.15	7,600		
		Spalding	2004		860	0.05	17,200		
Renew-ables	Onshore Wind	Clyde	2006		138	47.4	2.9	3.8	4.1
		Whitelees	2009		140	55	2.5		
		Heathland	2018		17.7	7.63	2.3		
		High Constellation	2020		17	13.2	1.3		
		Sandy Knowe	2020		21	3.89	5.5		
		Hagshaw repower	2021		23	2.7	8.3		
	Offshore Wind	Sheringham Shaols	2012		149	35	4.2	2.8	
		Hornsea 2	2022		1080	400	2.7		
		Norfolk Vanguard	2023		1080	425	2.5		
		Sofia	2024		1200	593	1.8		
		Hornsea 3	2025		1440	600	2.4		
	Solar	Cleeve Hill	Consent		39.2	4.9	8.0	8.6	
		Little Crow	Planned		16.8	2.3	7.4		
		Longfield	Planned		56	5.8	9.6		

Notes: Net power allows for load factor, as follows: nuclear and fossil fuel - 100%; onshore wind - 26% (Energy Numbers 2021); existing offshore wind - 47% (Energy Numbers 2021); proposed offshore wind - 60% (GE 2021); solar - 11.2% (Statista 2020a). 'Open' refers to commissioning or expected commissioning date. 'Close' refers to decommissioning date. Coal generation density takes account of the need for coal stock holding areas and large cooling towers whilst nuclear generation uses cooling by sea water and gas firing does not require these facilities. **Source:** Power from National Grid Transmission Entry Capacity (National Grid 2020a); Area either from owner publication or author survey using Open Street Map and Google Earth.

result in wasteful curtailment (Joos & Staffell, 2018), therefore resulting in wasted investment and unnecessary local environmental effects.

Beyond energy currently consumed through electrical power, future energy transition provision will need to cater for energy consumed in transport, industrial and consumer heating. Effective planning for future energy provision also needs to recognise the conversion efficiency together with the diurnal and seasonal fluctuations in demand (Wilson et al 2013, Wilson 2016). To meet all of these requirements the energy transition requires a substantial volume of dispersed energy production.

Decision making on siting dispersed energy therefore needs to take account of the volume required, the technical siting issues and the transportation requirement for each energy vector. Renewable energy offers substantial savings of greenhouse gas emissions over traditional thermal power generation. However, given the dispersal of these new energy developments and the substantial increase in land requirement, local environmental effects are likely to be extensively increased and more geographically dispersed. It would be disappointing if by undertaking major global programmes of energy development to 'save the planet' from climate change we extensively adversely affect other aspects of the environment. For example, by afflicting the landscape with inappropriately sited wind farms that impact visual amenity. Good stewardship (Worrell & Appleby 2000) suggests society should seek to minimise the local impact of the energy transition, or at least find the acceptable trade-off level between maximising the resources' development whilst avoiding excessive adverse environmental effects.

Programmes for UK offshore wind resource development, between 2015 and 2021, have shown some level of integrated or strategic thinking on how to develop the resource. Spatial analysis has been carried out under the auspices of the Crown Estates (Crown Estates 2019). This sieved technical constraints and identified potential environmental consequences, to establish areas most suitable for major offshore wind development. Whilst limited in environmental scope this approach suggests that it is at least theoretically possible to apply a considered planning approach to dispersed energy development. A considered strategy could balance efficient dispersed energy development whilst minimising adverse environmental effects. Otherwise, the UK may become a "prisoner of its past, with an energy asset base which may not be optimal for current energy policy objectives" (Keay 2016, p248).

1.2 The Problems of Onshore Decision Making

Onshore dispersed energy developments in the UK do not seem to benefit from the comprehensive organisation, or the planned approach, seen with offshore wind. Whilst UK government and its agencies set broad national targets or goals for dispersed energy (BEIS 2019, BEIS 2020), the decision process on where dispersed energy development is sited is desultory. The locational decisions are arrived at through a combination of developer choice and planning authority acceptance (Planning Portal). This results in a "lack of coherent criteria for locating" energy production (Braban & Parry, 2001, p59). This seems likely to produce unnecessary adverse local environmental effects. The developer preferences are driven by their best financial options and often constrained by grid access rights and the extant energy transportation system. Limitations of grid access rights often results in development around redundant or partially used historic points of generation (Bell 2009). Given that the power transmission system was engineered to suit traditional generation these locations are generally unsuited to new forms of energy. The reactive planning authority consents can be little more than passive assessments or checks of minimising the most adverse social and environmental interactions at each site (Cowell 2020).

In 2015 the UK government downgraded onshore wind farm development from being categorised as National Significant Infrastructure Projects (NSIP). Despite its critical importance to the energy transition no form of dispersed energy is designated as NSIP in 2020 (Smith 2017). In England and Wales all dispersed energy proposals need to be determined by local planning authorities. At the same time, the government require wind developments to be "in an area identified as suitable for wind energy in a local or neighbourhood plan" (SoSCLG, 2015, p1). However, few local authorities have designated areas for dispersed energy. Perhaps more significantly, government now requires wind farms to demonstrate that developments have the "backing" of "affected local communities" (ibid, p1). The government stated that where a local planning authority turn down a wind farm proposal that decision "cannot be overturned" on appeal (Smith 2016, p14). Extremely unusually within the planning system, this policy in effect denies a right of appeal. A local planning authority rejection effectively shows there is no backing or support from the local community. So, "local people have the final say on wind farms" (ibid, p14).

Given the importance of local decision making, the need to consider the affected local communities and the need for designating suitable locations, the potential for development of onshore wind energy appears to be severely constrained. Yet these inhibitions are in stark contrast with the considerable land requirement for the great amounts of dispersed energy needed to meet the government’s own net zero targets (BEIS 2020f). National policy still encourages new energy development (DCLG 2012), but there are grave questions on whether or not it is possible to develop dispersed energy. Approval rates for biomass are 52% of applications, advanced conversion technologies proposals only gain 62% approval, energy from waste 64% and solar 75%, whilst onshore wind proposals only achieve 44% approval (Harper et al 2019, p955).

Since the 2015 changes in planning practice, approvals of onshore wind developments in England and Wales have been rare. Only four wind farms over 10MW have been approved since 2015 (RenewablesUK, 2020). This appears to confirm Bell, Gray and Haggett’s (2005) observations of a ‘social gap’. Whilst there is broad popular support for renewable energy development the success rate of onshore wind proposals is low. In part Bell at al. (2005) attribute this to a mix of popular support being qualified (people vocalising local objections but not positive support) and local self-interest, which excludes the wider national (or global) concerns. Bell et al. (2005) also recognise that the challenge may also lie in planning processes not identifying suitable areas to minimise local effects. They observe that the planning system is not finding areas where the impact on residents is avoided. A developer-led system may not necessarily identify the most suitable sites. It is in the developer’s interests to find the most economic site rather than the least environmentally affected. The consequence appears to be an impasse resulting in a lack of development of required dispersed energy. Given the urgent need for the energy transition it would be useful to understand why and, if possible, how to resolve this.

The evolution of planning practice in the UK over recent decades (the 2000s and 2010s) has seen voids emerging in spatial decision making. The political focus has become localism (Localism Act 2011). The UK government removed Regional Spatial Strategies in 2010 whilst the Scottish government removed regional government in 1996. This has been replaced by ‘fuzzy boundaries’ of ad hoc sub-regional partnerships (Allmendinger & Haughton 2012). Formal development planning has been pushed into the background. While development ‘permissions’ are anchored with local planning authorities, policy and plan-making has accrued to ad hoc sub-regional cooperation, which are “larger than a typical local authority” (Allmendinger et al 2016, p39). Formal visionary place-making has been backgrounded. Since the removal of regional perspectives, pragmatic and effective planning for important issues has been achieved through city sub-regions. So, despite the planning practice changes there is still an appreciation, if only obliquely apparent, of the value of strategic thinking. Thus, the two-core functions of the planning system are still valid and present today: ‘thinking ahead’ and deciding development proposals. However, the focus on localism and ad hoc, rather than systemic, sub regional planning has omitted planning for dispersed energy (see Section 3.1.3).

It is interesting to note that the thinking ahead, or strategic planning, may occur at higher organisational level than local planning authorities. Significantly, despite developer influence, the importance of community voices and the politics of localism, there is still a recognised value in “positive planning” (Allmendinger Haughton & Shephard 2016, p48). In this thesis the concept of positive planning is used to describe an explicit detailed process of considering and making a plan. Applied to dispersed energy, such a plan sets out criteria for spatial provision of development, having assessed the potential, evaluated the alternatives and selected an optimal design. This is the core function of the archetypal ‘development planning’ process from the planning system. For whatever reason, this positive planning has not been applied to the provision of the new energy production required for the energy transition (see Section 3.1.3). That seems to be a crucial gap in policy and practice. Given the vital role of dispersed energy for the required climate change transition, this thesis considers whether there is a way to address this gap.

1.3 The Policy Gap Between the Two Stools of Energy Policy and Spatial Planning

Breukers & Wolsink (2007) have identified the two main domains which interact over dispersed energy development. These are spatial planning (known as town planning in the UK) and energy policy. They observe that these domains do not combine effectively. Essentially this can be identified as a gap between the two ‘stools’, or domains, of planning and energy policy.

In the UK, town planning takes a broad perspective of all land use development activity, from a local effects viewpoint. It determines land use suitability and makes decisions on physical development. The priority for planning, however, is on the locally perceived pressing needs, such as housing. Review of practice and guidance (as evidenced by the professional planning journals and planning guidance) shows that energy planning is not highly featured. Nor is it seen as an important activity within the town planning discipline. Whilst there is government guidance on renewable energy this is heavily caveated with recognising ‘critically’ important “local environment” effects and impact on communities (DHCLG 2015, p1).

The planning system operates through a two-stage process (Planning Portal, 2020): planning authorities prepare polices and plans for their area; whilst the second stage determines development proposals. Development proposals should only be approved where they conform with prepared policies and plans (DCLG 2015). Thus, in the absence of prepared policies and plans for dispersed energy any proposals are therefore likely to be rejected. For wind energy, developers report a lack of local planning policies on energy (Beddoe & Chamberlin 2003) and that “the planning process fails to mediate between the developer and the public to evolve a project that accommodates both interests” (Hadwin 2009, p532). The consequent track record shows this results in not putting forward wind energy proposals (Renewables UK 2020). This legacy position is reinforced by the 2015 Government statement requiring the backing of local communities (set out in Section 1.2). Environmental campaign groups have criticised the planning system, in England and Wales, for not making provision for onshore wind policies. They observe that planning authorities with substantial opportunities for dispersed energy, such as onshore wind, are not identifying suitable areas for development (Stone 2017, FoE 2019).

The overall picture is that energy provision is not seen as being within the core scope of the local planning system, or at least not as a priority. The accepted view appears to be that power comes from the national grid, so its production is abstruse. Consequently, since energy supply is hidden it is not a visible problem and does not seem to be perceived as a local problem. Downgrading onshore wind from national infrastructure has left onshore wind in limbo (Keay 2016). New energy production has ended up being neither a national issue nor a local responsibility.

In the energy field, the planning system is simply a hurdle to be overcome. Planning consent is required for energy development (DCLG 2015). There is broad encouragement from government to suggest to planning decision-makers that planning for energy is important (DHCLG 2015). But in reality, there is little if any practical reinforcement. It is left to developers to gain approval from the planning system. This may arise on a project or ad hoc basis, such as developing a wind farm (Miller 2015). The scope of government policy is limited to setting broad targets for the ambition of net-zero. Any operational planning, within National Grid and the power industry, is limited to the engineering requirement of the energy of the future. That, however, is only in the form of ensuring adequate dispatchable energy capacity, contending with the intermittency or grid reinforcement (National Grid, ETYS 2017). Auctions take place to organise subsidy to low carbon and capacity generation (BEIS 2020a, LCCC 2020, BEIS 2019a). However, all of these activities on energy programmes are largely aspatial. Not surprisingly, this uncoordinated approach results in spatial transmission problems (Bell 2009).

A further consequence of energy policy is that it tends to be directive, is largely technically based and insensitive to local environmental issues. This is a product of a top-down central policy approach. “At the level of central government, there is a growing top–down, technocratic, hierarchical way of thinking about how the planning system must be shaped” (Wolsink 2007, p2702). As well as the gap in the disciplines or silos, this can also be seen as a gap between levels of decision-making: the gap between policy and practice. National governments are setting objectives and targets for climate change adjustment and the energy transition. Whereas developers and local government are engaged with decisions of particular proposals, for individual sites. But there is little coordination between the levels of national policy and local practice. Onshore there is little in the way of attempts to resolve the gap between local and national. There is no suggestion of thinking regionally. “The UK is, in energy terms, the prisoner of its ideological past – unable to find an effective way of reconciling the 3‘E’s [1] because it is stuck in an uncomfortable half-way house between markets and central control” (Keay 2016, p248).

This gap between the policy and practice silos and levels of decision making do not necessarily exist outside the UK. Iceland has adopted a planning approach to geothermal and hydro development. Integrated planning allows dead ends about projects to be avoided, identifies areas which are excluded from development and finds projects that best suit the technical, economic and environmental circumstances (Steingrimsson et al 2008, Hreinsson 2008). In Italy local and regional governments have been authorised to develop regional energy plans to facilitate energy-saving measures and renewable generation (Brandoni & Polonaro 2011).

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[1] The ‘3Es’ are energy security, environmental growth and environmental protection. This is a description, also known as the energy trilemma, formulated by the International Energy Agency.

In one of Spain's poorer region a collaborative strategic planning approach has been applied to develop solar and biomass energy (Terrados et al 2005). This has led to the development of a regionally based strategic energy planning tool (Terrados et al 2009) (see Chapter 2 for more detail). However, other jurisdictions (Ireland & Czech Republic) incur similar experiences to England and Wales with problems obtaining local consents for onshore wind developments (Brennan & Rensburg 2016, Betakova et al 2015).

Whilst there are a few international examples of successful local planning for dispersed energy, the energy policy and local planning practice domains, in the UK at least, do not combine effectively to provide for effective local planning of dispersed energy developments. This thesis seeks to explore this gap to understand why it exists and particularly to consider whether it is possible to meet the needs of planning for dispersed energy. It examines this by asking how best to plan for dispersed energy.

1.4 The Research Gap Between the Two Stools of Energy and Planning

It is interesting to note that the policy and practice divide is largely reflected in a similar gap in academic research. For all the scholastic thinking and independent examination of the challenges of the energy transition there appears to be little research on this question of a local planning solution to the problems with developing dispersed energy. Instead, research has seen this rift as a problem of implementation or delivery of renewable energy programmes. The research observation is of largely popular support for renewable energy but, on the ground, real projects incur social resistance at the local level. The scholastic response, perhaps reflecting many academics' discreet preferences, has been extensive research on the 'problem' of social acceptance (Wolsink 2007, Breukers & Wolsink 2007, Devine-Wright 2009, Cowell 2010, Hobarty et al 2012, Wolsink 2018, Bout 2019, Harper et al 2019). However, it can be argued that this social acceptance issue might be an inevitable repercussion of the spatial extent of the requirement for dispersed energy.

Almost all the energy transition technologies require far larger spread of energy production. Nations need to move away from the traditional centralised energy production to 'distributed generation'. This dispersal of energy production will inevitably bring energy production closer to the population. Or rather, returns it to its historical position of being local (Huber &

Mccarthy 2017). A core argument of this thesis is that we should, at least seek, to plan for this. Rather than accepting the consequences of the institutional gap, we should plan for dispersed energy proactively, in a positive way. It is not sufficient to provide national and popular exhortations for new energy and simply research social acceptance or lack of. Active positive planning provision is needed for this localised dispersed energy. This thesis seeks to discover whether we can plan for dispersed energy. Is it possible to deliver positive local planning for the dispersed energy to fulfil the national objective of net-zero whilst minimising or avoiding local environmental effects?

From the planning sphere there has been very little research on the potential of positive planning for dispersed energies. Several authors consider the social acceptance of wind energy including debating so-called Nimbyism (Demski 2011, Hobarty et al 2012, Aitkin et al 2016, Wilson & Dyke 2016, Natarajan et al 2018, Bout 2019, Brown et al 2019, Wolsink 2018). The relationship between developers and affected communities has also been considered in terms of the role of community benefits (Aitken 2010, Kerr et al 2017). Cowell considered the programme in Wales of identifying area for onshore wind farms, but from a governmental/ institutional perspective (Cowell 2010). Some research has focused on onshore wind development to consider whether there are underlying problems with the planning system (Ellis et al 2009, Hadwin 2009, Miner 2009, Wolsink 2009). In one article this focuses on the particular role of Environmental Impact Assessment (EIA)(Smart et al 2014). Using a survey of planning authorities dealing with onshore wind proposals in Scotland, Kerr (2006) identifies problems using a market-driven system to identify sites and observes a conflict between national policies and local planning concerns. Whilst these identify challenges of dispersed energy provision there is little research to seek out whether a planning solutions might be found to address these.

The rescaling of planning governance, through devolved administration, has led to centralised sub-national consenting and generation targets in parts of the UK (Cowell et al 2017). In part this explains why Scotland has seen so much onshore wind development in the last decade. The English and Welsh approach of giving ‘local people the final say’ does not apply in Scotland. This contrasting experience, between the three countries, is a product of national planning approaches combined with the aspatial energy policy and financial support available throughout the UK. The aspatial subsidy for renewable energy means that where consents are available the developers will follow. The result has been large scale developments in Scotland, but these developments are several hundred kilometres from the main UK power demand centres. Whether this is an efficient use of the transmission system and results in the least localised environmental effects is an open question. Overall, the planning literature has not considered these questions. The research shows little attempt to weigh whether the siting of dispersed energy is optimal from the perspective of local effects, social impact and technically efficiency of energy production. And whether it represents a sound application of planning decision making, including whether decisions are consistent across Britain.

In the energy policy sphere most research tends to be inherently aspatial. A review of the energy and energy policy literature (in Chapter 2) shows that the emphasis is on technological advances, potential effects, encouraging public acceptance, market operations and energy efficiency (see Section 2.2). Whilst some of this considers countries and region there is only partial consideration of the spatial perspective. Some researchers have considered the spatial requirement for growing transmission flexibility to meet the requirements of dispersed energy. But this is usually from a grid development perspective, based on least-cost or energy flow optimisation arising from both the spread and intermittency (Oree 2017, Cormio et al 2003). Little consideration is afforded to local environmental considerations in these studies. Bell (2009) has considered the spatial consequences of wind generation developments on a national energy transmission system. He describes how UK transmission system constraints on grid connections for new energy generation inhibit development. This leads to prospective generators "having a choice between locating new facilities in areas of the system that are less constrained but perhaps less economically optimal for a production point of view, or simply bearing the increased risk of locating in the export constrained areas" (ibid, p7). Considerable delays in provision arise because of grid access issues. The transmission operators are unable to give firm dates for connection due to uncertainty in obtaining planning permission (ibid). Evidently, there is no coordination between transmission development and the planning system.

Just like the policy/ practice gap, the scholastic research seems to only sit within its disciplines and silos. There appears to be little to no attempt to bridge these disciplinary boundaries and

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[2] Author review the contents of Energy Policy, Energy and Environmental Science, Energy Research and Social Science, Energy and Environment, Renewable Energy, and Energy for Sustainable Development Journals.

little research crossing disciplinary challenges. The research gap and coverage in literature on the research question is covered in greater detail in Chapter 2, Literature Review. Chapter 3, Context, provides greater detail on the policy/ practice gap.

1.5 The Research Question and the Research Objectives

The research question addressed in this thesis then is: how best to plan for dispersed energy? This question is examined from two perspectives. Firstly, is it possible to plan for dispersed energy and, assuming it is, how would this best be done? It is of course possible that these policy, practice and academic disciplines gaps are insurmountable, that it is not possible to plan for dispersed energy. However, the examples from other countries and offshore in the UK suggests that this is not the case. The current lack of planning for dispersed energy, in the UK and elsewhere, may arise from genuine obstructions and difficulties. In examining this question, it is assumed that any plan would need to take account of both (a) the local planning and environmental effects considerations and (b) the technical needs of production and transporting the power to consumers. This goes beyond the conventional scope of town planning and environmental assessment. The research therefore needs to identify what factors need to be considered. What would the process be of integrating energy, planning and technical aspects of energy production and transport? What would a plan for dispersed energy look like? What factors does it need to consider?

The supplementary perspective to the research question considers whether it is institutionally possible to plan for dispersed energy? Are there reasons that no effective planning for dispersed energy takes place? Is this due to structural or systematic or institutional reasons? Perhaps it is not possible to integrate energy transportation, grid access, technical aspects of energy production and local planning issues. Can a plan integrate local environmental effects and technical engineering considerations?

The research question has importance globally. There is a pressing need to rapidly expand dispersed energy provision with appropriate power transmission. Without it the tools to address the climate change and greenhouse gas emission crisis look inadequate. Unlocking dispersed energy development may be crucial to success of the energy transition. There is a common international requirement to find ways to provide for the large spatial demands of developing dispersed energy provision in ways which minimise adverse local environmental effects. Considering this as a research challenge at a global scale appears insurmountable due to the varying dispersed energy resources, energy requirement and especially the varying institutional decisions frameworks. To cope with this, the research here is focused on one jurisdiction.

The UK has been selected due to the challenges and opportunity it presents. It is pertinent since the UK has committed to the energy transition and net zero by 2050 (with 75% emission reduction [of 1990 levels] by 2035). It faces the common problem of adapting its mature legacy energy system to the new energy vectors. The UK benefits from considerable dispersed energy resources and has demonstrated the capacity to effect change, although this change has been constrained by the gap between energy policy and planning delivery. The example of the UK includes a dense population which has demonstrated a sensitivity towards adverse environmental effects. There are examples of wind farms and other forms of dispersed energy being opposed socially. The UK also has a coherent system (its planning system) for dealing with local environmental effects. Whilst the distinction of the UK's planning system may limit application of the research finding for other jurisdictions there is broad value in setting out a path to balance the provisioning of dispersed energy with minimal local environmental consequences.

The research question is particularly pertinent to the UK. It is not clear that the UK has fully recognised the experience of earlier energy transitions and the importance of dispersed energy to the challenge for the future. In the UK's post-war industrialisation, a rapid expansion of electricity supply, transmission and universal consumption took place. During the period between 1948 and 1970 power supply capacity grew from 11.7 GW to 56 GW. Total electricity consumption grew from 38,821 GWh per annum to 193,907 GWh. In twenty-two years, generation capacity expanded 4.74-fold whilst consumption grew fivefold (Hannah 1982, tables A1 & A2). It is this scale of development that is required again. In 2019 renewables account for 37.1%, or 120,515 GWh, of UK electricity generation. However, nearly a third of this, 11.5% or 37,314 GWh, was provided by dispatchable thermal renewables (biomass) (DUKES 2020). The government sees this thermal biomass as only a temporary measure and would like to phase out thermal renewables (CCC 2018). This leaves only 25.6%, 83,202 GWh, of electricity generation from renewables. Other low carbon sources, such as nuclear, meet a further 17.3% of UK's electricity requirement, but without major investment in new plant this will life expire over the next decade (DUKES 2020).

The true scale of the UK's energy transition challenge is that electricity only accounts for 17% of the final energy consumption. Fossil fuels continue to dominate the provision in heating and transportation, as shown in Figure 1.1 (DUKES 2020, Open University 2019). There is a small, sustained trend of declining energy consumption: a temperature adjusted decline of 1.2% per annum. However, despite growth of renewable electricity, fossil fuelled heat and transportation accounted for 78.3% of UK final energy consumption in 2019 (ibid). The 2020 UK Energy White Paper foresees a doubling of electricity demand by 2050 to provide for electrification of light vehicles and some home heating as well as existing needs. To achieve net zero this requires "a four-fold increase in clean electricity generation" (BEIS 2020h, p42). Even without allowing for energy conversion losses, this represents a huge challenge for the energy transition. The current challenge requires an energy transition on the same scale as the post-war electricity expansion.

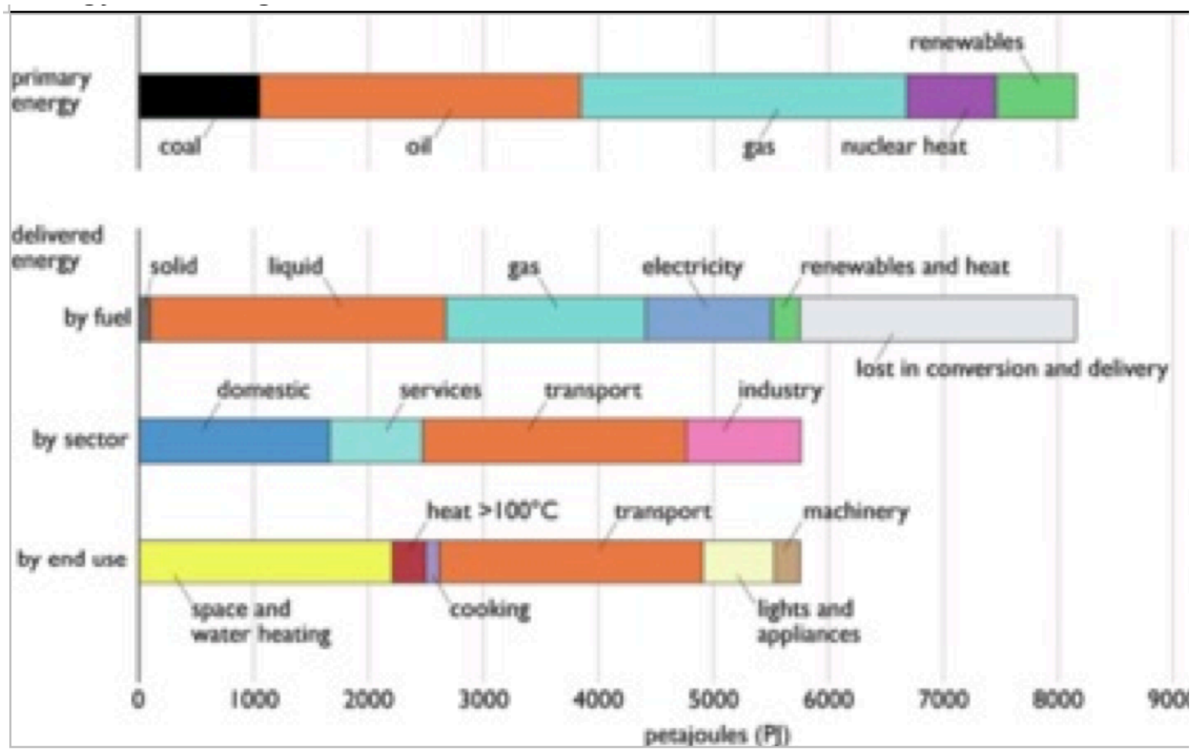


Figure 1.1: UK Primary and Delivered, or Final, Energy for Use, for 2015.
Source: Open University 2019

There is, however, a notable institutional difference between the post-war programme and current situation. Post-war there was an organised strategy and coherent governance to the development, in part due to central control via the nationalised electricity industry (Hannah, 1982). The number of stakeholders was small. The land use footprint of power generation was also small (Table 1.1). This meant that the plan could be discreet rather than explicit. It did not need to be shared amongst many potentially involved local authorities or groups of stakeholders (including potentially affected communities). Successful implementation was achieved by driving increasing generator size (through technical innovation) and building a series of large thermal power station (Hannah, 1982). "In the 1960s as central planning of generation determined that coal fields in the north of England and nuclear power around the coast should be used for electrical energy, bulk transfers of power became normal "between generating and consuming regions (Bell 2009, p3). The transmission infrastructure, with suitable capacity margins, was planned and built for in this plan. The major single-point locations of energy production focused the adverse environmental effects in ways which greatly minimised overall social and environmental effects.

With the advent of dispersed energy, the challenges of minimising adverse effects are likely to be far more substantial. At the same time, the UK has an impotent half-way house between a market based and a centrally planned energy system (Keay 2016). Reflecting the challenge in many developed jurisdictions, the question for the UK is, given the likely environmental and social issues, can this energy transition be achieved? Is the planning system fit for purpose to deliver to deliver the volume of dispersed energy required?

1.5.1 RESEARCH AIM AND OBJECTIVES

The aim of this thesis is to develop and demonstrate the value of an analytical technique for guiding the spatial planning of dispersed energy facilities. The ambition or purpose of this aim is the formulation of a methodological technique for a coherent dispersed energy development system which balances the necessary construction of energy facilities, sufficient for demand, with minimal local and global environmental effects, and at minimum cost to consumers. Significant to this research, this subtly amends the traditional energy trilemma, by explicitly recognising and requiring the taking due account of the local environmental effects arising from energy facilities, as well as the global atmospheric effects. As a means to minimising the potential local environmental effects and cost to consumers it also seeks a holistic whole-system approach to dispersed energy development.

Coming from this aim and purpose, this thesis has the following research objectives:

1. Recognising the different resources available, to identify the factors that requires to be considered in a whole-system spatial planning approach for dispersed energy (RO1).
2. To develop and set out the principles of a spatial planning methodology for the coherent holistic development of dispersed energy, that seeks to meet the set purpose (RO2).
3. To enable this methodology to have greater practical relevance in spatial dispersed energy analysis and planning, to make constructive use of actual rather than proxy data (RO3).

Identifying factors (RO1) that require to be considered in spatial planning logically proceeds the development of a spatial planning methodology (RO2). Use of constructive data (RO3) is applied to the factors and methodology, so qualifies the other objectives and follows on from these.

In seeking to research the development and demonstrate the value of an analytical technique for guiding the spatial planning of dispersed energy, the starting point would seem to be to identify all factors that need to be taken into account. This preliminary introduction has mentioned individual energy vector technology, the primary resource, the level of energy demand, the transportation of energy and, by no means leastly, the local environmental effects. There may be other factors. Given the thesis aim, it would seem important that all the factors that need to be considered are identified and the potential importance weighed in some way.

The research ambition seeks to formulate a methodological technique (or planning approach) to deciding where to locate dispersed energy facilities. In this introduction it has been identified that there are issues around the current incrementalist decision making, that energy policy is largely aspatial, research and practice both suffer from silo thinking, perhaps a lack balanced consideration of local environmental effects and other issues, which all suggests an absence of joined-up thinking. This is pointing towards a need for coherency and a whole-system or holistic approach to dispersed energy development. It therefore implies that a fresh approach is required. The second research objective therefore seeks to move towards this by at least identifying principles of a suitable spatial planning methodology if not developing a fully formed technique.

In reviewing the research literature, it is evident that some research, whilst valid in its own right, could deliver more value by not being dependent upon proxy data. In real-world planning and decision making it not possible to rely on proxy data because of the hard facts of circumstance. For an analytical technique for guiding the spatial planning of dispersed energy facilities to be of value indicates that the hard facts of circumstance have to be considered. The third research objective therefore supports research aim, purpose, and both the second and first objective, by seeking to deploy the constructive use of real, rather than proxy, data.

1.6 The Methodology to Address the Research Question

This section outlines how the research question will be addressed within this thesis. The research seeks to answer the research aim. It does this through the research objectives.

This problem, of the failure to adequately provide for dispersed energy, could be approached from many discipline perspectives. It could be viewed as a matter for policy and a problem of political science. It could be seen as a technical problem potentially with an engineered solution. It could be seen as an environmental problem because of the adverse potential environmental consequences. Or it could be a social science problem because of difficulties of social acceptance and the failure by society to resolve this aspect of the climate crisis. For this thesis the adequacy of provision of dispersed energy and seeking a solution to dealing with this is addressed as a ‘planning’ problem.

There are four reasons why dispersed energy provision falls most appropriately to the planning discipline. These partly follow Davoudi’s assessment of planning as an academic discipline (Davoudi 2010). Firstly, “planning deals with spatial relationships” (ibid, p635). The problem outlined above is essentially a spatial challenge. Secondly, planning is concerned with action and decisions. Planning is distinguished from the other spatial sciences, such as geography, in that it is concerned with societal choices and developmental decisions. Thirdly, planning is strongly engaged with "interactive knowledge" (ibid, p638). Davoudi (2010) is careful to identify this as interdisciplinary rather than multidisciplinary. But she emphasises that planning is concerned with the integration of knowledge. Utilising a planning approach for this research, highlights the need for any solution to merge effective interdisciplinary knowledge. Fourthly, planning implicitly "sees things whole" (Goldstein 2012, p493). This research problem requires a holistic approach as a starting point, that is not limited by traditional disciplinary, silo and policy boundaries. So, while this research may go beyond the conventional planning practice boundary, it is the planning discipline's capacity to consider the whole issue (of planning for dispersed energy) which is important.

1.6.1 OUTLINE OF THE RESEARCH METHODOLOGY

To address the research question, of how best we can plan dispersed energy, the thesis seeks to develop a trial plan or methodological technique for the development of dispersed energy facilities. This is a field trial or case study. This case study seeks to establish whether or not it is possible to develop a strategic plan for dispersed energy as a means to developing an analytical technique for guiding the spatial planning of dispersed energy facilities. The case study should prove or otherwise show that a plan for dispersed energy can be prepared. It should demonstrate how plans for dispersed energy can be prepared and set up a methodology for dispersed energy planning.

The plan or model broadly follows the processes used to develop a spatial development strategy, or a spatial plan, within town planning (DHCLG 2020). This includes elements of environmental impact assessment and strategic environmental assessment. By using the term 'spatial planning' for dispersed energy this intentionally avoids the known associations and limitations of Spatial Development Strategy, Structure Plans, Local Plans and Development Plans. These are all terms with known histories and shortcomings in planning, such as territorial, content and procedural constraints (Lainton 2018, Morrison 1978). The spatial planning for dispersed energy applied here seeks to circumvent these associations. Essentially spatial planning, as applied here, is a standard planning process, consisting of: identification of issues and setting objectives, gathering the relevant information, understanding the spatial context, generating and considering alternative scenarios and planning the optimal choices (Faludi 1973, McConnell 1981, Rydin 1993, Cullingworth 1999, Morphet 2016). There are, however, some notable differences from traditional planning approaches. These differences are given in Box 1.1.

Box 1.1 Difference Between the Planning Approach Adopted within this Research and Traditional Planning Approaches

1. **Scope:** The spatial planning, or model, will not be confined to purely planning matters within the usual scope of UK statutory town planning. Conventionally town planning, whilst taking account of technical or engineering aspects of a technology, does not engage with them. This planning experiment or model will go beyond the usual silo of the planning practice to consider these technical aspects.

Reason: Part of the issue with dispersed energy development may be that the silos obstruct coherent approaches. To consider this the plan will seek to bridge the silos, in an interdisciplinary way.

2. **Extent:** Local planning usually takes place within the confines of each local authority boundary. Whilst there is a “duty to cooperate” in practice and sometimes fuzzy boundaries apply, this has limited application.

Reason: Territorial barriers may inhibit planning for a coherent area. For the planning experiment here the area of study and planning will be selected on the basis of what is appropriate for the dispersed energy. The planning boundary may be more appropriate to be resource based rather than administrative. It may also need to take account of the transportation of the energy.

3. **Public:** A spatial plan or strategy would normally be subject to public consultation and comment. Inevitably local authorities preparing a spatial plan or strategy are making political choices which have a social perspective.

Reason: That is not possible in an academic exercise.

By applying a field trial or modelled example, the thesis considers whether planning dispersed energy is possible. The aim is to identify what the strength and weakness of planning for dispersed energy might be. The approach taken builds on existing practice applied in the UK system of local planning and environmental assessment. Under European law larger scale developments are required to consider the environmental effects of the proposal before consent can be given (Council Directive 2014/52/EU [EIA directive] 2014). For areas and potential multiple projects, a strategic environmental assessment is used (Council Directive 2001/42/EC [SEA directive] 2001). Many types of dispersed energy are likely to fall under these requirements. Statutory Local Plans provide a framework for deciding subsequent development proposals (TCPA 1990). Once prepared they set out where development may take place, identifying areas suitable for each type of development. These Local Plans may be on specific topics, such as housing and minerals. As discussed above, energy is seen as having a low priority remit of local planning policy and practice. For the purposes of this thesis dispersed energy is treated as having compelling importance.

1.6.2 THE VALUE OF MODELLING

Modelling, in a spatial planning context, is often used for forecasting, for example, how many houses are needed in the coming years. However, modelling also aids understanding of a problem. It can provide "insight into the phenomenon or observable system in the real world" (Hanson 1986, p51). Modelling provides a "framework of definitions of system components, boundaries and relationships" with a key value being the treatment of uncertainty (ibid, p51). Modelling for understanding seeks to identify underlying problems, identify alternative policies and choices, and determines the consequence of these alternative (ibid). It allows the consideration of different scenarios.

The planning process is potentially very complex. It needs to consider a wide variety of factors and components as well as placing the resource, the zone of potential effects, the various receptors and the environmental context in a spatial situation. With the need to consider alternatives and experiment with planning options the planning process may need repeating with iterations to achieve an optimal outcome. Spatial modelling offers a potential solution to handling this complexity. "Models are simplifications of reality" (Schrojenstein-Lantman et al 2011). This reality does not just apply to what exists but can also apply to what *could* exist. Modelling offers a way to break down a problem into constituent parts and then build those parts back together with an improved overall understanding. "Models are tools for understanding and explaining the causes and consequences of land use dynamics" (Veldkamp & Verburg 2004, p1). The extent and scope of land use planning and environmental assessment modelling is varied. One component of this land use planning and assessment modelling is simulation of the actual decision-making process (Evans & Kelley 2004, Huigen 2004, Ligtenberg et al 2004). The modelling envisaged in this thesis fits comfortably into this subset. It considers the policy decisions available for the development of, say, a dispersed energy resource.

A key requirement of modelling is that it be explicit. “In explicit models, assumptions are laid out in detail, so we can study exactly what they entail” (Epstein 2008). Epstein makes clear that “modelling does not obviate the need for policy judgement” (ibid, p1), rather modelling helps by exposing detail. Epstein suggests there are at least sixteen reasons to apply modelling. Seven appear to be relevant here: explain, illuminate core dynamics, illuminate core uncertainties, to bound the outcomes to plausible ranges, demonstrate trade-offs /suggest efficiencies, to reveal the apparent simple to be complex and apply discipline to policy dialogue (Epstein 2008). The modelling envisaged here seeks to explain the consequence of dispersed energy development, to illuminate the core dynamics involved on how the effects of an energy type interact with other land use activities. The modelling should expose the bounds of plausible outcomes, such as whether or not it is possible to fully develop the energy resource. It should highlight the trade-offs or efficiencies such as whether developing the resource results in unacceptable adverse effects and the level of effects arising. Overall modelling here seeks to demonstrate the complexities of large-scale dispersed energy development and should provide a guide for a consistent policy.

The spatial planning or strategy here needs to consider: the spatial distribution of the energy resource; the technical capability to convert or produce the energy in a usable form; the spatial distribution of the demand for the energy; the capability to transport the energy from the production point to the demand location; the environmental effects of producing the energy; and the environmental effects of transporting the energy. Taking account of these it seeks to identify areas of opportunity suitable for the dispersed energy.

Having developed a spatial plan or strategy for one form of dispersed energy the thesis then turns, in the Discussion Chapter 6, to consider how this could be applied to other types of dispersed energy. The second part of the research question here is considered by examining what general principles can be deduced from this particular dispersed energy modelled to all other forms of dispersed energy. What are the strengths and weaknesses of the method that has been developed? What institutional barriers exist to planning for dispersed energy? What framework and structure would best suit effective dispersed energy development?

1.6.3 SELECTING WHICH DISPERSED ENERGY TO STUDY

Given the likely different range of challenges and requirements for each form of dispersed energy this thesis focuses on one type of energy for study, as an example of how a spatial strategy for any dispersed energy could be developed. Selecting one form of dispersed energy reduces research complexity and offers improved research value rather than seeking to cover all forms of dispersed energy. The obvious choice for which type of dispersed energy this thesis should focus on is onshore wind. It will be important to many countries in the energy transition. In the UK onshore wind is a particularly important resource. Given the policy hiatus and the lack of onshore wind development over much of the country it is timely to study whether it could be developed. This section explores the potential for using onshore wind as a case study. However, due to the complexities involved it concludes that onshore wind is not a viable case study for this thesis. Nevertheless, this summary examination of the issues involved in the planning for onshore wind energy illustrates the extent of the issues which ought to be considered within planning for dispersed energy together with the complexities which make it unsuitable for this thesis.

A plan for any kind of dispersed energy needs to start with recognising the technical aspects of the resource. Any planning for onshore wind, for example, needs to understand the distribution of the wind resource. In the UK the wind pattern shows a clear occurrence of stronger winds for sustained periods in North and West Britain. Winds are more moderate in the South and East (ETSU 1999, Global Wind Atlas 2020). Winds are also stronger on higher ground. The topography of Britain, with higher ground in the North and West, aligns with the recorded pattern of historic wind data. It would therefore be appropriate, from a purely resource perspective, to develop onshore wind resources in the North and West of Britain. However, all of Great Britain has medium or high economically viable onshore wind resource (Harper 2019a, Figure 5(a)). Figure 1.2 illustrates the wind resource for Great Britain and Europe. The mean wind speed in lowland Britain is typically around 6m/s whilst on higher ground in Scotland, northern England and Wales is 10m/s or over (Global Wind Atlas 2020). A further technical dimension is the ability to convert the resource. Wind turbines vary in size, swept area, output and energy conversion efficiency (Biswas et al 1995).

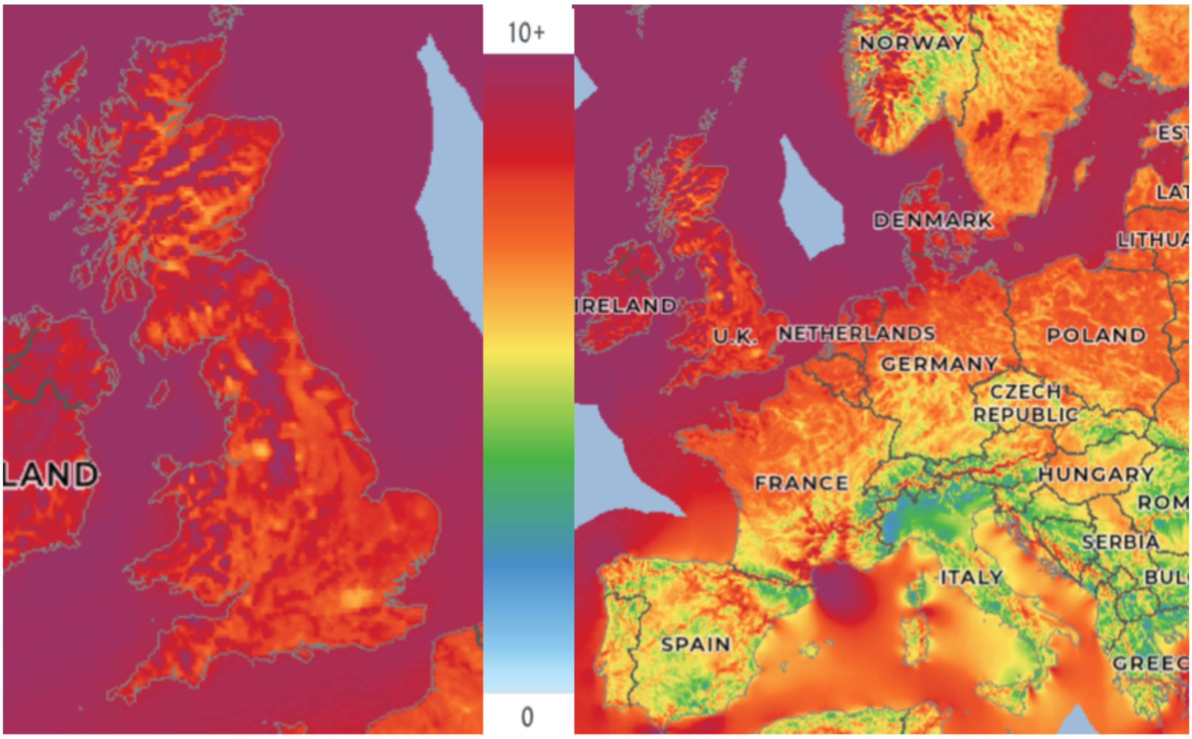


Figure 1.2: Great Britain and Europe Mean Wind Speed.

Key: Centre bar shows the mean wind speed colour gradient between 0 – 10 metres per second predicted at 100m above ground level. Left of bar: Great Britain. Right of bar: Europe. **Commentary:** All of Great Britain has good wind speed with values between 6m/s in lowland areas or steep sided valleys and around 10m/s on the higher ground in Scotland, northern England and Wales. All offshore waters around Great Britain have mean wind speeds of 10m/s or greater. **Source:** Global Wind Atlas 2020.

As well as the production of energy consideration needs to be given to the demand. There is little point in producing energy without considering where the energy is required. A power consumption map of Great Britain shows that while consumption per electricity meter tends to be lower further South, the number of meters strongly correlates to the size of the population (DECC 2010, BEIS 2019b). Consequently, the consumption of power in Great Britain is greater in the larger population centres of northern, midland and specifically south-east England. The strongest areas of potential onshore wind resources therefore do <u>not</u> coincide with the location of largest demand.

As with all forms of dispersed energy, consideration of onshore wind has to examine environmental, social and regulatory factors. A cursory review of the factors determining wind farm developments is set out in Table 1.2. This summarises the factors which have been considered, in both policy and consents planning stages, by five local authorities across Southern Scotland. This area covers the geographic region known as the Southern Upland of

Table 1.2: Factors Influencing Wind Farm Determinations in Southern Scotland

Category	Effect
Environmental	Landscape impact
	Highly sensitive bird areas
	Geographic area and landscape types
	Natural heritage
	Carbon rich soils and peatland areas
	Topography
	Powerline visual impact
	Carbon payback
	Accessibility
Social	Visual amenity
	Noise
	Shadow flicker
	Historic features, buildings and areas
	Key tourist areas and routes
	Inventory of gardens and designed landscapes
	Archaeological sensitive areas
	Radar, defence, aircraft interference and telecommunications
	Historic battlefields
	Public access, long distance footpaths and cycle routes
	Net economic benefit
Planning & Regulatory	Designated areas: National Nature Reserves, National Scenic Areas, Ramsar sites, Sites of Special Scientific Interest, Special Areas of Conservation, Special Protection Areas, Regional Scenic Areas, Hadrian's Wall heritage sites, World Heritage designation
	Green Belt
	Conservation Areas, Scheduled Monuments and Listed Buildings
	Cumulative effects
	Wind turbine/ farm scale
	Seismic and meteorological recording station.
	National planning Policies: Third National Planning Framework, Scottish Planning Policy & Scottish Energy Strategy.
	Habitat Regulations
	Community separation and 2km settlement sensitivity
	Social cohesion

Source: Author assessed information from Dumfries and Galloway, Scottish Borders, South Ayrshire, East Ayrshire and South Lanarkshire Councils planning policies.

Scotland. This area offers considerable resource for onshore wind, has relatively low population density and has seen a significant number of proposals for wind farm proposals in the last twenty-five years (Renewable UK). The determining factors in the Table are loosely grouped into primary headings of environmental, social and planning. However, there is some overlap. For example, landscape impact having both an environmental value and a social consequence, under visual amenity.

The Table 1.2 shows those factors which are explicitly being considered in planning policy and decisions. As mentioned above, there are other factors which influence onshore wind developments, such as grid access and power transmission. Due to silo boundaries these are excluded from scrutiny within the current planning system. Yet, a key determinant of onshore wind development is accessibility to the electricity transmission network (Bell 2009). An assessment of wind farm proposals in Southern Scotland shows a concentration of developments along the line of the north-south 400kV national grid transmission lines, which runs along the line of the main Scotland-England communications corridor from Glasgow to Carlisle. Wind farms have been built within reasonable proximity to the existing infrastructure, due to the cost of grid connections. Developments are relatively scarce to the east, in the Scottish Borders where grid access is constrained. Developments in the west of the Southern Uplands have only started to move forward since the development of the South-West Scotland Connection Project (SPEN 2019, Build Scotland 2018).

Beyond the local grid connectivity other factors influencing wind farm development are policy and the national market for generation. As explained earlier, policy practice varies considerably between Scotland and England and Wales. The restrictions in England and Wales have been outlined earlier. In contrast, Scotland is actively promoting onshore wind (Scottish Government, 2017). The market for electricity generation operates nationally, across the island of Great Britain with generators able to connect at any point to the national electricity network. The subsidy for low carbon energy also operates on a national basis. Subsidy is organised by technology, rather than geographically (BEIS 2020a). Across the network electricity generation and demand varies at different times in each location. The electricity system operator has to balance these (Ofgem 2020). The balancing takes place between supply and demand, between intermittent and dispatchable generation and across different regions (ibid). These regions are identified as 'constraint boundaries' on the national grid. The "best wind load factors in Britain can generally be found in the north – Scotland and the north of England", yet there is "limited capacity of the system to transfer power southwards" (Bell 2009, p1 & p3). There is therefore an important national geographical factor to be considered for onshore wind generation. Consequently, there are identified zones where onshore wind might be developed within the existing infrastructure (National Grid 2017). Without this wasteful curtailment of power generation can arise (Joos & Staffell, 2018). Figure 1.3 shows the Great Britain electricity transmission system, transmission constraints boundaries and the resulting transmission wind development zones. Beyond existing infrastructure, new clusters of generation might require the transmission infrastructure to be reinforced or extended.

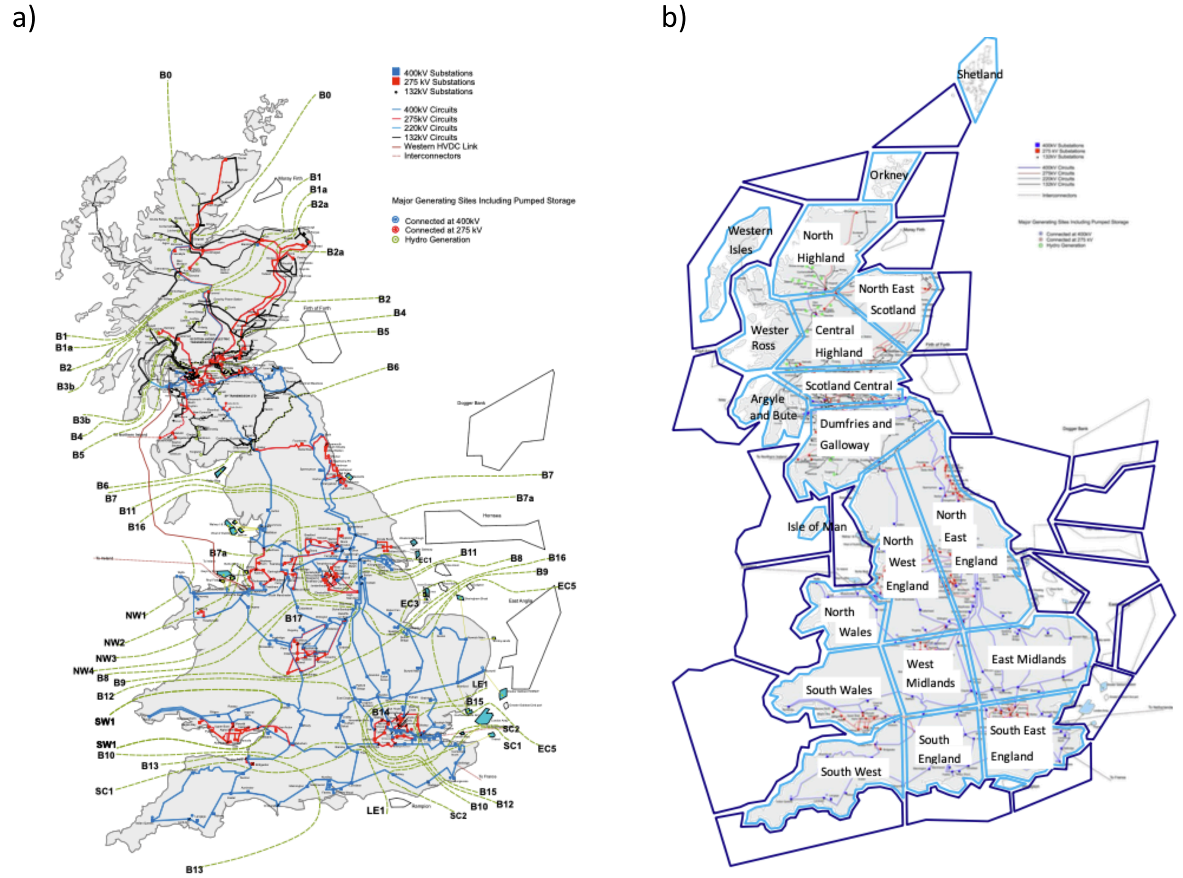


Figure 1.3: Great Britain Electricity Transmission System, Transmission Constraint Boundaries and Wind Development Zones for Transmission Purposes.

a) Shows the National Electricity Transmission System (blue-400kV, red-275kV, black 132kV) and Transmission Constraint Boundaries (green) together with major generation stations. b) Shows the resulting wind development zones for transmission purposes. **Notes:** The general power flow in Great Britain is from NNW to SSE. **Source:** National Grid, Electricity Ten Years Statement 2017 (a), Long-term Market and Network Constraint Modelling 2017 (b) National Grid wind development zones 2018.

Developing a spatial strategy for onshore wind development is therefore extremely complex. To prepare a plan for onshore wind development would need to take account of the local environmental, social and planning issues (identified in Table 1.1) together with an understanding of the wind resource. Any meaningful plan would also need to take account of the electrical engineering requirements of connecting to the energy system and the transmission of energy across the country. The broad challenges of siting wind farms to recognise the geographical balancing of the national grid appear particularly complex. Possible planning options might also need to recognise the potential to build new transmission capacity for the national grid. Extensions to the transmission system might best be supported by clusters of wind farms.

An important choice for a spatial strategy of any dispersed energy is selecting an appropriate scale or region for the plan. There is a strong arguable case that spatial planning for onshore wind should be undertaken on a GB-wide basis. Not only does a plan need to take account of where the resource and demand for energy is, it also needs to consider the full local environmental consequences of all potential development. For an onshore wind spatial strategy this probably requires detailed topographical assessment to consider the visual effect. The plan would need to contend with a myriad of options and choices. For example, locating a substantial cluster of wind farms in North Highland, Scotland, is likely to require transmission reinforcement lines all the way down Great Britain, from Northern Scotland to the existing large-scale grid system in the Midlands (see Figure 1.2). Wind farm clusters in Wales would require far less distant transmission. Developing wind energy spread through Southern, Midlands and Northern England might well avoid any need for significant transmission but would probably increase effects on receptors. Quantifying these options appears problematic.

Overall onshore wind is therefore considered too complex to be dealt with adequately within a PhD thesis. Whilst Crown Estates (2019) have shown that coherently planning for offshore wind is possible with large corporate manpower resources, this is far less complex than onshore. In an offshore situation the environmental, planning and social factors are either not applicable or far simpler. The technical and electrical engineering issues are much less complex.

Given the substantial challenges of onshore wind an alternative form of dispersed energy is sought for study. Consideration has been given to each of the dispersed energy technologies. Solar offers a far simpler field of study than onshore wind. However, solar energy suffers from many of the same transmission grid intricacies as onshore wind. At the same time, it has a much lower energy yield per hectare (Hiteva 2019). Carbon capture use and storage offers considerable potential in stripping out emissions (Gibbins & Chalmers 2008). However, it has struggled to gain viability. The spatial dimension appears unquantified. The geographically based resources, of geothermal and compressed air, are in the early stages of understanding of their potential. Biomass and anaerobic digestion have footprints based on agricultural activity whilst energy from waste is suited to urban settings (Van Fan et al 2018). Whilst industrial cogeneration has high energy efficiency its location is difficult to identify and therefore difficult to model (Cormio et al 2003).

Having reviewed the various alternatives it is considered that shale gas offers the most appropriate technology to study the planning and the development of a strategy for dispersed energy. Shale gas, although not renewable, conforms with the definition used in this thesis for 'dispersed energy'. It is both locationally tied and the resource is spread across a large area. Planning for the development of shale gas offers a distinct form of dispersed energy which can reasonably be dealt with in thesis-scale research. It is a sufficiently distinct resource that the extent of thesis level research can cover it without being overwhelmed. It offers sufficient geographic coverage, over a reasonably diverse area, to be of research valuable. The potential local environmental effects needing careful planning consideration also contribute to the research value.

In the UK context shale gas offers the key ingredients which need to be considered for an examination of dispersed energy spatial planning. The geographic extent of the resource has been identified and established with known boundaries (Andrews 2013). This has shown that the shale resource existed in grouped regions or basins. These basins form definable and manageable zones for research purposes. The technology behind shale gas development is mature, particularly in the US. Therefore, the technical or engineering requirements for planning purposes are clear. The knowledge of how shale resources would be developed is well established. The consideration of shale gas proposals, within the planning system between 2014 and 2020, indicate which environment effects are likely to be influential in determining suitable locations for development (see chapter 3). This experience has also highlighted the social dimension and the value of planning to avoid adverse residential receptor effects. Overall, UK shale gas development provides a suitable case study subject to examine whether dispersed energy can be strategically planned. Further details on the resource, technology and environmental requirement for modelling are discussed in the Context Chapter 3 and Methods Chapter 4.

1.7 Thesis Structure

This section sets out the structure of the thesis and provides an overview of the scope of the research. Chapter 2 provides a detailed examination of the pertinent academic literature. Particular focus is given to the gap in the scholastic knowledge which this thesis seeks to bridge. Chapter 3 looks at the policy and practical context for this research. It sets out the existing circumstances in the study location and the regulatory position for the particular dispersed energy studied in the thesis. Chapter 4 sets out the detailed methodology for how the case study research was conducted. It provides both an overview of the research method and details on how the research was conducted. Chapter 5 states the results and findings of the research. Chapter 6 discusses these results and findings: both in detail of the case study modelling findings and the wider issues for spatial planning of dispersed energy. It discusses the potential value and challenges for planning dispersed energy, deduced from this research. It also discusses the institutional perspective best suited to planning for dispersed energy. Chapter 7 provides the broad conclusions of the overall research and the thesis. It identifies the potential value of this research, consider recommendations for practice and indicates where further research would be useful.

2. Literature Review

This chapter reviews the published academic literature relating to the research question addressed by this thesis. The research question is two-fold: to establish whether it is possible to plan for dispersed energy; and to explore what the prerequisites to planning for dispersed energy are. Are there reasons that no effective planning for dispersed energy takes place? Is this due to structural or systematic reasons? The first part of this Chapter explores the academic research which demonstrates the gap in planning for dispersed energy, examines whether and how it is possible to plan for dispersed energy and the factors that need to be considered when developing a plan for dispersed energy. For the second part of the research question this literature review looks to see if there are reasons why no effective planning for dispersed energy takes place: does the literature show if we can deliver a plan which integrate local environmental effects and technical engineering considerations into a plan for dispersed energy? Whilst this is perhaps a policy and practice question the review in this chapter is seeking scholarly insight into this.

Where relevant to the academic literature, this chapter also refers to governmental statutes, regulations and guidance. The issues around decision-making for dispersed energy development, which set the context for this thesis, are dealt with in Chapter 3. Inevitable in this field academic literature is closely connected to the applicable law, since governmental regulation sets the parameters for certain activities. For example, the reasonably unique UK planning system is established in law and operates in a specific way due to practice guidance and caselaw. Much of the literature on dispersed energy decisions, planning theory and practice is therefore appropriate to the prevailing planning and energy law. Similarly, the way environmental effects, aggregate and cumulative effects are dealt with reflect the legislative provision for these. These legislative frameworks and policy approaches vary by jurisdiction. Whilst international literature is informative and relevant, the focus in this thesis needs to be appropriate to the way environmental effects are considered for dispersed energy in the UK. However, the wider international perspective is also considered. Where pertinent to the subject matter, this literature review points out where important legal differences exist between the UK and other jurisdictions. There is an unavoidable overlap between this chapter, on academic literature, and the next chapter, on the research context. The emphasis of this chapter is on the academic literature whilst the next chapter emphasis the legal and regulatory context.

The chapter is organised into sections. It firstly reviews the relevant broad literature on planning. General planning approaches to development are examined. Since the research comes from the planning perspective, the review then starts to focus down to considers specific relevant parts of the literature. This includes cumulative environmental effects (CEA) within the field of environmental impact assessment (EIA) and, where relevant, in the closely related field of strategic environmental assessment (SEA). This section also considers cumulative effects assessment and management (CEAM) together with adaptive management (AM). In the second section the literature review turns to focus on energy. Initially this section reviews the literature on general energy policy. Then the review focuses on insights available from traditional energy. This section is completed by examining the research on the spatial dimension or planning of dispersed energy. The third and final section of this literature review merges the planning and energy perspectives to look at the literature on the spatial planning of dispersed energy. This is firstly applied to all types of dispersed energy. This section is seeking to ascertain whether the thesis research question has been investigated and what lessons can be taken from that. As has been explained in Chapter 1, the case study modelling within this research has been applied to shale gas development in the UK. Attention is given to research on the spatial planning for shale gas: firstly, covering literature regarding the world generally; then specifically research which has considered UK spatial planning of shale gas.

2.1 Planning and Related Literature

This section of the literature review considers planning and relevant planning related research. These related areas include environmental impact assessment (EIA), cumulative environmental effects (CEA), cumulative effects assessment and management (CEAM) together with adaptive management (AM) and strategic environmental assessment (SEA).

2.1.1 PLANNING AND PLANNING APPROACHES

The thesis question here is approached from the academic field of land-use, spatial or town planning. In the UK this is also known as town and country planning. The shorthand name 'planning' is used for this. The planning field is concerned with a governmental process supported by a vocational practice. Established in post-war legislation, planning arises out of the government's desire to direct and control the development of land, on behalf of society. The vocational activity is backed up by planning theory and academic study.

There has been debate as to whether or not planning is an academic discipline and what standing it has (Davoudi 2010, Goldstein 2012, Andrews et al 2020). But the underlying objective of this scholarly endeavour is to support the practice of planning. Much planning literature in recent decades (2000 to 2020), particularly in the UK, has reflected discourse around the merits of the style of planning being deployed by the government of the day. Following periods of power for Labour and Conservative led governments, this includes the 'spatial turn' (Davoudi 2010) introduced in the 2000s and the resiling from this in the 2010s (Allmendinger & Haughton 2013). The spatial planning of the 2000s changed traditional town planning by "integrating policies for the development and use of land with other policies and programmes" (Baker et al 2010, p574). Regional planning guidance and bodies were replaced by 'regional spatial strategies' (Nadin 2007). Whilst this might superficially appear to provide a close bridge to strategic environmental assessment (SEA) this link was never intended (Hanusch & Glasson 2008).

'Spatial planning' is part of post-structuralist conception of space and planning where grand narrative or plans have passed and planning is a pastiche of free-floating un-systemised approaches (Davoudi & Strange, 2009). It is therefore perhaps not surprising that whilst several saw spatial planning as a new era for planning (Gallent 2008), it was seen retrospectively, by Allmendinger & Haughton (2013), as being all things to all people. Whatever the spatial turn did give to planning as a discipline was, in any event, swept away shortly after 2010. As Ellis and Henderson concluded, during the 2010s English planning went into crisis as the “rich utopian tradition that underpinned the town planning movement in England is dead” (Ellis & Henderson 2016, p1). After 2010, planning was changed into something more difficult to discern: not the previous idealised social vision more a prosaic process, deciding where development should take place. As well as doing away with regional spatial strategies (DCLG 2011) the current era shuns any sense of blueprint or comprehensive planning. It “created a hiatus in the planning framework” and a vacuum on “important strategic planning issues” (ibid, p55). This rejection of common blueprints is ideological (Allmendinger et al 2016). No planning for planning’s sake.

The subject area of greatest change since 2010 is in planning for development. Having removed regional spatial strategies and blueprint planning, the proactive part of planning has evolved into ‘soft spaces’ (Allmendinger & Haughton 2013) or fuzzy structures (Marshall 2020). In part this is a repackaging of “planning not as a barrier to growth but as a facilitator“ of growth (Allmendinger & Haughton 2013, p954). A form of neo-corporatism with a kind of structured theory of interest groups, rather than a pluralism (ibid). Yet territorial planning authorities remains and rather than regional planning strategies local planning authorities must coordinate through at ‘duty to cooperate’ (PAS 2020). By soft spaces Allmendinger is suggesting that, rather than traditional territorial based town planning (at either the city, county or regional level), the emphasis has moved to local actors coming together in novel formations. These are ad hoc groups forming to respond to different challenges, for example ‘city deals’ for city regions (O’Brian et al, 2019). Rather than being top-down or based on formal structured government, current policy is to encourage local actors to work out for themselves the geographies and the functional scope that is required (Allmendinger & Haughton 2013). As well as traditional territorial planning authorities, these local actors include business-led ‘local enterprise partnerships’ (BEIS 2020b). These soft spaces appear to be designed to fill the void between localism and national government, whilst avoiding formal structures such as regional government (Allmendinger & Haughton 2013). So, a form of development or positive planning still exists. These soft spaces enable a pragmatic response to apparent common problems. For the research question here, particularly the institutional capacity aspect of the second part of the research question, this represents an interesting opportunity.

Despite the severe challenges to planning over the last two decades the fundamental tools of town planning have remained available. The core components of planning legislation, approved at its modern founding in the Town and Country Planning Act of 1947, are still in place today (Booth 2014). Planning retains the two-part system of ‘development planning’ and ‘development management’ at its core (Corkindale 2004, Booth 2014, Rydin 1993, Rydin 2003). Allmendinger characterises these two planning functions. The first, embedded in development or positive planning, is ‘thinking ahead’ and orientating policy to future needs through reaching out to “coordinate” physical development where required (Allmendinger et al 2016, p40). The second function, development management (also known as development control), “involves a more responsive, legal role of allocating rights in order to implement or execute the plan (the regulatory) to determine and allocate property rights, i.e., planning permission” (ibid, p40). The details of the UK planning system are outlined in Chapter 3. The thesis research question, of whether we can plan for dispersed energy, and the second research objective, RO2 (section 1.5.1), appears to be supported in that positive planning still exists. Whether this is sufficient in scope, to include technical considerations outside the sphere of traditional planning disciplines, is discussed below.

Before moving on, it is useful to define terms as there is considerable scope for confusion. Particularly to establish the difference or overlap between ‘planning’ and ‘strategy’ or a strategic approach. Healey observes that lots of claimed strategies are just names and political rhetoric for electioneering or funding applications (Healey 2009, p439). The important distinction she makes is substance. Strategy is integrative and “geared towards efforts to change direction, to open up new possibilities and potentials, and to move away from previous positions” (Healey 2009, p440). Albrecht sees strategy as requiring an “accurate understanding of the real situation, realistic goals, focused orientation of available strengths and persistence of action” (Albrecht 2015). However, the terms ‘planning’ and ‘strategy’ are to a degree interchangeable. Planning being a process of deciding in detail to do something. Strategy being a general plan intended to achieve something (Collins 2020). Planning can be seen as the process of preparing a plan whereas strategy may be seen as the action or choices element of the plan (Albrecht 2006). Whilst this emphasis is sometimes used in this thesis, I will also use the terms interchangeably. The term ’planning’ can also refer to the ‘planning system’ which is the legal constituted process of managing the development of land and buildings in the UK (Planning Portal). Planning involves an element of timing. “Planning ensures that the right development happens in the right place at the right time, benefitting communities and the economy” (DCLG 2015, p4).

The planning system today is far from perfect with considerable shortcomings in its inability “to deal with social inequality and environmental injustice” (Rydin 2013, p187). While elements of this are long standing it may be increasing due to the move to adapt development planning into two modes of operation: bottom-up localism and top-down programmes and strategies. There is tension between these (Gallent 2008). The bottom-up approach of localism empowers neighbourhood planning (Brookfield 2017, Parker & Street 2015, Bradley 2015). This involves strong community involvement but that can be frustrated by uncertain priorities, local tensions and process (Parker et al 2017). In the soft spaces there is a move towards supra-local, top-down, strategic decision making, particularly for infrastructure as well as city regions (Bafaraset 2016, Marshall 2020, Morphet, 2016). These initiatives are usually government led, following national priorities (Marshall 2020). But the compromised local government system (Bafaraset 2016) often results in tension with local interests (Gallent 2008). Infrastructure development decision making at the supra-local level is seeking to make faster, leaner decisions (Gallent 2008).

This thesis is concerned with decision making in the latter mode, of a positive planning strategy. It treats ‘dispersed energy facilities’ development as an infrastructure. The issues considered in this thesis are therefore quite limited. It is primarily concerned with the technocratic feasibility of planning for dispersed energy at an appropriate scale of development. This assumes that a pragmatic response to apparent common problems of coordinating dispersed energy is possible. As explained earlier, it does not include the social, inequality and environmental justice issues associated with many dispersed energy developments (see Box 1.1). The thesis does not consider whether or not a type of dispersed energy in principle should go ahead. The focus of this thesis is on the quantification of the potential environmental effects of dispersed energy (in the UK) and seeking to establish whether a methodological technique for the spatial development of dispersed can be provided with minimal adverse local environmental effects. From the analysis of literature considered for this review, the research focus here appears to be unusual, possibly novel, in that is seeks to combine the technical with environmental in a coherent spatial context.

As pointed out at the opening of this section, much planning literature in since 2000 considers the merits of the planning system deployed by changing governments. Perhaps surprisingly, very little literature really seeks to cover the vacuum left by the absence of regional planning. There is also very little planning literature on the provision for dispersed energy. For regional scale wind development in Wales, Cowell considered whether environmental effect have been appropriately addressed when the technical feasibility was assessed, from an institutional viewpoint (Cowell 2010). This thesis partly seeks to examine the potential of supra-local or regional planning of dispersed energy. It considers, if holistic (possibly regional) planning was applied to dispersed energy, whether the environmental effects of dispersed energy could be reduced.

The lack of planning literature on the planning of energy is despite the shared obligation across all policy fields to seek a response to climate change. Planning includes goals for sustainable development (Cullingworth & Nadin 2003, Batty 2006, Piper 2002) but, curiously, this has limited coverage of energy. This appears to arise for two reasons. Rather like roads, transport, defence, health and other state developments, the planning legislation largely left energy development under separate legislation (e.g., the Electricity Act 1989). So, in practice energy was dealt by other parts of government (previously DECC and currently BEIS). Secondly, the power energy infrastructure has been largely unchanged since the 1970s (Hannah 1982, Bell 2009). So, for several decades there has been little need for planning to consider energy developments. The planning literature has generally followed this practice. This thesis seeks to explore this void.

For most dispersed energy types planning consideration is limited to the local environmental and social effects: looking at each proposal on a stand-alone basis. There is no consideration of technical feasibility within the planning perspective. This means that key factors, which are pertinent to planning decisions on dispersed energy, are omitted. For example, for onshore wind energy Bell (2009) has identified a series of factors which influence the potential for development, which are excluded from planning consideration. Factors such as transmission grid access and national transmission constraint boundaries prevent viable development of onshore wind in several locations. Or they require substantial investment in new transmission infrastructure (ibid). Any new proposals, such as the Beauly-Denny transmission line is considered individually on its own merit, as a single project (Miller 2015). Similarly, wind farm proposals are considered on a stand-alone basis. Consideration can be given to cumulative effects but without breaking out of disciplinary boundaries. Town planning research, following practice, does not seek to consider positive planning for energy developments in a holistic way. This appears to be a constraint arising from planning's disciplinary boundaries. To evaluate and plan effectively for the development of this type of dispersed energy therefore requires the planning discipline to move beyond its traditional sphere or silo. This thesis does this and seeks to examine a holistic positive planning methodology for dispersed energy.

This thesis aims to use planning theory, principals and concepts, but moving beyond its usual planning sphere to include technical factors, to build a methodology to create a framework for planning dispersed energy development. It seeks identify the factors that require to be considered in such an approach (under RO1), for example to balance technical feasibility of resource exploitation with consideration of the environmental planning effects of dispersed energy. The thesis seeks to discover if taking a cross-disciplinary approach could create a more effective methodology for the planning for dispersed energy (for RO2). The methodology developed here may also be utilised, with appropriate adaption, in development of all forms of dispersed energy types.

2.1.2 CUMULATIVE ENVIRONMENTAL EFFECTS

This subsection considers the academic literature on cumulative environmental effects and related fields of environmental assessment. Cumulative effects assessment (CEA) is part of the wider literature concerned with Environmental Impact Assessment (EIA) or environmental assessment (Glasson et al 2012). Outside Europe, cumulative environmental assessment has evolved to encompass cumulative environmental assessment and management (CEAM). CEAM has been extended to incorporate Adaptive Management (AM). Since these fields of academic research are pertinent to the research question, together with the research aim and objectives, these extensions to EIA and CEA will be considered here. This section is organised by briefly considering EIA then moving into a fuller discussion of CEA.

After this the literature around CEAM and AM are considered before coming back to the UK context to distinguish which issues in the literature are directly germane to this thesis.

The aim of environmental impact assessment (EIA) is to assess "the impact of planned activity on the environment" (UNECE 1991). A fuller definition for EIA, provided by the International Association for Impact Assessment (IAIA), states environmental assessment is "the process of identifying, predicting, evaluating and mitigating the biophysical, social and other relevant effects of proposed development prior to major decisions being taken and commitments made' (IAIA 2009, p1). Environmental assessment is clearly relevant to the research in this thesis, particularly the first research objective. The IAIA sees impact assessment both as a technical tool, providing information and analysis on the consequences for the environment of planned interventions, and as a legal procedure (ibid). As Glasson et al (2012, p5) identify, EIA is a process with well-defined stages involving: screening as to whether an EIA is required; scoping of the environmental issues to be considered; details of the proposal; identification of the baseline pre-proposal situation; consideration of alternatives; identification and prediction of potential environmental effects of the proposal; an assessment of the environmental significance of those effects; and consideration whether significant effects can be mitigated or avoided. EIA is undertaken for major development projects. According to the UK government:

> "The aim of Environmental Impact Assessment is to protect the environment by ensuring that a local planning authority when deciding whether to grant planning permission for a project, which is likely to have significant effects on the environment, does so in the full knowledge of the likely significant effects, and takes this into account in the decision-making process" (DHCLG 2019, p1).

Even in the early days of environmental assessment Cocklin et al (1992) observed that two characteristics of EIA were troubling. Firstly, EIA is reactive with assessment only carried out in response to development proposals. The second is that, since EIA is project based, the combined effects of two or more developments are often overlooked (Cocklin 1992a). Cocklin (ibid) describes this notion, where effects of two developments produce combined effects, as 'cumulative environmental change'. They report that attempts to address this type of change were being developed through initiatives referred to as Cumulative Effects Assessment (CEA), led by Canada in 1985 (ibid). They suggest that whilst project-based EIA is an established procedure providing reliable information, CEA is better addressed at the regional scale.

The research on the issues, scope and the requirement for CEA was expanded in 1993. Spaling and Smit (1993) observe that CEA refers "generally to the phenomenon of temporal and spatial accumulation of change in environmental systems in additive and interactive manner" (1993, p689). They describe cumulative effects as "destruction by insignificant increments" (ibid, p587). The 'increments' implied in their statement are individual projects. It is noteworthy that Spaling and Smit are suggesting that the implied cumulative 'destruction' is insignificant or not visible or recognised at the level of individual projects. Spaling and Smit (1993) are also identifying two important new components of CEA. Firstly, that cumulative effects can arise both over time, with different projects, and spatially, with projects within the same vicinity. Secondly, the manner in which cumulative effects arise can be both additive, where effects from several projects aggregate together, and/or interactive, where some secondary effect is produced from the effects of two or more projects.

Recognising that one of the major shortcomings of CEA is the institutional context in which it is applied, Spalling and Smit (1993) also add to the thinking on cumulative effects by recognising two essentially different approaches to CEA. The first reflects the traditional role of EIA as being an information gathering or information providing process. Here CEA, like EIA generally, is a scientific analytical process designed to feed into, but distinct from, subsequent decision making. This accords with Cocklin's (1992) reactive role of environmental assessment. The second approach to CEA "utilises planning principles and procedures to determine an order or preference among a set of resources allocation choices" (Spaling & Smit 1993, p593). In this second approach CEA is embraced within decision making. Perhaps setting priorities, weighing alternatives or trade-offs between environmental, social and economic objectives (ibid, p597). Here CEA is integrated into planning and decision making. This is pertinent to the second research objective (RO2). As Spaling and Smit emphasise, these two approaches expose quite distinct positions and roles for CEA. This observation represents a split in, or branches of, the thinking on CEA. This thesis will examine the merits of each of these two approaches. The branching in the literature is reflected in subsequent thinking about CEA, probably derived from different institutional arrangements, either side of the Atlantic Ocean. In the EU, and in particular in the UK with its well-developed planning system, decisions sit firmly within the planning remit where environmental assessment provides an information base for decisions. In the US and Canada, where federal-level governmental agencies have responsibility for protecting valued ecosystem components (VECs) and nature resource management, academic thinking has expanded CEA to enable environmental assessment to take on board a management of VECs role. In Canada CEA is concerned with "safeguarding VECs sustainability in the face of development" (Duinker 2006, p154).

The Canadian guidance has added more substance to the understanding and thinking around CEA. It restates the importance of spatial and temporal boundaries and highlights the importance of the source-pathway-receptor model for effects (CEAA 2014). It has also distinguished four specific type of cumulative effects. These are: additive, where the effects from two or more projects is aggregated; synergistic, where the interaction of two or more projects results in a combination greater or different than simple addition; compensatory, where the effects from two projects in some way offset each other; and masking, where the effect from one project hide or obscure the effects of a second project so that the no cumulative effects arise (CEAA 2014). Compensatory effects are sometimes referred to as countervailing or antagonistic (IFC 2013). But reflecting on the Canadian CEA system Noble (2010) notes that scale matters (project v regional) and cumulative effects are problematic for project-based EIA. "The mandate of project-based EA and of CEA do not always align" (Noble 2010, p10). This thesis will examine whether these observations are applicable to UK dispersed energy. It will also consider whether the types of cumulative effects are distinguishable.

By 2010 Canter et al recorded that "cumulative effects continue to be a persistent analytical challenge", with the "long standing areas of concern" for CEA identified earlier remaining (2010, p259 & 260). In North America the widened remit for CEA evolved into 'cumulative effects assessment and management' (CEAM) (Canter & Ross 2010). The addition of 'management' to CEA arises from the "frequent necessity of proactive planning to main development opportunities in specific study areas", through regulatory requirements and through recognising the value of a holistic planning approaches to mitigate cumulative effects (ibid, p263). In other words, in-line with the research aim of this thesis, they see an important connection between the scientific analysis of potential effects and decisions on development. The process for CEAM includes: identifying "other past, present and reasonably foreseeable future actions within the space and time boundaries" that could create cumulative effects (ibid, p263); "assess the significance of the cumulative effects"; and developing effects management measures (ibid, p264).

Canter and Atkinson (2010) take this management augmentation to CEA further by supplementing this with 'adaptive management' (AM). This involves changing the traditional predict-mitigate-implement model of environmental assessment into a predict-mitigate-implement-monitor-adapt model. AM moves beyond the decision into monitoring effects as developments are undertaken and, if required, adapting the developments. This approach enables decisions to be more flexible, or rather provisional. It enables large scale development programs to be implemented as a coordinated approach facilitates improved control over cumulative effects. This AM approach moves beyond purely project-based environmental assessment and starts recognising that cumulative effects can be managed at the regional scale (ibid, p287). The ability to operate at large regional scale is linked to moving "beyond piecemeal" or incremental thinking (ibid, p289), and aligns with the research purpose here. Duinker & Grieg also advocate regional scale CEA to address problems with cumulative assessment (2006). Whilst laying out the fundamental elements of AM Canter and Atkinson point out that this includes a "quantitative prediction" of the anticipated cumulative environmental effects (Canter & Atkinson 2010 p293). They also suggest that AM can be used to identify and evaluate alternatives (ibid). Canter and Atkinson's (ibid) thinking appears to be related to the research question which this thesis seeks to address, as they are distinguishing different 'planning approaches' of incremental project-based decisions or regional-scale strategy. Essentially, the regional scale adaptive management is akin to the positive/ holistic development planning envisaged in this thesis to be applied to dispersed energy (under RO2 and the research ambition). To test Canter and Atkinson's (ibid) perspective the analysis within this thesis will require 'quantitative prediction' of likely environmental effects.

Over the Atlantic CEA and EIA in Europe is driven by the regulatory requirement which arise from EU directives (Glasson et al 2012). Consideration of cumulative effects within environmental assessment first arose in 1997 with the EU amending (Council Directive 97/11/EC) the earlier EIA Directive (Council Directive 85/337/EEC). It is proposed by the author that in the UK, at least, cumulative effects were in some way considered within the planning system through structure planning (Booth 2014). But it is noteworthy that legislative recognition of cumulative effects within Europe was far later than in North America. Following the 1997 directive the EU issued guidelines on CEA (Walker & Johnston 1999). These guidelines confirm the consistent problem of how to define cumulative effects. Different from earlier North American thinking on cumulative effects, the EU identify three types of effects. These are: indirect impacts sometime called secondary effects, which do not directly result from a project but arise as a consequence of a change created by a project; cumulative effects, which are aggregate effects, similar to CEAA's additive effects; and interactive effects, similar to the CEAA's synergistic effects. In 2001 the EU introduced strategic environmental assessment which also included cumulative effects (Council Directive 2001/42/EC). Much thinking on CEA in North America comes from academics with encouragement from environmental agencies. It is notable that there is less academic literature in the EU on cumulative effects and little coverage of any management of cumulative effects. For example, there is no evident recognition of a creeping baseline when noise from wind farms is based on tolerating a 5% increase over background noise (ETSU 1997). The lack of research focus on managing cumulative effects perhaps arise, at least in the UK, due to the extant role of planning.

In part, the evolution of thinking on cumulative effects in Canada and the US towards CEAM and AM is a product of the regulatory system there (Spaling et al 2000). In Europe and particularly the UK, the planning system provides the regulatory mechanism to directly control development. In the European context environmental assessment therefore remains a "decision support instrument" (Bragagnolo & Geneletti 2012, p39). It acts in an information provider role without the need to encroach upon development management or decisions. A further contextual difference is that in North America environmental assessment is engaged in protecting large areas of nature resource management and valued ecosystem components (Hegmann & Yarrington 2011) while in the UK the emphasis is on mediating the impact of development on the human populations (Piper 2016). The UK and European branch of the evolution in thinking and research on cumulative effects has moved in a different direction. For the UK, Cooper & Sheate (2004) have suggested integrating CEA into strategic planning. Echoing Cocklin et al (1992) and Canter & Ross (2010), Cooper and Sheate (2004) again recognise the limitations project-based CEA. They prescribe a strategic approach on the basis that: cumulative effects occur at different scales; strategic planning authorities are better positioned to address cumulative effects; mitigation of cumulative effects is often beyond project level; and CEA needs a proactive strategic approach (Cooper & Sheate 2004). They affirm that cumulative effects “could be better addressed through strategic planning” (ibid, p8). This thesis seeks to test the validity of their observations by developing a methodology for holistic spatial planning for dispersed energy (RO2), effectively strategic approach, which can be compared to extant incremental decision making, as a means of consideration of cumulative effects.

Cooper and Sheate also suggest that CEA should be undertaken as part of strategic environmental assessment (SEA). SEA in the UK and EU, however, is concerned with a “higher level in the hierarchy of planning” for ‘plans and programmes’ (Piper 2016, p42, ODPM 2005). These are not necessarily part of strategic planning and may well exclude some cumulative environmental effects. It has also been observed that conducting CEA within SEA presents considerable challenges (Gunn & Noble 2011). Whilst geographic and temporal boundaries are often or can be made to be sufficient, the topical boundaries or the scope of CEAs are often inadequate (Bidstrup et al 2016). In part the issues of conducting CEA within SEA arise because of regulatory restrictions and the motivation for SEAs is often simply to “meet legal and regulatory requirements” (Lobos & Partidario 2014, p34). It therefore appears that SEA does not necessarily provide the capability for strategic planning to deal with cumulative effects in the way that Cooper and Sheate (2004) envisaged. Whilst Cooper and Sheate’s observation of the need for CEA to be part of strategic planning is interesting their final solution, of cumulative assessment within SEA, appears problematic. I shall consider the appropriateness and value of SEA in context of cumulative effects in relation to dispersed energy development in Chapter 3 (Section 3.2.3).

Piper gives an updated review of CEA practice in the UK (Piper 2016). This records that the perineal problems of CEA persist. She confirms that in the UK the aim of CEA is to provide information to assist decision making within the planning system. From the practical case studies covered she notes that a useful prediction and evaluation method for CEA includes modelling. She cites the application of modelling of CEA to cover noise and traffic (Piper 2016). Piper also points out that for CEA for concurrent similar developments “developers are unlikely to work together” (ibid p45). She suggests a strength of CEA, where it is part of strategic planning, is that “much greater flexibility may remain possible in terms of location and the nature of projects” (ibid, p46). This is a recognition that when project proposals are formally put forward the planning authority has little choice but to determine the proposal on its merits. Whereas within a strategic planning process the location for projects can be indicated after taking account of and minimising cumulative effects. The UK regulatory context for cumulative effects assessment and planning for this thesis is outlined and discussed in Chapter 3 on the Context for the research question.

From this review of the literature on cumulative effects assessment several broad observations can be made. The literature makes clear that there are considerable problems with CEA. There is a lack of clear definition of what cumulative effects are. Many CEAs do not adequately cover the scope of likely cumulative effects, so there are issues around scoping. And there is further challenge of understanding which other projects, past present and future, need to be taken into account. Yet despite these shortcomings there is a perennial desire, throughout the literature, to see cumulative effects assessed effectively, recognised and properly addressed. There is clearly a substantial need to try to bring clarity to cumulative effects and CEA. Overall, cumulative effects assessment is a challenging area of research.

Of central relevance to the research question in this thesis is the recognition that significant differences arise between project-based CEA, which often inadequately deals with cumulative effects, and the benefits of regional scale assessment. These two can be seen as linked to alternative planning approaches (development planning and development control). This thesis therefore can be seen as contributing to the thinking on CEA by considering the viability and practicability of assessing the cumulative effects of dispersed energy, in the UK. The thesis can consider the different types of cumulative effects (additive, synergistic, compensatory, direct, indirect) and review what impact each type of effects has. Relevant to the first and third research objectives (RO1 and RO3), this research can consider the temporal and spatial dimensions of dispersed energy.

Perhaps reflecting the lack of clarity on the term, cumulative effects are often associated with specific processes which tend to reflect some form of interaction of effect for two or more projects. In the European and UK context at least, this does not necessarily include the aggregate or overall environmental effects which might arise from a programme of related development (for example, a plan for dispersed energy). Given that a coordinated programme of developments is envisaged, in the second research objective (RO1), it useful to be able to identify the overall level of effects which arises from a plan for a programme of development. For example, the plan envisages traffic effects arising in various parts of the region covered. It would be useful to know what this overall or aggregate effect of the plan might be. To avoid confusion with the restricted definition of ‘cumulative effects’, I will refer to these overall or aggregate effects as ‘accumulated’ effects. Such accumulated effects need not necessarily be cumulative effects.

2.2 Dispersed Energy

This review now turns to consider literature on energy policy. It first looks at general energy policy and then considers any useful lessons from traditional energy development activity. The section then moves on to consider the spatial dimension of energy policy. Whilst international research is considered, particularly in respect to spatial aspects of energy policy, the section focuses on the UK energy policy.

2.2.1 GENERAL ENERGY POLICY

Like many countries, the UK experienced major expansion of its power generation, transmission and consumption in the post-war decades. For the UK this was under a centrally planned nationalised industry (Hannah 1982). The late 198Os saw a major policy shift away from centralised control and planning to a market-based energy system. The early decades of market-based operation, during the 1990s, coincided with a period which required no fundamental revision to energy production and transmission (Helm 2003). Since the millennium’s turn energy policy has shifted fundamentally to recognise the global environmental consequences of climate change, driven by emissions from fossil fuels energy (Stern 2006). A series of policy upgrades and steps introduced the requirement for low carbon energy production and the phasing out of fossil fuels for production of electricity (Fan et al 2018). Keay argues that “energy policy is to a large extent about the long term and about an integrated holistic overall approach”. He recognises that “all countries have different resource bases, geographies, national priorities” and that “this is reflected in different attitudes to particular sources” (2016, p248). Keay’s observation imply each country and area requires a reasonably unique solution to the energy transition. Like many countries, the UK energy system is now a hybrid with power generation market orientated but with centralised socialisation of subsidy to encourage low carbon power production. This is typified by the operation of the transmission system, which is nominally privately owned and operated but under tight regulator and government direction (Ofgem 2020). While the energy system and generation are operated by private companies there is some centralised government rationale and strategy to development (BEIS 2019).

The current structure of the UK power market and the levers available to government have been set up through ‘electricity market reform’ and new government directives (Newberry 2013). A ‘merit order stack’, giving priority to lowest cost generation, with significant modifications has persisted. High carbon-emitting fuels sources are being phased out and/or paying a premium for carbon emission pricing (ibid). Meanwhile ‘pricing taking’ must-run power sources, such as wind and nuclear, have introduced issues of intermittency and inflexible generation. This has resulted in an increased role of dispatchable generation. As with many countries, this has resulted in a requirement to offer guaranteed wholesale pricing for low carbon energy developments. This subsidy was initially provided through ‘renewable obligation certificates’ and later via ‘contract for difference’ (Simshauser 2019). To address potential market-wide consequences of intermittency, a ‘capacity market’ now operates to assure the availability of sufficient dispatchable generation (Grub & Newberry 2018). Overall, the current UK energy policy provides: a guaranteed price for new low carbon generation, a tax on carbon emissions, a capacity market to sustain adequate levels of dispatchable power and a generation emission restriction designed to discourage coal. It comprises a mixed decision system of market orientation and some centralised control (Pollitt 2013).

Whilst the UK government has set broad energy mix ambitions and a target direction for emissions, the operational delivery of policy is largely left to the market (BEIS 2019, BEIS 2020a). In the relation to the transportation of power this has resulted in an incremental or ad hoc approach to developing requirements. Bell (2009) describes how government partially overcame industry resistance to grid access restrictions for new dispersed generation by introducing a practice known as ‘connect and manage’. This enables prospective new generation sites, such as new wind farms, to apply for grid access anywhere in the country. The transmission system owners offer a connection to the nearest transmission point tied to the construction cost, together with details of other grid reinforcement ‘enabling works’ required to be carried out before connection. The broader network reinforcement costs are socialised whilst direct connection cost is borne by the developer. Once accepted the generator's right to access are "held in perpetuity" but without a guaranteed connection date. "This is defended by the transmission licensees on the grounds that the main risk to completion of the works is that of obtaining the necessary planning consents, which they argue is largely outside of their control" (ibid p2).

What Bell points out is that, whilst the transmission network was design for 'planned power transfer' between energy exporting and importing power regions, the current network reflects historic pattens of power generation and demand. There is little opportunity for provision for major structural changes to the network to accommodate new dispersed energy development, although ad hoc reinforcements can take place (Pipelzadeh et al 2015). Unfortunately, the literature follows the regulatory structure by showing assessment of environmental effects is only confined to a project basis. There is no strategic or comparative assessment of network reinforcement. There is therefore no comparative consideration that one grid development project may have greater or less local environmental effects than another. There is no evidence of weighing the merits of a dispersed energy development or cluster on the environmental effects of wider network reinforcement. This appears to be a gap in study which this thesis, particularly the research ambition, RO1 and RO2, attempts to consider. Given the lack of coverage of this situation in research further details of the structure of decision making are given in the Context Chapter 3.

The literature is demonstrating that the potential obstruction to grid improvement is indicative of wider malaise over developmental issues within the power system. This is largely due to the situation of a "half-planned, half market-based" energy policy (Keay 2016, p249). To a degree, a country's energy systems is a "prisoner of its past, with an energy asset base which may not be optimal for current energy policy objectives" (ibid p248). UK energy policy is in a limbo of "the worst of both worlds – without the coordination and direction which could come from a centralised approach" or the efficiency of a market (ibid, p247). For dispersed energy development it is for the market and individual developer to decide where to site new generation. However, "generators might therefore be seen as having a choice between locating new facilities in areas of the system that are less constrained but perhaps less economically optimal from a production point of view, or simply bearing the increased risk of locating in the export constrained areas" (Bell 2009, p7). The lack of centralised control means any need for large transmission development is unlikely to be met. Whilst central government exhorts local planning authorities to recognise the need for dispersed energy it does very little to require local authorities to identify "suitable areas for renewable and low carbon energy" (Smith 2016, p6). Local authorities "no longer have to adopt targets for wind farm" developments (ibid, p9). The literature is recognising the loss of historic centralised implementation or any coordination of local developments within energy policy.

This literature review of energy policy illustrates a vacuum in research. Having undertaken a detailed content analysis of energy scenarios, Harper et al concluded that the "environmental impacts of energy scenarios were rarely considered". "Evaluation of environmental impacts of energy pathways is almost always lacking" (Harper et al 2019, p397, p405). They point out, that while energy pathways are often defined at the national scale, the environmental impacts are site specific and arise at the local level (ibid). Most energy policies only consider environmental effects in terms of climate change, i.e. global environmental effects (the conventional energy trilemma). There is little cross disciplinary interaction between energy policy and planning. There is only partial or ad hoc consideration of the spatial dimension of policy. Yet there are important points of common challenges that need to be addressed, regarding the need to develop dispersed energy to address the climate crisis. The grid access issues and lack of centralised thinking regarding dispersed energy development highlights shared issues. Whilst the market system means that "contracts for difference has been incredibly effective at reducing the cost of … wind projects" (Hanlon & Cummins 2020, p3), there is no evident consideration of any potential local environmental effects. There is explicit recognition that the lack of cross silo activity means there is significant limitations on the delivery of new energy infrastructure. Through the research aim and second objective (RO2), this thesis seeks to explore whether there would be research and societal benefits in improved cross disciplinary research which takes account of, if not integrates, both energy policy and local environmental consequences.

2.2.2 INSIGHTS FROM TRADITIONAL ENERGY DEVELOPMENTS BETWEEN 1988 AND 2019.

The thesis Introduction suggested there has been no significant development of traditional power production in the UK since the post-war boom in electricity generation and consumption. More precisely, there has been no development away from traditional power generation sites. Since the privatisation of the UK electricity industry in 1988 and the removal of governmental directive for power to be produced from coal, there have been developments of gas-fired power stations. It is worth looking at these in light of the potential lessons for and differences to dispersed energy development. Cowell (2020) provides a longitudinal study of UK gas power station developments from 1988 to 2019. In England and Wales 111 major gas power stations proposals have been submitted. Nearly all of these have either been at extant or former coal fired power station sites, former heavy industry sites such as for iron or chemicals production (which usually incorporate energy production) or on land adjoining these sites. In 85% of these cases the number of public written representations on the proposal amount to less than 25, with 62% receiving less than 5 public representations. "95% of applications gained approval without recourse to an appeal", with two still under consideration (Cowell 2020, p77). Only three proposals were made for greenfield sites, away from 'established use' historic thermal energy sites, all of which were withdrawn due to local public opposition.

In assessing public opposition to these conventional energy developments Cowell observes that generally the public accepted re-use of the derelict or redevelopment on existing power production sites. However, he notes these "projects have effects that spill beyond site boundaries and that it is these that attracted most concerns" (Cowell 2020, p80). Local environmental effects are, of course, usually experienced beyond the site boundaries of developments. This is due to receptors being located beyond the development site boundary. The contrast between these conventional energy developments gaining public and statutory approval relatively easily whilst some sustainable dispersed energy developments struggle to achieve approval is stark. The recorded acceptance rate for UK onshore wind proposals is only 44% (Ref Harper 2019). The reason for this low approval rate appears to be due to dispersed energy developments routinely being proposed at new energy production locations. Whereas the gas power stations proposals are exploiting 'established uses', where local communities are accustomed to the local environmental effects of the development. Such effects might include the adverse visual effects of large-scale cooling towers and plant. Subsequent development, such as housing, might well be sited away from these power sites to provide a buffer and ample separation.

Underlying the conventional power approvals, Cowell (2020) is reporting the sense that the choice of the location is settled or entrenched and socially accepted. Beyond land use planning considerations, these extant sites may provide local employment. Not only does this provide a connection to some residents in the local community it could be known throughout the community. This acceptance suggests local communities have acclimatised to the local environmental effects and adapted to the presence of the established use. Dispersed energy, frequently requiring development in novel forms and on greenfield sites, often faces the challenge of being a new entrant and the source of a new disruption in new localities. The poor record of approvals for onshore wind may also arise because the development planning process is giving inadequate signals and direction on where these types of development should be located, as a consequence of a vacuum in planning for dispersed energy.

2.2.3 Dispersed Energy including Spatial or Regional Dispersed Energy Perspectives

Having considered the research on energy policy generally and the experience of traditional energy development, this review now turns to focus on literature on dispersed energy. Since dispersed energy requires considerable geographic spread (Table 1.1) this also includes spatial or regional perspectives. The issues identified in energy policy above means that there is little consideration of different perspectives of dispersed energy in the UK. This means the inherent issues with delivery of dispersed energy and regional perspectives on energy planning are only rarely explicitly considered in the UK. Where research has considered the spatial dimension of dispersed energy in the UK this is highlighted. In the main this relates to wind energy. There is some overlap between this section on dispersed energy and the next section which considers planning for dispersed energy.

For this thesis these various energy sources with distinct, often large-scale, footprints are treated as dispersed energy. Conventional power generation is locationally flexible and therefore policy can be aspatial. Thermal coal or nuclear station could be sited anywhere. Their siting could be based on purely economic choice (Hannah 1982). The newer forms of energy do not have this flexibility. A distinction of dispersed energy is its specifically spatial prerequisite. The dispersed energy types have spatial circumstances which are tied to geographical or geological location. And/or they require significant geographical spread. Hence there is an important requirement to pay particular attention to their spatial situation and circumstances. Due to this there is a strong need to consider this locational dependency, within spatial planning decision making (relevant to RO2). As a tentative starting point for the first research objective (RO1), I suggest that appropriate consideration of dispersed energy needs to consider the location of the resource, the extent of area required and the transportation of the energy, together with local environmental effects arising. Considering all of these factors might be called a holistic or regional energy planning approach.

Before moving into this subsection, it is important to be clear on terms here. The term 'local environmental effects' is used in this thesis. It is well known that environmental effects arising from traditional fossil fuel energy generation produce greenhouse gases. In the main it is the accumulation of these emissions across the globe which is creating the climate crisis and the need for the energy transition. Local environmental effects are taken be all other effects that might arise from energy production and transmission. These, non-global, environmental effects predominantly arise locally. For example, air pollution from burning fossil fuels for power generation is local to the point of production. Likewise, visual amenity, landscape, shadow flicker and noise are local effects from wind turbines. Essentially the term local environmental effect is used in this thesis to distinguish from global environmental effects.

This literature review of research on dispersed energy considers whether and to what extent the literature considers the locational dependency of dispersed energy. Attention is given to spatial or planning decision making. In the international literature consideration has been given to geothermal, solar, biomass thermal storage, compressed air, hydroelectric storage, CCS and bioenergy with CCS, and hydrogen. This review briefly summarises these then moves on to consider spatial planning for dispersed energy and techniques deployed.

Stephenson et al (2019) identify the various sources of geologically-based dispersed energy resources – including thermal storage, compressed air, hydroelectric storage, CCS and bioenergy with CCS, hydrogen and geothermal. They note that methane gas, produced from shale or conventional resources, is likely to be used for blue hydrogen until green hydrogen is available. A recent study expects blue hydrogen to dominate hydrogen production, with green hydrogen technology only becoming sufficiently mature to be cost competitive in the late 2040s or early 2050s (OGA 2021). A crucial theme for Stephenson et al's research is the locational dependency of these energy vectors. They identified a need to characterise rock geochemically and geomechanically to be able to determine where these resources might be developed (Stephenson et al 2019). In Iceland a strategic approach has been taken to developing the extensive geothermal resources there. There integrated planning allows dead ends about projects to be avoided, identifies areas which can be excluded from development and finds projects that best suit the technical, economic and environmental circumstances (Steingrimsson et al 2008, Hreinsson 2008). In Spain a collaborative strategic planning approach has been applied to develop solar and biomass energy (Terrados et al 2005). This has led to the development of a regionally based strategic energy planning tool (Terrados et al 2009). In Italy legislation has been passed to facilitate a regional planning approach for the promotion of renewable energies and energy efficiency measures. This shows that it is possible to promote renewables away from a centralised national government view and that it is possible to develop dispersed energy from a regional perspective (Sarafadis et al 1999, Brandoni & Polonaro 2011). In Australia regional energy master plans have been adopted to facilitate development of dispersed energy (Cheung et al 2019), although in practice these are quite limited in scale and largely represent supra-local funding programmes for ad hoc dispersed energy projects.

Moving to more coordinated planning or semi-planning approaches, Cormio et al (2003) outlines how it is possible to develop an energy system which considers energy supply, including intermittency of some dispersed energies, together with efficient transmission expansion and consumption. They develop a methodology for regional energy planning, which considers the regional environmental consequences through an environmental impact assessment (ibid). However, like many studies, this is a calculation of aggregate overall greenhouse gas emissions from fuel consumption used in energy production. Whilst this and efficient transmission are important factors in energy development programmes this is not recognition of 'local environmental effects' of the dispersed energy. This thesis seeks to include this within a holistic energy planning perspective.

Several jurisdictions have a similar experience to Great Britain with problems obtaining local consents for onshore wind developments (Brennan & Rensburg 2016, Betakova et al 2015). The literature suggests this often arises due to social acceptance (or lack of) of dispersed energy, particularly onshore wind (Wolsink 2007, Breukers & Wolsink 2007, Devine-Wright 2009, Cowell 2010, Hobarty et al 2012, Wolsink 2018, Bout 2019, Harper et al 2019). The leading researchers in this field recognise that social concerns arise because of the lack of connectivity between the “two main domains- spatial planning and energy policy”, where energy policy “at the level of central government is a growing top-down, technocratic, hierarchical ways of thinking” conflicts with local planning (Wolsink 2007, p2693 & 2702). The general solution in this field of research is to suggest that a deliberative approach is taken allied to ‘fair decision making’ (ibid). Hettinga et al (2018) evolve this through a multi-stakeholder decision support system which can facilitate collaboration at the local level to prepare an energy plan for a local area. Such a system takes account of local environmental effects by providing opportunity for those affected to voice their concerns. This thesis seeks to build on the lack of connectivity between planning and energy policy by exploring this relationship to consider whether it is possible to plan, or develop a spatial planning methodology (RO2), for dispersed energy and what institutional arrangement are best suited to address this.

Several studies have considered the transportation dimension of dispersed energy. Without these, unwarranted local effects can arise or results in wasteful energy production. This implies a sensible trade-off between the production of energy and local effects. The research on this is often approached from the perspective of making the transmission system efficient. Oree et al (2017) developed a network planning optimisation model. Joos & Staffell (2018) illustrates the consequences of failing to plan strategically for dispersed energy. Inappropriately located dispersed energy, or rather locating development without adequate provision of transport infrastructure, can lead to wasteful plant. Wind farms located in Southern and Northern Scotland, which sit behind UK transmission constraint barriers resulted in up to 30% curtailment (ibid). This suggests that dispersed energy projects should not be developed in isolation, since without some level of overview, investment can be wasteful and unproductive as well as giving rise to unnecessary local environmental effects.

Palmer et al (2017) have considered the spatial dimension of solar power including the ability of the UK transmission grid to cope with this. They observe that “little work has been presented on temporally and spatially resolved generation and its link to existing infrastructure”. But that “it is not sufficient to examine individual systems and then simply scale up to the installed capacity” (ibid, p2). They illustrate the problems of solar energy in sunlight hours, with daily and seasonal peaks, and that planned appropriately this does not need to stress the existing transmission infrastructure. Unfortunately, they omit consideration that this temporal generation is largely contrary to the UK energy demand pattern and grid access is limited (Hiteva 2019). Nevertheless, it is encouraging that research effort has been applied to thinking about the spatial and temporal dimension of dispersed energy including its transportation. This thesis supports this think but seeks build on this, under RO1 and RO2, by incorporating consideration of the local environmental effects to produce a system for guiding appropriate siting choices for dispersed energy.

Several studies have looked at dispersed energy from a systems planning perspective. A number of these studies have used GIS analysis to identify locations for dispersed energy development (Braban & Parry 2000, Simao et al 2009, Baseer et al 2017, Harper et al 2019). These often use geospatial analysis to identify environmental, demographic and sometimes technical factors. They are described as providing "a decision support tool regarding optimum wind farm locations" (Braban & Parry 2000, p61). Braban & Parry adopt a methodology of applying wind farm location criteria through GIS (ibid). They select criteria such as wind speed, topography, settlement proximity, distance from the transmission grid and various other factors. This early application of GIS analysis demonstrates the potential of geospatial analysis. Interestingly, they are combining both technical and environmental data into their spatial analysis to select sites. Simao et al (2009) have used GIS to build a multi-criteria spatial decision support system. Responding to the social gap / social acceptance perspective, this applies GIS modelling to facilitate a deliberative process amongst stakeholders in balancing the set criteria. Overall GIS provides a useful spatial perspective (which is relevant to RO2), but analysis has had varying success.

Harper et al (2019) have undertaken a spatial data analysis of the potential success of wind farm proposals for Great Britain. This retrospective geospatial modelling compared the approval and rejection of wind farms with factors of influence including economic, proximity to nature designations, demographic, planning authority political composition and proximity to other wind projects, through spatial regression. A related second paper applies GIS based Multi-Criteria Decision Analysis (Harper 2019b). They found the most influential factors were project size and distance to urban regions. This suggests, perhaps not surprisingly, that larger projects stand greater chance of success in remote areas. Overall, they find that demographic factors influence planning outcomes which can inform regional level energy strategy. It is also interesting to note that they recognise the restriction of the transmission network, that remote regions well suited to wind farms often have poor energy transport connectivity.

The challenge of these types of models is the granularity and the generalisation of factors (Joao 1998). The data granularity can obscure the influential effect. For example, the Harper study used demographic data from census units. This identifies population centres but omits that the planning decision criteria is usually adverse visual effects on residents located in the local vicinity (Harper 2019). It seems likely that more suitable social data should be distance to visually impacted dwellings, rather than census unit data. Since all factors cannot be included in these studies, applied factors are selected as surrogates for a group of influences through a process of generalisation. This generalisation of direct determinants undermines the analysis. Overall, the GIS based analytical impact on dispersed energy is informative. However, as Harper et al accept, “geospatial modelling should integrate local understanding if they are to provide realistic estimates of wind turbine sites” (Harper et al 2017, p963). In subsequent research Harper et al acknowledge that “greater emphasis must also be placed on non-geospatial issues such as the planning process” (Harper et al 2019a, p167). This thesis seeks to overcome the weaknesses in their methodology by identifying factors which have direct local environmental effects by modelling a planning process decision system. It is these direct environmental effects which influence planning decisions and the opportunity to develop dispersed energy projects. Use of this direct or ‘actual’ data, rather than proxy or surrogate data, within dispersed energy planning is highlighted in the third research objective (RO3). This thesis seeks to assess whether by replacing analysis based on proxy data with actual data the value of the geospatial modelling can be significantly enhanced. Doing this would appear to strengthen the potential of achieving the second research objective (RO2) and aid fulfilment of the research aim and purpose.

2.3 Planning for Dispersed Energy

Having consider the literature on planning and energy policy as distinct fields, the review now turns to consider planning for energy development. The prime focus of this section is planning for dispersed energy, particularly the types of new energy which have considerable spatial spread or are tied to particular locations. The section initially considers planning for dispersed energy generally. Since the selected dispersed energy for the case study in this thesis is shale gas the review then focuses on planning for shale gas development (SGD) research. This considers the global planning literature for SGD. Since the case study is based in the UK the review then concentrates on literature covering planning for SGD in the UK. Whilst the emphasis of this literature review is planning it is also beneficial to include the literature which considers the environmental effects, particularly accumulated effects. As pointed out above (Section 2.1.2) the UK has the capability to view dispersed energy through a proactive planning perspective.

2.3.1 PLANNING AND CUMULATIVE EFFECTS IN DISPERSED ENERGY - GENERAL

For the review of literature on non-shale gas development the focus is on energy developments which require an extended spatial coverage or are location tied. This excludes nuclear and traditional thermal power generation, which require large single point forms of development (Table 1.1). Biomass, which is grown alongside other agricultural and forestry products, is also excluded. Biomass fuelled power generation has often occurred by conversion of traditional thermal power sites. Industrial cogeneration is difficult to distinguish. The potential energy types which have similarity to the coverage and form of development, similar to shale gas, are wind and solar energy. Like shale gas development (SGD) both also largely occur in non-urban locations. Whilst there are important differences both of these can require extensive dispersed spatial coverage resulting in various cumulative effects. Due the state of technology and resulting scale of investment the literature on wind energy is more extensive (Willis et al 2018).

For onshore wind energy the primary environmental effects are on landscape and visual amenity (Hevia-Koch & Ladenburg 2019). There is therefore a need to protect valued landscape and to avoid issues of social acceptance within affected local communities. Cowell (2010) outlines how attempts to develop a spatial wind power strategic plan for Wales have led to a tendency to use prior land use designation to identify search areas. This approach leads to reinforcement of already degraded areas, which render certain environmental qualities and accumulative effects malleable. Cowell's (2010) research identifies challenges in the process of planning energy development across large areas. It does, however, confirm that strategic planning for spatial distributed energy development is possible. In this case the strategic planning process supplanted formal cumulative effects assessment. This demonstrates that, in the UK at least, strategic planning and cumulative effects assessment are juxtaposed but are to a degree substitutable. Also relevant to this thesis, Cowell explains the methodology employed in developing the strategic planning process. This identifies significant environmental effects through a process of "cumulative constraints mapping" (Cowell 2010, p226). This sieving technique includes the technical capacity where the wind resource is available, securing the amenity of settlements by creating appropriate buffers together with assessment of the key environmental (landscape) effects. This thesis takes the principles of cumulative constraint mapping and applies these to shale gas development to predict accumulated environmental effects.

Away from the UK there have been several attempts to consider the potential effects of spatial strategies of wind and other energy developments (Moller 2005, Terrados et al 2007, Ohl & Eichhorn 2008, Simao et al 2009, Balog et al 2016, Gonzalez et al 2016). There has also been consideration of optimisation of technical capacity (Roy 1997, Veira & Ramos 2009). Balog et al (2016) used simulation to produce a regional model of wind energy development. Ohl & Eichhorn (2008) show the importance of aligning surface spatial planning with other influences that determine the resource development. In Spain regional planning was a valued approach for the development of solar and biomass energy (Terrados et al 2007). Whilst in Denmark Moller (2006) applies a deterministic approach to predict the likely visual impact on landscape and local populations to reinvigorate regional planning of onshore wind energy development. He has also applied his spatial modelling to analyse planning and economic consequences of offshore wind (Moller 2011). This literature demonstrates that it is possible to deploy regional, or larger area, approaches to plan dispersed energy development.

Perhaps the most appropriate work relevant to this thesis in the international literature is the importance of understanding the impact of different planning approaches on the effects arising from onshore wind energy strategies in Ireland. Gonzales observes the government's desire to avoid greater centralised coordination by placing the responsibility for decision making at the local level. Gonzales concludes that this "resulted in highly disjointed and heterogeneous policy setting" (Gonzales, 2016, p12). A "lack of a standardisation national methodology for landscape character has resulted in considerable variation of the assessment parameter" resulting in varying environmental effects (ibid, p18). Although not by design, this suggests that different planning approaches or criteria can have an impact on the level of environmental effects that arise with dispersed energy developments. This thesis seeks to investigate this determinant on the relationship between the ability to plan for dispersed energy and the institutional arrangement that are required to facilitate such planning.

Attention has been paid in the literature to spatial planning for offshore wind energy. The UK is recognised as a leader in offshore wind deployment with a potential 48GWe of power generation. The development was initiated through SEA but involved a distinctly British planning approach (Toke 2011). The unique form of British planning with a flexible ‘discretionary’ approach contrasts with the zoning system applied in Europe and the US (Davies 1999). Toke observes that ”it is at the level of strategy that many key decisions about offshore wind are taken” (Toke 2011, p527). This arises because “offshore wind power is much more under control of central government” … as “consent is dispensed centrally with local authorities having no more than a consultative role” (ibid, p530). As well as a consistent planning processes (by a single agency) offshore wind decision making is exercised through ownership of the seabed. Toke compares the various European decision systems and identifies the main barrier to development is costs. He notes that “there are some specifically British ways of doing things in the planning sphere.“ That the success, of the UK offshore programme, arises because “the British tradition of ‘criteria’ based planning appraisal of windfarms proposals is the optimum approach” (ibid, p533). The literature unfortunately pre-dates the programme applied by the Crown Estates, in 2018, to select offshore wind developments zones using planning sieving techniques. Given the lack of academic coverage since 2018 and since these may offer useful insights, these programmes are reviewed in this thesis in Chapter 3. Nevertheless, Toke’s conclusions confirm that the British criteria-based planning system offers an appropriate venue for testing the hypothesis of whether we can plan effectively for dispersed energy which minimises local environmental effects.

The potential value of the British planning approach within energy policy implementation is reinforced by Jay (2010). He notes that British “spatial planning can broadly be defined as a decision-making process for influencing or determining the way in which physical space is used” (Jay 2010, p495). This includes a ‘future-orientated’ strategy to achieve goals and is concerned with shaping human development whilst protecting natural environments. In practice, in the UK, this means deciding individual development proposals in line with a planning policy framework. This is sometimes called a plan-led system. Confirming Gonzales et al (2016) and Toke (2011), Jay (2010) observes that for offshore wind energy development this is more effective when conducted through a "higher strategic level of planning" rather than by locally administered decisions on individual projects (Jay 2010, p498). Strachan has recognised the interdisciplinary nature of the energy system. He stresses the need to develop modelling tools to aid effective implementation of UK energy policy and identified that the geographic perspective is especially important (Strachan 2011). Recognising the potential advantages of this British planning sphere approach, particularly a strategic approach, and the need for energy system modelling tools, this thesis seeks to consider whether and how this can be applied to onshore dispersed energy development (under RO2).

2.3.2 PLANNING AND EFFECTS ARISING WITH SHALE GAS DEVELOPMENT – GENERAL

Having reviewed the thinking on planning and cumulative effects for dispersed energy generally I now turn to review the academic literature which focuses on planning and the environmental effects of shale gas development (SGD). As set out in the Introduction Chapter 1 and explained in more detail in the Methodology Chapter 4, SGD is selected for the case study modelling in this thesis. The literature review for SGD is divided into two parts. Firstly, considering international SGD research, which is mostly concerned with the US, and then looking at the literature which is focused on the UK. As has already been pointed out, the UK planning/ environmental assessment regulatory arrangements are distinct. The UK also contrasts geographically. Compared to the US and Canada the density of population is higher in the UK and there is a lack of large predominantly natural wilderness areas (2018 - USA: 35 people/km^2; Canada: 4 people/km^2; 2019 - UK: 275 people/km^2, of which England: 432 people/km^2, Scotland: 70 people/km^2 and Wales: 152 people/km^2 (Statista 2021)).

Before moving into planning and environmental literature concerned with wide area effects and oversight of SGD it is worth reviewing certain research due its influence. Adgate, Goldstein and McKenzie's paper on the potential for public health exposure from unconventional natural gas development risks is widely cited (Scopus reports 228 citations - 18/3/20) in the academic discourse on SGD (Adgate et al 2014). It identifies the major stressors of "air pollution, ground and surface water contamination, truck traffic and noise pollution, accident and malfunction and psychosocial stress associated with community change" (ibid, p8307). Their paper places the identified possible effects of SGD into five radial zones, from site to global, and calls for further research to clarify uncertainty of effects. This thesis is a small contribution to that call for an academic response. Sovacool (2014) undertook a broad ranging literature study considering the technical, economic and social 'pros and cons' of SGD (Scopus reports 133 citations -18/3/20). For the 'pros' he observes SGD provides considerable positive economic activity, is likely to displace dirtier fuels (coal and oil) and will lower energy prices. For the 'cons' he suggests SGD brings technical complexity with increased risks, environmental degradation, potential public health risks, climate change impacts and social impacts with possible social division. Overall, Sovacool concludes SGD carries tangible benefits, an irresolvable polemic debate, and different development trajectories dependent upon governance. Whilst the social issues are beyond the scope here this thesis seeks to identify approaches to SGD which minimise the negative and maximises the positive effects, including externalities.

Several international papers outline various approaches which seek to model SGD in some way. Some of these consider some aspect of environmental effects of SGD whilst others consider efficient or optimal serial shale gas site development. A feature of the literature reviewed here is that these all consider effects arising from SGD across a large area or region. Understandably, where environmental effects are considered, authors orientate their research to the environmental issues which are important in the location of their studies. Hence in North America considerable attention is given to impacts on water resources and forestry (Rahm & Riha, 2012; Davies & Robinson 2012; Eshleman & Elmore 2013; Evans & Kiesecker 2014; Racicot et al 2014; Meng 2015; Slokner & Milheim 2015; Milt et al 2016). In Poland the emphasis is on land use conflict and landscape fragmentation (Baranzelli et al 2015). As discussed in detail in the next section, in the UK the focus is on social sustainability, traffic and environmental carrying capacity or conflicts with land uses (Cooper et al 2018, Goodman et al 2016, Clancy et al 2018, Burbridge and Adams 2020). This thesis, applying a case study to the UK, focuses on the pertinent impacts of SGD in the UK. Whilst the international papers may be concerned with environmental effects not relevant to the UK it is however valid to examine research which has been employed in other jurisdictions. The international literature offers some instructive insight into approaches to the spatial development of shale gas. The common theme of this international literature is that they study the accumulation of effects from SGD and a sense of trying to mitigate this.

The driver for much of this international research is that the number of SGD sites across large areas leads to an accumulation of effects which are not recognised. Some literature is concerned with simply measuring or predicting these accumulated effects and then exhort regulators to address these. Others also move into consideration of the management of these effects. This is similar to the addition of management to CEA, discussed earlier (Section 2.1.2). Tacitly management often includes decisions or suggestions on the siting or the planning of SGD across a basin. For this thesis both the system of analysing, or predicting, accumulated effects and the thinking behind planning or managing the development of sites is of interest. This subsection of the literature review initially considers attempts to measure accumulated effects of SGD and then moves into the literature which also considers SGD decisions systems rather than exhortations.

Davies and Robinson developed a GIS based modelling system to assess accumulated effects of SGD. In line with the thesis question here, part of their objective is to "test whether a rational, ordered site selection system can reduce ecological impacts" (Davies & Robinson 2012, p25). It is interesting to note that others are considering whether there are alternatives to uncoordinated SGD. Whilst taking an area perspective, however, Davies & Robinson (2012) use a formulaic technique for interpreting data from maps and then predicting the scale of certain accumulated effects. This thesis, whilst concerned with quantification of environmental effects, seeks to provide a less generalised, more rigorous approach to quantifying effects. Thesis RO3 is relevant here. Echoing Adgate's (2014) spatial rings effects around shale gas sites, Meng (2015) developed a distance-based risk assessment for SGD. This considers potential SGD effects on both the environment and urban population. The technique employed identifies effects within 1, 2 and 3km bands around sites and allocates risk levels with varying weighting for feature sensitivity. The technique recognises that effects gradually decline over distance. It could be applied in the prediction of environmental effects, such as noise. An alternative approach to measuring effects around SGD site is the spatial footprint engaged by Slonecker & Milheim (2015). Again, seeking a comprehensive assessment of potential impacts, they apply GIS mapping of SGD sites to quantify the number of susceptible features (such as watercourses, forestry loss and population) within set distances.

Moving beyond simple measurement or prediction of environmental effects of SGD Baranzelli et al (2015) start to scope out the accumulation of effects under different scenarios of development, for Poland. They develop a methodology to simulate extraction of shale gas over time, using a standard land use competition modelling tool, in order analyse the possible impact on landscape. Also, relevant to this thesis, is that they seek to understand variations in effects under different legislative restrictions. They develop a business-as-usual prediction for other activity and then consider alternate regulatory adjustments as well as no SGD. Working in 5-yearly time sequences they locate pads based on a land use change suitability score, proximity to access water infrastructure and avoiding sensitive areas. The scenarios consider existing and more restrictive regulation, including water supply and variable setback zones, together with SGD technology parameters. This considers two alternative spacings between pads. The study authors accept that considering only two alternatives is limiting. The most obviously limitation, which this thesis seeks to move beyond, is the structure of the modelling tool. Under RO3, this thesis seeks to model SGD in ways which are tuned to the specifics of the environmental effects.

Similarly combining assessment of effects with a degree of prediction of SGD is Evans & Kiesecker's (2014) cumulative impact assessment. Uniquely, they compare the cumulative effects of shale gas and wind energy effects. The technique used to assess accumulated effects identifies likely sites, to quantify likely effects, but with a focus on disturbance to water quality. They use surrogate effects measures rather than direct potential environmental consequences. Taking a spatial database of existing wind and gas sites, development scenario modelling is used to predict future development. For shale gas this entails deducing patterns of pad coverage, then extrapolating to achieve full exploitation of the resource, but excludes regulatory guideline restrictions. Whilst this projection takes account of development restrictions, such as surface slope, shale disposition and proximity to roads, these appear coarse criteria. A 'predict and assess' approach has also been applied in Canada, focusing on forest fragmentation (Racicot et al, 2014). They test two scenarios for pad locations with minimum regulatory exclusion zone (from buildings, water supply wells and other infrastructure) and broader ecological constraints (wetland, deer yards protected woodland). Again, using GIS, they sieve out 260ha standard coverage units to assess overlap with sensitive features and then assess areas of conflict. Whilst this technique takes account of pads, access roads and export pipelines it is still a coarse means of measuring impacts.

It is interesting to note that there is little consideration of alternate densities of pad development in the literature. One study considers two options (Baranzelli 2015). Most of these international papers, which are orientated towards environmental impacts, do not consider the engineering component of SGD. Several papers adopt a standard distance for well site separation (Davies & Robinson 2012; Baranzelli 2015; Evans & Kiesecker 2014; Meng 2015; Slonecker & Milheim 2015;). Given that the technology behind SGD is evolving (Braziel 2019) this appears to be a significant omission in the literature. This thesis seeks to remedy that gap. Whilst many of these international studies focus on some form of accumulated effects assessment at the basin, large area, watershed or regional scale many are constrained by use of proxy measures of effects rather than direct effect impacts. There appears to be a need to be specific about the environmental effects of SGD and then quantify the accumulation of these under several development scenarios. Under RO3 and RO2, this thesis endeavours to develop a methodology which addresses this gap.

Before turning to literature which take a more comprehensive approach to measuring accumulated effects and planning from an environmental perspective, it worth considering literature which seeks spatial SGD optimisation from an economic efficiency viewpoint. This is a well-developed field as it is important to the hydrocarbon production industry (Gupta & Grossmann 2012, Mauter et al 2013, Cafaro & Grossmann 2014, Bartholemew & Mauter 2016, Gao & You 2017, Gonzales et al 2018, Ondeck et al 2019). There are two subject areas of interest, relating to economics and sustainability. It is in the industry's interest to maximise the production of gas by increasing the coverage and efficiency from a single pad (Ondeck et al 2019). It is also in the interests of operators to optimise the production of gas from a group of pads. To that extent increasing the number of wells to extend shale unit coverage from a single pad, coincides with the environmental interest. The maximum number of wells from a pad is driven by optimising economies of scale within technical capability (Cafaro & Grossmann 2014). Given a choice to produce shale gas, these objectives are in line with minimising environmental effects by, for example, minimising transportation and the number of transport routes required. Some literature blends economic with environmental interests. Bartholomew and Mauter et al (2016) consider minimising environmental impact of water use, waste and transportation, within an operational economic context. Gao and You (2017) consider the optimisation of the triple bottom line (profit, people & planet) for shale gas. Whilst Mauter et al consider strategic reductions of environmental impact of SGD, they call for “regional environmental impact analysis and associated mitigation efforts” for SGD (Mauter et al 2013, p6). This thesis is in-line with much of this thinking. It aims to assess a regional environmental impact, in the UK. As well as quantifying accumulated or overall effects this thesis considers ways to mitigate these through better planning choices.

Rahm and Riha (2012) have considered multiple sites for shale gas development (SGD) across a large area or basin from the perspective of the potential impact on water resource. Particularly the management of water withdrawal for SGD operations and effects arising from SGD wastewater disposal. Whereas in the UK 25 utilities supply water to cover 99.9% of the population (an average 2.68m population per utility) (Discover-water 2020), in the US water supply is predominantly community based with an average population served per system of approximately 5,500. The US also suffers water scarcity (EPA water-sense 2008). Water resources and SGD industry use of water is therefore a key issue in some states. Taking a regional perspective Rahm and Riha consider the accumulated effects of SGD on water supply. Their research compares two approaches to SGD water resourcing in the Marcellus basin. They conclude that project-based assessments are insufficient to consider all effects that arise with SGD. “While individual well pads may have limited or sporadic impact on water resources, the collective impact of such rapid and dense industrial activity is likely to lead to further negative environmental consequences if not managed properly” (Rahm & Riha 2012, p20). They advocate that “collective impacts from multiple projects” (ibid, p20) requires a regional collective impact analysis. This requires a strategic management approach. Whilst their research is concerned with water resources, rather than all potential environmental effects, it shows that SGD presents particular problems for project-based assessment. It also suggests that the dispersal of activity, in a series of reasonably small sites across a large spatial region, presents particular challenges for traditional environmental assessment. This reiterates the earlier observation on CEA, that project-based decision-making may not offer the most optimal approach to regulation (Section 2.1.2). Rahm and Riha (2012) also argue for a planning-based approach to SGD to contend with the temporal and spatial challenges. Under RO2, this thesis adopts much of Rahm and Riha’s thinking and applies this to all potential environmental effects and areas-based planning, in the UK.

Whilst taking an economic rather than environmental approach to SGD Arredondo-Ramirez et al. (2016) have elevated the planning of SGD into taking a strategic perspective on fracking development. Whereas in other literature, ‘planning’ is concerned with minimising negative effects, for Arredondo-Ramirez et al (2016) a strategic approach focuses on maximising the positive benefit. They look at SGD in remote areas where there is little access infrastructure. They have developed a technique applying econometric calculation to the investment requirement to provide the required infrastructure as well as scheduling pad development, drilling and hydraulic fracturing operations across a basin. This approach seeks to minimise transport and maximise the efficient use of equipment, machinery and manpower. Whilst not looking at environmental effects per se the consequence of this model is to minimise macro-scale negative effects of transportation and disturbance to the environment (Arredondo-Ramirez et al 2016). This thesis incorporates that approach but adapts it to take on board the need to minimise environmental effects of SGD.

One international paper of note that looks at a specific environmental impact is Banerjee et al (2012). This focuses on the effects of SGD on traffic. Their paper is notably distinct from previously mentioned literature, which use surrogates and proxies to generalise the environmental effects of SGD. Banerjee considers a direct environmental effect. They break down the traffic requirement for SGD sites to identify the characteristics of the traffic generated, identifies the number of movements required, estimate the distances travelled and the type of roads used, in each stage of production. This results in a detailed dataset of the traffic by ‘vehicle miles travelled’, which is then used to derive the level of damage done by SGD traffic to roads in the state of Texas. This detailed analysis provides a useful approach to demonstrate that the direct environmental effects of SGD can be quantified. This thesis seeks to emulate this technique to quantify the direct effects of potential SGD in the UK. In line with RO2, if this approach can be successfully applied, it can provide a far more rigorous method of quantifying accumulated effects than the approaches outlined earlier. This assessment of the direct effects potentially provides a platform for planning to mitigate these.

In drawing this section on international research on SGD aggregate effects and planning to a close I look at probably the most significant literature on SGD of relevance to this thesis. This is the perspective taken by Milt et al (2016). They too recognise that there have been several attempts to quantify “the environmental effects of shale-gas surface infrastructure” and “infrastructure planners try to minimise” economic costs. However, they observe no one has examined the possibility of “spatial optimisation of siting well pads, access roads and gathering pipelines to minimise environmental impacts" of SGD, across a large area or basin (ibid p1152). The research question, the ambition and RO2, addressed in this thesis, closely aligns with their field of study. Milt and Armsworth are suggesting that we can plan for SGD as well as other dispersed energy types. However, I go beyond this to also consider the influence of the decision-making system, or the planning approach, on the basin-wide or accumulated effects of shale gas development. The methodology employed in this thesis subtly differs from Milt et al's approach. They address the challenge of considering spatial optimisation by seeking to "quantify the site-level costs of avoiding environmental impacts", develop a spatial optimisation algorithm to shuffle proposed sites and estimate the trade-offs between environmental impact avoidance and construction costs (ibid p1153). They do this by determining where and how much infrastructure is required, assess the consequent environmental impact and then consider the economic cost of reorganising to avoid environmental impact through an iterative process to reduce impact. The iteration finishes when termination criteria are met.

There are three major difference to the method applied in this thesis. Firstly, I apply a more planning orientated approach to spatial optimisation. This is optimisation by design rather than iteration to meet or minimise set criteria. Secondly, as might be expected, the key environment effects considered are appropriate to the UK context. This results in dropping gathering pipelines from assessment (due the different gas network arrangements in the UK). Thirdly, as with much other literature, Milt et al take no account of the petroleum engineering dimensions to spatial optimisation as they rely on standard pad coverage. However, under RO1, this thesis recognises the importance of petroleum engineering to planning for SGD. Full details of the methodology applied in this thesis are set out in Chapter 4. Milt et al assert that they "are the first to explicitly optimise the planning of wells pads, access roads and gathering pipelines to minimise aggregate impacts of shale-gas development at reasonable construction costs" (ibid p1152). There is an absence of significant literature coverage on this since their publication. I therefore conclude that this thesis is a significant study globally, in that it optimises the planning of wells to minimise accumulated environmental effects of SGD. Importantly, this thesis applies a planning approach to the objective of optimising SGD to minimise accumulated environmental effects. The next section reviews the literature which has looked at the environmental effects of SGD for the UK.

2.3.3 PLANNING AND EFFECTS ARISING WITH SHALE GAS DEVELOPMENT – UK

There have been several studies which focus on the potential environmental effects of UK shale gas development (SGD). Some of these studies start to indicate how planning and development choices ought to be shaped. A driver for some studies is really to suggest that, for various reasons, the UK is not a suitable location for SGD and that shale gas development should not take place (Smythe & Haszeldine 2017, Watterson & Dinan 2016). While an interesting and important question, that issue is not within the scope of this thesis and is not considered here. Since this thesis is concerned with what effects would arise and whether it is possible to plan for SGD as an exemplar form of dispersed energy, the focus of this section of the literature review is on the effects that might arise, particularly accumulated effects and the planning choices, if SGD takes place. The review of literature here therefore focuses on the potential effects of SGD and the planning choices, within the UK.

Cooper et al (2016) have undertaken detailed studies of the effects of fracking in the UK using a life cycle technique looking at the economic, environmental and social sustainability of shale gas and future scenarios (Cooper et al 2014). More recently they have focused on social sustainability and presented the “first and most comprehensive study on the social sustainability of shale gas production” in the UK with a focus on the main shale gas basin (Cooper et al 2018, p3). They offer some interesting insights such as “shale gas development will likely be limited to a small number of sites, which could amplify impacts such as noise, traffic and pollution” (ibid, p15), but it is “unlikely that at these distances noise generated by shale gas development would cause major disruptions or adverse impacts on hearing and general wellbeing” (ibid, p12). They conclude that the “main benefits that could arise from shale gas production stem mostly from job creation and financial gains for communities impacted by development…., a large proportion of jobs could be sourced from local labour, … communities stand to benefit from direct investment through funds” (ibid, p16). Whilst their study is broadly based and apparently provide a detailed assessment of the effects of fracking, they have derived their estimate of fracking activity from external reports. So, their level of fracking activity is based on estimates. Overall, this research is useful in terms of indicating effects but, due to lack of detailed consideration of the level or form of development, does not provide a sound basis for likely effects.

Goodman et al (2016) have looked specifically at the traffic effects of SGD in the UK. They have applied a traffic impact model to SGD, based on the methodology deployed by Banerjee (reviewed earlier in Section2.3.2) (Banerjee 2012). Goodman et al (2016) identify that heavy-duty vehicle (HDVs) traffic may be required to travel on roads inappropriate for their use. HDVs create increased annoyance to others especially on inappropriate roads. This annoyance is intensified because the flow of traffic is concentrated during the construction phases. They create a model of traffic demand, assigning this to time and road space which is compared to baseline traffic. The model is used to consider greenhouse gas emissions, local air quality and noise, and road surface wear. The traffic impact model is based on a set separation between SGD sites of 1.5 kilometres, thereby giving 100 pads per 225 square kilometres or an area coverage of 2.25 square kilometres per pad. This equates to 44 pads per 100 square kilometres. The requirement for material and consequential traffic, however, is based on external sources (Goodman et al 2016). The model has been applied to a theoretical road network which reflects typical road categories of rural village roads, suburban roads, major roads and motorways, with a notional allocation of category use. Their model therefore produces a notional aggregate effect rather than being applied to real-world locations. Overall, the model provides a useful insight into potential emissions from traffic involved in SGD activity. Although far from complete the study does quantify some effects. This thesis seeks to address the gaps left by Goodman, particularly under this thesis RO3.

Clancy & Worrall (2017) and Clancy et al (2018) have looked at fracking from the point of view of shale gas site environmental footprints and the carrying capacity of onshore hydrocarbon sites in the UK. They observe that whilst there have been estimates of hydrocarbon resources these have not taken account of surface access issues. “Accessible resource estimates around the world have not considered the carrying capacity of the surface or subsurface footprint and how well-site placements are restricted by the current surface environment, e.g., proximity to domestic housing” (Clancy et al 2018, p587). Their solution is to develop a method for calculating the footprint of a fracking site and from this to calculate the carrying capacity of a geological basin. The assessment of footprints is based on clearance distances, or setbacks, to certain features, such as dwellings and infrastructure. They conclude that only 26% of the basin can be developed when a setback distance of 152 metres is applied, thereby significantly reducing the extractable gas resource. They deduce “the carrying capacity of the land surface, as predicted by this approach, would limit the technically recoverable gas reserves for the Bowland Basin from the predicted 8.5×10^{11} cubic metres to only 2.21×10^{11} cubic metres" (Clancy et al 2018, p594).

More recently Burbridge and Adams (2020) have applied an interdisciplinary spatial assessment to gauge the potential environmental risk of SGD, from the social justice perspective. They estimate an overall environmental risk based on a novel methodology which recognises the spatial dimension of air and water pollution, seismicity and traffic flows. They apply this to 643km^2 of the Vale of Pickering (approximately 5% of the Bowland shale unit), which lies in the rural north-east of the Bowland basin. They predict traffic effect using Goodman et al's (2016) modelling method. For water pollution a Digital Elevation Model is employed to predict spread from well sites. The seismicity effect is based on a universal impact within 1.5km radially around well sites. Receptor and energy justice consequences were judged using census block zonal data. For this thesis RO3 this is treated as 'proxy data'. Burbridge and Adams's (2020) suggest that traffic effects "would be insignificant" (ibid, p499), the risks from water pollution "are low" (ibid, p502) and that the risks from seismicity "is currently unclear" (ibid, p503). They point out that their methodology only provides high-level predictions and the uncertainty in their results arises from uncertainty over possible well site location. This thesis seeks to overcome that issue by taking into account the petroleum engineering of the shale resource. Overall, Burbridge and Adams (2020) observe that no "methodology exists for exploring" the "impacts for subsurface resource developments or" connecting this to surface spatial assessment (ibid p508). This thesis seeks to meet this need, under RO2, by developing a methodology for assessing the consequences of shale gas development which takes account of both surface and subsurface factors.

It seems there are very few studies which consider the overall potential accumulated environmental effects of fracking across a basin. The UK studies that consider the overall effects of basin-wide SGD (Cooper et al 2018, Goodman et al 2016, Clancy et al 2018, and Burbridge and Adams 2020 for a basin subregion) are in some way limited in their perspective and often based on quite constraining assumptions. There are also no studies that consider the potential consequences of a strategic or planned approach to fracking development in the UK or elsewhere and whether a different approach to the current system of decision making may on its own change the level of effects.

The UK studies which seek to consider overall effects of SGD activity, like international studies, are overwhelmingly based on *estimates* of the level of activity which might take place. There is a need for something more than this rule-of thumb approach to the possible level of development. This is considered in this thesis via RO3. A more realistic calculation of the potential scale of SGD activity across the UK is required. The calculation should not only be able to assess the level of activity but also calculate the associated environmental effects, particularly accumulated effects, which would arise. The goals of Cooper's approach (2018), in seeking to establish a quantification of the effects of fracking, have considerable merit, but their approach has significant shortcomings without a proper evaluation of the likely level of SGD activity. Resting on assumed or earlier estimates of likely activity is not sufficient. The research in this thesis, particularly under RO1, seeks to overcome these difficulties by incorporating petroleum engineering and geological factors into a more refined prediction of development activity.

This calculation of total or accumulated environmental effects and the efficacy of a planned approach requires some realistic calculation of the number of fracking sites that can be developed and the effort that is needed to conduct this. Planning for all dispersed energy types requires a realistic estimate of possible levels of activity. Something along the lines of Arredondo-Ramirez et al's (2016) strategic assessment, Rahm & Riha's (2012) strategic management and Milt et al's (2016) optimisation with Banerjee et al's (2012) detailed effects quantification is required, except applied to the environmental and social effects which arise, rather than the financial efficiency, and applied to the UK context. This is reflected in this thesis's aim, purpose and all three research objectives.

As Clancy et al. (2018) have identified, there are likely to be pockets where development is probably not possible due to surface restrictions. However, restrictions using setback is not the most appropriate approach. Setbacks, or exclusion zones, are an artificial construct designed to minimise land use conflict. For SGD this concept may have relevance for noise limits, but it is not clear that they are relevant to any other effect. Even for noise it may be possible to adjust the noise effect, by acoustic barriers around the machinery, whilst in some locations a noise setback may be inappropriate due to surface features.

The approach applied by Goodman et al. (2016) seems to be a useful starting point for consideration of traffic effects. But as currently applied it is based on one fixed density of fracking pads and it would not take account of Clancy et al.’s (2018) possible pockets where pads cannot be developed because of surface restrictions. Goodman’s traffic impacts analysis is also applied at a theoretical level rather than to the particular geography of the UK basin, as by Clancy. Goodman is using proxy rather than real-works actual data. As referred to in RO3, rather than a theoretical (or a proxy) road network it would be more informative to assess any traffic effect by applying the real-world road network in the basin. Cooper et al’s (2018) approach appears to have useful objectives but also has limitations. However, the overall conclusion for the UK-based research is that there has been little serious attempt to consider the overall, accumulated or basin-wide environmental effects of SGD. Even Burbridge and Adams’s (2020) approach falls somewhere well short of this.

It seems the current UK-based research does not provide an understanding of the likely overall effects of SGD based on a realistic identification of the likely effects. The research seem to fall short of a serious attempt to establish what the potential full scale of fracking will be and what consequent accumulated effects might arise. Any such study would need to consider: the location and distribution of the hydrocarbon resources together with any geological constraints on extraction; the surface geography and any surface constraints on pad locations; the social impact and any social restrictions on SGD activity; and the engineering capability to access and extract the hydrocarbon resource. This specification provides a starting point for the identification of factors that need to be considered in a whole-system spatial assessment, under RO1.

None of the published UK-based research goes beyond effects to consider whether the decision system itself is influential on the level of activity and consequent effects produced by fracking. If the societal aim is to minimise negative effects and maximise positive effects of dispersed energy it seems the consequence of the decision system should also be considered. This thesis also seeks to address this by considering a case study of SGD as an exemplar for dispersed energy.

Overall, the literature, for planning and cumulative effects, energy policy and planning for dispersed energy, has shown that there is a considerable gulf in the spatial provision for dispersed energy. This appears to be because there is a gap between the two principal domains of energy policy and local planning. Whilst the UK has particular issues in this regard, it is clear that related concerns exist in other jurisdictions. Whilst CEAM and AM have attempted to address this in North America the underlying challenge remains. Both the international and UK literature demonstrates a common requirement to combine energy policy for new dispersed energy provision with effective local provisioning which minimises the potential local environmental effects. This also seems to require at least an appreciation if not full understanding of the technical aspects of the development of a dispersed energy resource. The literature on shale gas development, internationally and the UK, embodies this gap between the choices over development, potential environmental effects and an acceptable trade-off between these. This thesis examines this gap and seeks to ascertain how best to plan for dispersed energy. This should facilitate an analytical technique for guiding dispersed energy facilities and aid the formulation of a methodology for the development of dispersed energy which recognises local environmental effects. This methodology (RO2) should identify all the relevant factors (RO1) and wherever possible be based on actual rather than proxy data (RO3).

3. The Context for Dispersed Energy Planning

This Chapter sets the scenes and outlines the circumstances in which the research question here is being examined. This chapter explores the policy, legislative, spatial and general context for the research in this thesis. The thesis seeks to inquire whether we can plan for dispersed energy, and if so, how? Related to this the thesis seeks to examine whether is it to formulate a methodology technique for the development of dispersed energy which takes account of local environmental effects in a coherent plan. It is therefore important for this Chapter to outline the institutional arrangements which apply to dispersed energy planning. The particular focus of this research is the UK, so this review of institutional arrangements applies to the UK. The inquiry of whether we can plan for dispersed energy in this thesis is examined by a case study modelling the potentiality of a plan for dispersed energy. This case study is applied to shale gas development across the Bowland basin of Northern England. Details on the context are therefore given on shale gas development (SGD) and the local circumstances of the study in Northern England.

This Chapter is organised in three parts: The first part looks at dispersed energy in general; The second part considers the context for the case study and UK shale gas; The third part summarises where present approaches are seen to be deficient and therefore provides a take off point for the subsequent Chapters of the thesis.

The first part on dispersed energy (Sections 3.1 - 3.3), reviews UK energy policy and the planning system in the UK. It then looks at a particular UK example of planning for dispersed energy. As has been recognised earlier (Section 2.3.1), the British planning system is quite distinctive from similar development consenting processes in other jurisdictions. Ergo, attention is given to explain the mechanism and tools within the planning system. The focus of this first part is on the potential gaps between the silos or domains of energy policy and local planning.

The second part of this Chapter (Sections 3.4 – 3.6) delves into the context for the case study, which considers whether it is possible to plan for the dispersed energy of shale gas. This opens by looking at details of the characteristics of the study area. The study area has already experienced decision making on shale gas development (SGD) proposals. In a sense these provide a real-world early test of the effectiveness of decision making on dispersed energy. This decision making is therefore analysed to see if it offers any insights. This part concludes by looking at publicly available estimates of the potential and environmental consequences for shale gas in the study area. These may provide a useful basis for comparison with the subsequent case study findings. This Chapter does not provide a detailed description of the shale gas development process. However, as this process, which includes the petroleum engineering required for the development of shale gas, are important to understanding the case study this is provided in an Appendix B.

The third concluding part of this Chapter (Section 3.7) offers an assessment on where the present approach to dispersed energy development, mainly in the UK but also wider, and the research on this, might be deficient. It therefore places this thesis into the overall context and provides clarity on where this thesis can build on the existing research and policy system.

3.1 UK Policy on Energy and Climate Change

This section outlines the UK policy on energy and climate change. It then turns to consider the implementation programmes and practice relating to the various types of dispersed energy.

3.1.1 NATIONAL ENERGY POLICY GOALS

The UK has a population of 67.9 million, a land area of 242,500 square kilometres (ONS 2020, Clark 2020) and is the world's fifth largest economy (CEBR 2020). It is made up of four constituent parts of England, Scotland, Northern Ireland and Wales. Of these England has 83%

of the population and 54% of the land area. Overall, the UK is prosperous, densely populated and has a developed economy. It is reasonably rich in natural resources (Barrow 2020). The UK has a well-developed energy system which saw major expansion of power production and transmission in the post-war period (Hanson 1982). In 1989 the UK's then Prime Minister raised concerns on the potential for climate change in an address to the United Nations (Thatcher 1989). In 2002 the UK introduced a subsidy system to support and promote the development of renewable energy. In 2008 the UK parliament approved a Climate Change Act setting a legally binding target of emission reduction of 34% by 2020 and 80% by 2050 compared to 1990 levels (Climate Change Act 2008). In 2019 the UK committed to net-zero emissions by 2050. In 2021 the UK government set an interim target, on the path to net-zero, of a 78% cut in emission by 2035 (HMG 2021). The UK sees itself amongst the world's leading countries seeking to address climate change and is a signatory to all major climate agreements (Priestley 2019).

The energy transition measure is being implemented through four main policy instruments (HMG 2009). The prime focus of the transition was emission reduction in power generation. A Carbon Floor Price is a UK taxation addition to the EU Energy Trading Scheme designed to add a penalty price for carbon emission to power generators. Emissions are pro rata for carbon levels and therefore disincentivise higher emissions (Hirst 2018). The UK has implemented the EU Large Combustion Plant Directive which required either improvements to power station emissions filtering or reduced operating times of plant by 2015 (Council Directive 2001/80/EU). In 2015 the UK government announced the closure of all remaining coal fired power generation by 2025 (BEIS 2018) through its Emission Performance Standard (DECC 2014). As well as restrictions on high emitting power generation, the UK has sought to incentivise low carbon power generation. It introduced renewable power guaranteed feed-in-tariffs. From 2002 it operated a scheme of Renewable Obligation Certificates (ROC) requiring major power producers to either meet a steadily increasing target for the proportion low carbon generation or pay a penalty premium (OFGEM 2020). The ROC scheme has been phased out since 2017 and has been replaced by a Contract for Difference (CfD) wholesale price guarantee (BEIS 2020a). The CfD scheme operates by competitive auctions. Over these auctions, between 2015 and 2019, guaranteed average prices have fallen from £138/ MWh to £43/ MWh. In 2020 the CfD scheme provides energy for the equivalent of 27% of the UK's 19.1m households (LCCC 2020). Beyond the power sector, policy has encouraged energy saving through improved home insulation, through Renewable Heat Incentives, Green Deal, Energy Company Obligations and Warm Home Discounts (HoCL 2019). In 2017 the UK launched a Clean Growth Strategy (HMG 2017) and also undertook a Cost of Energy Review (Helm 2017). In 2020 the UK government started to consider reducing emissions of transport, heat and other sectors (CCC 2020).

A key characteristic of UK energy policy is the mix of market-based and public sector control operations (Keay 2016). As Harper et al (2017) outlined, UK energy policy is set nationally but without specific consideration of local environmental effects. The national policy position is that it is for developers and proponents of each energy projects to seeks sites and obtain consents which comply with local environmental and planning requirements. At the national level the UK governments set policy targets for and lays out a broad plan for the transition (BEIS 2019, BEIS 2019a, BEIS 2020).

3.1.2 IMPLEMENTATION OF POLICIES FOR DISPERSED ENERGY

This subsection examines the implementation and measures which are taking place to develop dispersed energy in the UK. It is organised by technologies, starting with nascent types of dispersed energy and moving into more mature types. Since shale gas is covered in greater detail in the case study sections (3.4 to 3.6), this is excluded here. The subsection concludes with a characterisation and overview of the implementation of policies for dispersed energy.

The technologies of biomass, anaerobic digestion, energy from waste, industrial cogeneration, hydropower are not considered in detail. The UK has authorised biomass for thermal generation and has provided financial support for the conversion of some for coal fired thermal generating plants, such as Drax power station (Drax 2020). However, the production of biomass is essentially an agricultural or forestry process. It has long been recognised that the UK has insufficient land to provide adequate biomass for energy as well as for food (MacKay 2012). While there is some domestic production most biomass for thermal power is imported (DUKES 2020). The UK government sees thermal power from biomass as a temporary measure and wishes to see it phased out in the medium term (BEIS 2019b). It is therefore not seen as an important form of dispersed energy from a future provision and planning perspective. It would only become so if carbon capture and storage were added to the process.

Similarly, for anaerobic digestion, energy from waste and industrial cogeneration. Anaerobic digestion is mostly an agricultural by-product and an improvement in emissions from agriculture. Energy for waste is a biproduct of human waste and is likely to require small thermal generation plants in or near urban centres. Industrial cogeneration is a side process in industrial product. The development of industrial cogeneration which have occurred are of largely localised potential. For example, Stevens Croft power station in Lockerbie utilises locally grown wood whilst providing heat for the adjoining timber processing plant (EON 2020). Whilst producing local environmental effects within their vicinity, all of these measures are unlikely to have a significant accumulated spatial footprint due to the limited scale of potential development. The UK government has supported measures in these technologies through financial support, largely to prime conversion, and through signposting. These technologies could be usefully incorporated into regional dispersed energy planning.

For the geothermal energy the UK has reviewed its available resources. There are either surface shallow resources or deep geothermal potential. The deep geothermal resource is predominantly located in Cornwall in South-West England (Busby et al 2009). A trial geothermal power scheme is being developed in Cornwall. The aim is to produce 10MW of electrical power and 55MW of heat for local distribution (GEL 2020). Given the modest scale of the UK geothermal resource and the nascent nature of the resource it appears premature to consider wider spatial planning requirements for geothermal energy, at this time. Compressed-air energy storage (CAES) offers the possibility of large-scale energy storage for daily peak and inter-seasonal energy storage. Two early CAES projects are under development in the UK in Cheshire, England and Larne, Northern Ireland. Both of these early developments are associated with existing salt caverns (Beutal & Black 2004). Whilst this technology has wider potential (Lund & Salgi 2009) it is too early to consider the spatial planning requirements. Liquid air storage is being trialled (Lempriere 2020). It is likely to be located in industrial areas and is unlikely to have a significant environmental footprint.

By contrast hydropower is a very mature technology. It has been extensively developed in the UK particularly in the mountainous areas of Scotland and Wales. Hydropower development activity peaked between the 1920s and 1960s, however, due to the high capital cost subsequent development has been severely restricted (other than micro-scale hydro). Most recent development have been for pump storage utilised for peak energy load balancing (Engie 2020, Drax 2020b). The capital cost and the significant footprint, however, means further projects appear to have limited prospects. More recently coastal tidal power has been considered for tidal lagoons and barrages (Tidal Lagoon Power, 2020, REUK 2020). However, whilst the energy potential of these development appears substantial there is concern over their economic viability and environmental impact. For example, a barrage across the Severn Estuary could potentially produce 5% of the UK's power generation capacity but would have "unprecedented" impact on extensive environmentally designated areas (HMG 2010, p5).

Carbon capture use and storage (CCUS) is a technology which the UK has considered. In 2009, 2011 and 2012 the UK government considered commercial scale storage demonstration projects. However, each of these was withdrawn because "the cost to the consumer would be high … before it was cost-efficient" (Tiley 2020, p17). The implication of these failed pilots being that the technology is not yet mature. In the 2017 Clean Growth Strategy the government stated that whilst the UK wished to be a global technology leader for CCUS it only envisaged deploying this during the 2030s and then only subject to costs coming down (ibid). A CCUS task force was established to consider viability. Overall CCUS is in early stages of development, and for the purposes of this thesis the spatial planning requirements are unclear.

Hydrogen also offers considerable potential for dispersed energy. This is considered to be an important energy vector which may offer low carbon solution for home heating and transport (Thornhill & Deasley 2020). However, again the spatial planning requirements for this form of dispersed energy are still unclear. Mouli-Castillo et al (2021) suggest that expired offshore gas fields offer sufficient storage capacity to cope with the entire seasonality for UK domestic heating. The UK is considering increasing the content of hydrogen within the methane-based national gas grid to 20% as well as long term conversion of the methane gas grid to hydrogen (National Grid 2021). This suggests that for the UK the remaining challenge for deployment of hydrogen is production (OGA 2021).

Of all the dispersed energy technologies wind energy is the most mature. This also has the clearest requirement for planning for local environmental effects. The potential need for planning for offshore wind is discussed later in section 3.3. This section therefore summarises the implementation of measures for onshore wind in the UK. Onshore wind has been heavily supported by UK and devolved governments. Onshore wind energy was seen as of prime importance during the 2000s. In the last decade this has been caveated and seen some retrenchment in the face of social acceptance challenges (Smith 2016). During the 2000s, as well as receiving financial support from ROCs, spatial planning for onshore wind was driven through Regional Spatial Strategies. Research was undertaken to assess the potential renewable energy capacity of English regions (DCLG 2009). This was used to attempt to set targets for each region. However, given the diversity of coverage of the regional strategies it was found that the approach was inconsistent. While regions had been given responsibility for delivery of renewable energy targets, they were given no consistent or standard approach on how and what to deliver. “A review of existing regional targets reveals considerable inconsistency in the expression and adoption of regional renewable targets” (ibid, p19). It appears the regions were adopting their own methodology for assessment of both need and potential. Whilst nominally regionally based, it appears that this attempt at regional planning for renewables, focused mainly on wind, incorporated little in the way of spatial environmental assessment, nor a coherent planning approach. The later abandonment of this approach not only arose due to a change of government and policy, but it also reflected the inadequacy of the work undertaken.

With Regional Spatial Strategies withdrawn in 2012 in England and Wales, the UK government encouraged local planning authorities to promote renewable energy development through the National Planning Policy Framework (Smith 2016). This was supported by guidance under a National Policy Statement for Renewables Energy Infrastructure (DECC 2011). This sought to guide onshore wind energy development decisions. This recognised the need to appreciate wind resources and avoid nationally designated habitats and green belt, with consideration of the historic environment, landscape and visual impacts, noise, shadow flicker, transport and grid access. However, this cannot be considered to be a methodology of the assessment required. It is merely an indication of factors which might need to be considered and therefore relevant to RO1. While local authorities were to encourage wind energy there was no requirement to attain targets.

In 2015 the UK government withdrew national decision making for wind energy and placed the responsibility for onshore wind development decisions entirely with local planning authorities. This left a “responsibility to help increase the use and supply of green energy” on local authorities, “but this does not mean that the need for renewable energy automatically overrides environmental protection” (HMG 2015, p1). The same year the government stated development should only proceed “in an area identified as suitable for wind energy development in a local or neighbourhood plan”. And, where “it can be demonstrated that the planning impacts identified by affected local communities have been fully addressed and therefore the proposal has their backing” (Smith 2016, p14). Unusually, the government suggested that if a local planning authority rejected a wind farm proposal this indicated that the local community did not back the proposal. Effectively this policy meant that ‘local people have the final say’ on wind energy proposals (ibid). The result has been very few wind farm proposals being proposed or developed in England and Wales in the last decade (BEIS 2020c).

In England and Wales this revised national policy approach was reflected in guidance to planning authorities on renewable energy development (DHCLG 2015). Whilst this guidance placed responsibility on all communities “to help increase the use and supply of green energy” (ibid, p2), there are strong caveats. The guidance frames the need for dispersed energy provision as only “local planning authorities may wish to establish policies which give positive weight to renewable and low carbon energy” (ibid, p3). It stresses the need to take account of local amenity and that “local people have the final say on wind farm applications” (ibid, p9). Whilst the guidance gives local authorities responsibility for identifying ‘suitable areas’ for renewable energy, there is not prescription on how this is to be done. The guidance only suggests ‘criteria-based’ policies. Confirming the approach taken in this thesis, the guidance confirms that planning for dispersed energy needs to take account of technology. It also affirms this thesis’s approach, that “there is an important contribution to be made by planning” … of “getting the right land use in the right place” (ibid, p6).

Planning and energy development decision making (but not energy policy) has been devolved to Scotland since 1998. This has enabled the Scottish government to take a different approach to England and Wales. With 70 persons per square kilometre, Scotland has a far lower population density than England, at 432 persons per square kilometre (Statista 2021). The land area of Scotland includes extensive upland uninhabited areas where wind resources are good. The Scottish government has not adopted the UK policy, applicable in England and Wales, of giving ‘local people the final say’ on wind farms. In marked contrast to the UK, the

Scottish government has centralised planning decision making on wind energy. It retains direct decision-making control for wind farms larger than 50MW and directs local authorities to be sympathetic towards onshore wind farms (Scottish Government 2014). It has advocated a 'business as usual approach' where they expect developers to "make every effort to find opportunities to collaborate and to reduce potential local landscape impacts" (Scottish Government 2017, p14).

It is noticeable that this Scottish policy does not explicitly recognise the interests or allow for the views of local affected communities, in ways similar to England and Wales. This system is described as "a favourable planning and consenting regime" for wind energy (CCC 2020b, p64). Recognising that much wind energy resource does not comply with the extant electricity transmission network the Scottish Government has identified that "the capacity of parts of the system needs to be increased to facilitate this transmission" (Scottish Government 2009, p59). The result of this policy has produced a programme of exiting operational wind energy and pipeline of 23,246 MW. The contrasting policy outturns of each constituent country in Great Britain are shown in Table 3.1. It is notable that the Scottish Government approach does not include any local strategic planning and directed coordination of development. The decision process entails developers identifying sites and then seeking approval from local or Scottish government depending on project size. Significant numbers of site proposals have been rejected.

Table 3.1: GB Onshore Wind Projects Capacity and Pipeline by Country

Projects capacity in MW	In pre-planning preparation	In planning	Consented	Being built	Operational	Total - operational and in programme	Refused
England	53	41	170	12	2,928	3,204	6,025
Scotland	6,095	4,096	4,456	384	8,215	23,246	7,073
Wales	349	216	338	16	1,230	2,149	876
Great Britain	6,497	4,353	4,964	412	12,373	28,599	13974

Source: Renewable UK database – June 2020

Assessment of the onshore wind proposals that have been approved in Scotland suggests that these are not determined only on the basis of local environmental considerations and planning criteria. With a developer-led system a key influence on development is access to the transmission grid. Whilst grid access and energy transport are a requirement under any arrangements, experience shows developers choice of site locations are heavy influenced by the needs to gain grid access and the associated cost. The position of extant transmission access points is often the preeminent consideration for developers and a leading influence on the programme of realised development of the wind resource. Figure 3.1 Illustrates the resulting concentration of approved and proposed wind farms on the high ground clustered around a transmission grid access point in Southern Scotland, in 2020. The figure is based on the cumulative assessment for a proposed wind farm, which identifies 440 turbines in this vicinity (3R Energy 2020). Similar high ground elsewhere across Southern Scotland do not have these wind farm clusters. While the approved wind farms meet the local planning criteria these sites do not necessarily represent the least adverse overall environmental effects or optimum use of the wind resource. The developer led system, of incremental project decision making, does not necessarily result in the same programme of overall energy development as under a positive planning system. A positive planning system seems likely to take a more holistic view with a different balance of environmental priorities. Whilst energy transmission is an important consideration it is far from the only factor that needs to be considered.

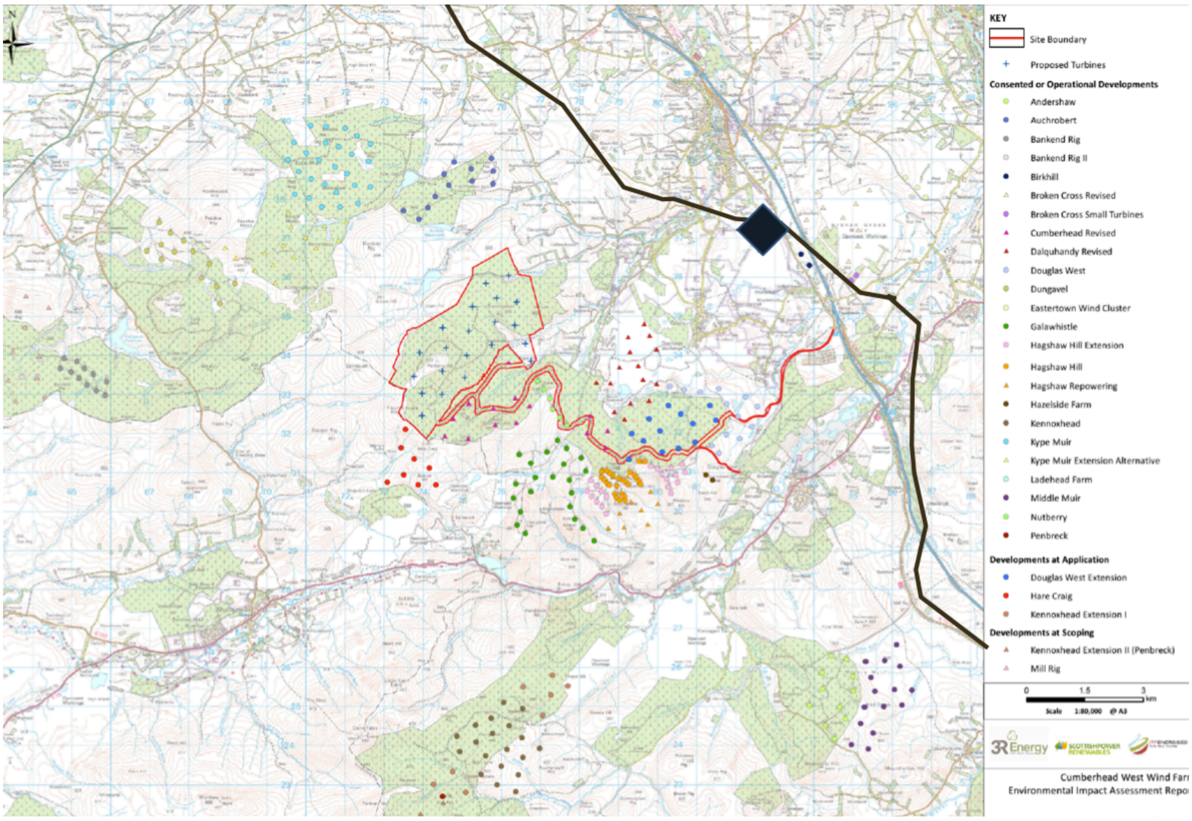


Figure 3.1: Onshore Wind Farms Clustered Around a Transmission Grid Access Point

Key: Black line = UK National Grid high voltage power transmission line (between Central Scotland and England). Black diamond = Transmission substation and grid access point. Coloured circles, triangles and crosses = wind turbine sites for various wind farms. Red line – area designating extent of site for a proposed wind farm. Background map = Ordnance Survey 1:50,000. **Notes:** The map is derived from a cumulative effects assessment for a proposed wind farm in Southern Scotland. It illustrates the clustering of existing and proposed wind farms on the high ground around a transmission line substation. The substation provides an access point to the power transmission line. **Source:** 3R Energy (agents for the proposed Cumberhead West Wind Farm) 2020, with author highlighting of the transmission line and substation.

3.1.3 THE ADEQUACY OF SOFT SPACES PROVISION FOR DISPERSED ENERGY

This subsection examines the measures which have the potential in the England to develop dispersed energy in the last decade. It particularly examines the provision made by the informal soft space entities (Allmendinger et al 2016) which have responsibility for local or regional energy provision in England. Local energy actions are devolved matters for Scotland and Wales. Following the removal of regional governmental agencies (Section 3.1.2), the UK's industrial strategy in England has placed funding support with Local Enterprise Partnerships and local authorities to prepare 'local energy strategies' for their local area or region (BEIS 2020d, Bendell 2020). Several energy strategies have been prepared (e.g., SE-LES 2018, NELEP

2018, WMCA 2018, LEE 2018, OxLEP2020). The intention is to provide complete coverage of local energy strategies across England. Hypothetically this government instrument could fulfil a central question of this thesis: of planning locally for dispersed energy.

The plans provided in these energy strategies tend to be generic aims and goals. Many plans restate UK wide energy policy objectives and place these into the local context. These documents include ambitions for low carbon heat, renewable generation, energy efficiency, smart systems, creating high value local employment from clean growth, improved energy affordability, reduce carbon emission and a transport revolution (SE-LES 2018, NELEP 2018, WMCA 2019, LEE 2018, OxLEP 2020). The strategies vary considerably in their content and coverage. For the West Midlands the strategy envisages Energy Innovation Zones to provide for simplified "infrastructure transition, investment and accelerated deployment of innovation" (WMCA 2019, p31). However, these strategies cannot be said to provide comprehensive plans for energy transition in their region. Whilst several strategies recognise various forms of dispersed energy, they are circumspect on details. They do not include site selection criteria and specifics. They do not comprehensively or even partially address the siting of dispersed energy. In relation to onshore wind development one strategy states "development of onshore wind in the short and medium term is too problematic to form part of a coherent strategy and action plan" (SE-LES 2019 p38). Reflecting the policy / planning gap identified earlier (Section 1.3) the LEP concluded that onshore wind is "effectively un-investible" and that "only national government action will unlock these issues" (Ref ibid p39).

The energy strategies tend to shy away from definitive commitments and rarely include site specific activity. Whilst these strategies demonstrate a clear 'change of direction', as described by Healey (2009), there is a tendency for them to equate to being a 'kind of document'. Applying Healey's criteria, these energy strategies lack substance. They do not represent the strategic precision of action, advocated by Albrecht (2006) (Section 2.1.1). These documents do not cover the identification of areas and sites specific for development, as suggested is required by the UK government (Smith 2016) and previously provided in structure plans. They fall well short of being positive development planning strategies setting out criteria for dispersed energy development. The strategies do not consider local environmental effects in any meaningful way. Whilst some of these local energy strategies are prepared by or in association with city region bodies, which have strategic spatial planning responsibilities, there is no spatial provision for dispersed energy within the strategies. However, these regional energy strategies do represent an attempt at bridging the gap between energy transition policy and local level action. Whilst described as “patchy across the country” (Mullard 2019, p7), perhaps these are tentative steps towards bridging the gap between energy policy and local planning practice. In that sense, they reaffirm some of the rationale for this thesis.

3.2 Planning and Local Regulation

Following the review of the energy policy context this section now examines the planning and regulatory context for dispersed energy. This outlines the two principal modes of planning – positively planning for development across an area and reactively managing specific site proposals for development. Within the planning system these are known as ‘development planning’ and ‘development management’ (or development control). The section then moves on to consider the regulatory requirement for Environmental Impact Assessment, Strategic Environmental Assessment and particularly Cumulative Environmental Assessment, in the UK.

3.2.1 DEVELOPMENT PLANNING V DEVELOPMENT MANAGEMENT

The planning system is designed to regulate all types of building, land use change and physical development. Planning authorities handle many diverse types of development within their territory. Before moving into the details of how the planning system regulates dispersed energy it is useful to outline the planning system overall.

The modern planning system in the UK has been in place since 1947. Post-war legislation ‘nationalised the right to development’ (Booth 2014). This took away landowners’ sole right to choose whether any building or land-use might change. Allied to this control over development, government also took responsibility to carry out a positive planning activity: to consider how and where cities, towns and rural areas would be developed. In some cases, this resulted in entirely ‘new towns’ as well as shaping how existing urban areas would re-develop. Associated legislation provided for conservation of natural areas and culturally important places. Recognising the inherent uniqueness of place and land, the planning system attempted to balance human and environmental needs (Rydin 2011). Planning operates in the spatial and temporal dimensions. Its prime focus is change. Planning seeks to manage that change (Faludi 1973).

Whilst nationally controlled and directed the planning system deploys the principle of subsidiarity. This is the principle that decisions should be taken at the lowest possible level within government and closest to where they have effect (Sheppard & Ritchie 2016). Inevitably this leads to tensions between local and national interests. A development which is a national priority is almost always likely to have local effects. For example, a new high-speed railway between major cities will lead to a loss of land along the chosen route, cause disruption during construction and noise to neighbouring areas when operating. Reflecting the principle of subsidiarity, the planning system controls development through distinct instruments appropriate to different scales. At the small level, such as an extension to a house, development within specific terms is granted automated consent. At the largest scale, such as the Third Heathrow Runway and HS2, development is approved by a dedicated Act of Parliament, after a public inquiry. Below this other Nationally Significant Infrastructure Projects (NSIP) are sanctioned by a government Minister after a Development Consent Order process applied by the national planning agency. NSIP projects include major industrial, roads, transport, water, waste and some energy projects, including electricity power generation and transmission lines (PINS 2020). Most routine types of development, for example for a new house or an estate, needs approval by Planning Permission from the Local Planning Authority (LPA) (Planning Portal 2020). LPAs can ‘block approve’ certain standard forms of development, such as factories in an industrial estate. Figure 3.2 illustrates the instruments available at each scale of development. LPA decisions are guided by national policy through the National Policy Planning Framework to maintain consistency (DCLG 2012).

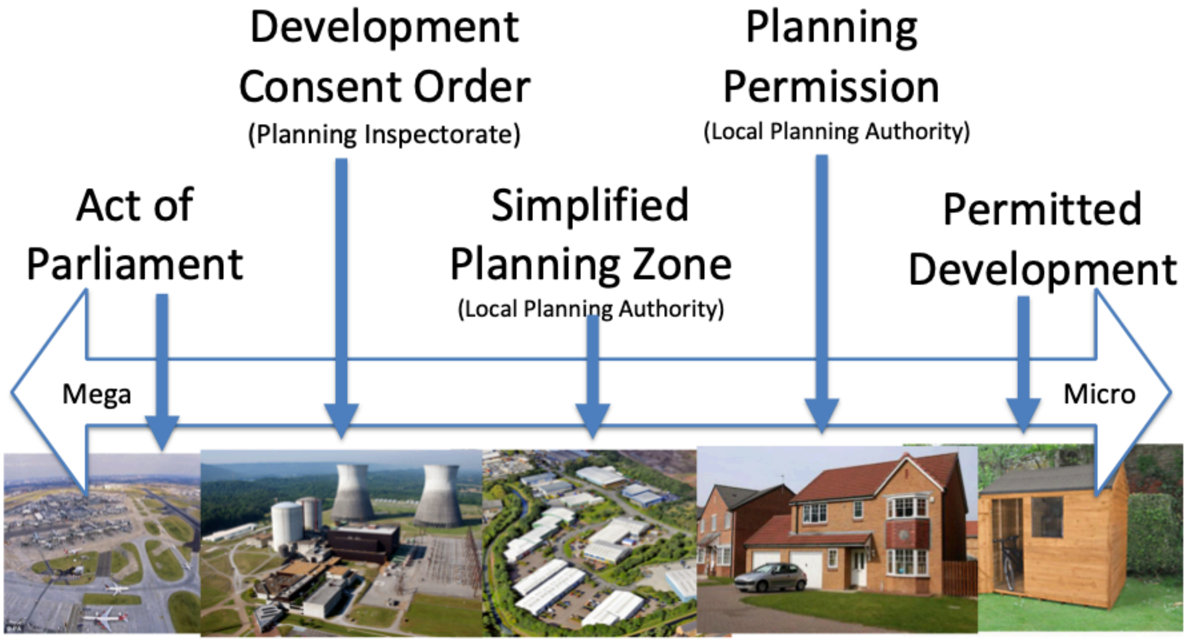


Figure 3.2: Planning System Instruments by Development Scale - England

An important question arising and examined within this thesis is what is the appropriate scale for decision making on dispersed energy development? Should each dispersed energy site proposals, such as wind farms, be treated as an individual project? Or should the development of a series of sites across a large area be coordinated or controlled centrally? If so, how?

The UK legislation provides the planning system with two principal modes of operation: ‘development management’ and ‘development planning’. The approval of development proposals, as outlined above, falls within development management. Historically this was known as ‘development control’ and in the current legislation is still referred to as the ‘control of development’ (TCPA 1990, part III). Planning legislation requires that anything that constitutes “development”, within the meaning of the act, requires “planning permission” by the appropriate planning authority (TCPA 1990, section 55 and 57). Development management is essentially a reactive process, where planning authorities respond to individual proposals put forward by developers.

‘Development planning’ deals with the planning for, or considering, the future of an area. Planning authorities examine and anticipate what development is needed for an area and decide where it should be located. For example, how many homes are needed, what type of housing should be provided (by size, type and density) and where these should be located. As explained in Chapter 2 Section 2.1, ‘development planning’ has been subject to considerable revision in the last two decades (2000 to 2020). Nevertheless, the core of the development planning process and purpose remains. Planning authorities still need to prepare ‘Local Plans’ for their territory. These need to cover housing, retail space, commercial and industrial space, the natural environment, green belt, public institutional facilities and minerals. Everything that is required to sustain communities in the built environment (Planning Portal 2020a). Planning authorities are required to keep their local plans up to date, so they will revise these every few years (DHCLG 2020).

Development planning and development management are interlinked. Proposed development being brought forward by developers is a signal to the development planning about what is possible. Decisions on applications for planning permission are legally required to take account of the policies set out in development plans (Planning Portal 2020b). This is known as a ‘plan-led’ system. However, it is possible that unanticipated types of development are brought forward by developers where the development planning policies do not cover the proposal. This has occurred with shale gas development (see Section 3.5 below). Local Plans in affected areas have made provision for possible conventional hydrocarbon sites in the traditional onshore oil and gas provinces. However, the potential of shale resources has taken the potential for hydrocarbon developments into new areas. In these situations, planning decisions are obliged to recognise the new circumstances. When coming to decisions planning authorities are required to consider development plans “unless material considerations indicate otherwise” (PCPA 2004, section 38(6)). The phrase ‘material considerations’ is legally important, much debated and not widely understood (Planning Portal, 2020c). The scope of material consideration has been defined by case law though the courts (Lowe & Dehon 2019). The phrase essentially means everything that is relevant to the planning matter-in-hand. Material considerations includes Local Plan policies, national policies and priorities, together with other environmental matters in the public interest. Overall, when determining proposed development, planning authorities are required to weigh all the relevant planning matters and reach a legally scoped judgement on the ‘planning balance’ or ‘planning merits’ of each case (DCLG 2012). It is this judgement that makes the UK planning system a ‘discretionary’ development approval system (Booth 2014): each proposal is judged on its merits.

The research question for this thesis asks whether we can plan for dispersed energy and whether we have suitable institutional arrangements. In asking 'whether we can plan for dispersed energy', the thesis ambition and research objective RO2 (see section 1.5.1), the planning approaches examined in this thesis is 'development planning'. This is also referred to as 'positive planning'. Any development planning for dispersed energy would be led by a planning body seeking to plan or create a strategy to organise the development of dispersed energy. The thesis does not examine the political, social, institutional, or structural issues around a develop plan for dispersed energy. The thesis also considers of what is the appropriate scale for any plan for dispersed energy.

3.2.2 ENVIRONMENTAL IMPACT ASSESSMENT

Planning legislation requires an environmental impact assessment (EIA) to be carried out before certain consents are given (TCPA-EIA 2017). This sits within Planning and related legislation, such as the Electricity Act 1989. EIA was supplemented to the planning system: incorporated after the 1985 introduction of environmental assessment into environmental law by the EU (Council Directive 85/337/EEC). Specific large-scale developments, such as a nuclear power station, are automatically required to prepare an EIA if they fall within Schedule A of the regulation (TCPA-EIA 2017). Certain slightly smaller, mid-sized, projects require an EIA where it is felt they have a notable effect on the local environment. This may include, for example, wind turbines where there are 'more than two' with 'hub height greater than 15 metres', where the 'character of the development' in certain 'environmentally sensitive locations' may meet various 'potential impact' criterion (TCPA-EIA 2017- Schedules 2 and 3). Consequently, not all forms of dispersed energy require an EIA. However, even where an EIA is not officially required some form of planning assessment, similar to but less formal than EIA, will often be undertaken for dispersed energy developments. It is therefore instructive to explore the potential of EIA and what it may conclude on the environmental effects arising, if applied to dispersed energy (Glasson et al 2012).

Before delving into the detail of EIA it is useful to briefly outline the guiding principles of EIA, its role, purpose, and relationship to the planning system. EIA provides a structured way of considering and assessing the environmental effects of a development. It is carried out before an application for planning permission or development consent, it identifies possible effects of a development and then assesses these to distinguish significant effects. The assessment then considers whether or not these significant effects can be mitigated, reduced, or avoided. Unavoidable significant effects are therefore identified. Overall, an EIA provides a baseline of the existing environmental situation and the consequence of the proposal (Glasson et al 2012). Importantly, EIAs do not of themselves take development decisions. Instead EIAs ‘inform’ and contribute to the planning assessment and judgement. The assessed effects are weighed within the planning balance of the proposal. EIAs supplement rather than replace planning assessment. EIAs are carried out by or on behalf of the developer. Where a planning authority feels the EIA is inadequate, they can request further additional information.

The EIA is prescribed by regulation to cover certain environmental factors. These are “direct and indirect significant effects” on “population and health”, “biodiversity”, “land, soil, water, air and climate”, “material assets, cultural heritage, and landscape”, together with any “interaction between the factors” (TCPA-EIA 2017, section 4(2)). The scope of planning matters which fall within ‘material considerations’ goes well beyond these environmental factors (see section 3.2.1 above). Consequently, as well as administrative-type aspects, such as local and national policy, planning considerations take a far wider perspective of environmental effects. Planning consideration might include the traffic generated, amenity, privacy, or the appearance of a building. Any planning judgement is not limited to the environmental effects covered within an EIA. The planning authority is also not bound by the information and the judgements on the potentiality of environmental effects provided in an EIA. It is important to note that whilst there are some superficial similarities and some overlap, significant environmental effects may or may not be considered as ‘material considerations’ (see section 3.2.1 above) within the planning judgement.

Overall, therefore EIA is a useful contributor of information to planning judgments, but these may not be the only or overriding considerations within the planning balance for a planning decision. Being project based, EIAs are required for individual development consents, under the development control part of the planning system, but are not carried out during development planning.

3.2.3 STRATEGIC ENVIRONMENTAL ASSESSMENT

As noed in Section 2.1.2, Cooper and Sheate felt that cumulative effects assessment should be undertaken within Strategic Environmental Assessment (SEA). In their view, cumulative effects “could be better addressed through strategic planning” (Cooper & Sheate 2004, p8). In practice they mean through SEA rather than development planning (ibid). Given its name, strategic environmental assessment would seem to be a logical arena to examine accumulated or strategic effects. It is therefore worth considering SEA and whether it offers a useful way of assessing cumulative or aggregate effects. And, from the point of view of this thesis, whether it offers a useful vehicle for developing a plan for dispersed energy.

SEA was formally introduced into the UK following the EU Directive (EAPP 2004 and Council Directive 2001/42/EC). It is notable that whereas EIA falls under planning system statutes, the SEA requirements are separate. It is also curious that the regulations and the directive establishing SEA do not include the phrase ‘strategic environmental assessment’ (Ref EAPP 2004), yet the government’s initial guidelines on SEA are the “Practical Guide to the Strategic Environmental Assessment Directive” (OPDPM 2004, p1). The regulations provide for “the assessment of the effects of certain plans and programmes on the environment” (EAPP 2004, p1). The guide explains the SEA regulations cover “high level” protection of the “likely significant effects” of “plans and programmes” (OPDPM 2004, p9). These relate to “legislative, regulatory and administrative provisions” (ibid, p9). In other words, SEA do not relate to individual ‘projects’ in the way that EIAs do. SEA is intended for higher level programmes and plans, but notably not policy. What is also clear is that SEA is intended to be carried out by government and governmental bodies. SEAs are not for developers to undertake.

If SEAs are for plans and programmes, it could be argued that a plan which seeks to coordinate dispersed energy across an area falls within this ambit. The regulations make clear that SEAs incorporate plans which set the ‘framework for future development consents’ for projects listed in the EIA regulation’s schedule. The guidelines state that plans that “set the framework for future development consent of projects would normally contain criteria or conditions which guide the way the consenting authority decide an application for development consent”. Also, “development consent is defined in the EIA directive as the decisions of the competent authority … which entitles the developer to proceed with the project” (OPDPM 2004, p11). This seems to put beyond doubt that, if dispersed energy projects were to fall under the EIA regulations and if there was a plan to coordinate dispersed energy projects, then a SEA is required. Whilst at present dispersed energy projects may not require EIAs it would seem at least prudent for any plan for dispersed energy, which goes beyond individually decided projects, to include a SEA.

Any SEA for area development of dispersed energy would need to identify an 'environmental baseline and current problems', 'predict significant effects' of the plan, consider 'strategic alternatives' and address any adverse environmental effects through mitigation. The guide suggests that any SEA is integrated into the plan making process and takes account of the geographic extent of the plan (Ref OPDPM 2004, p14). While SEAs do not normally predict effects at the project scale it is necessary to do that where specific development locations are proposed (ibid).

3.2.4 REGULATORY APPLICATION OF CUMULATIVE ENVIRONMENTAL EFFECTS ASSESSMENT

This subsection looks at the guidance and regulated practice on consideration of cumulative effects. Whilst cumulative effects are extensively covered in academic literature (see section 2.2 and 2.4), within planning practice in the UK there is very little dedicated explicit coverage. The principal planning practice guidance, the National Policy Planning Framework, has no dedicated section on cumulative effects (DCLG 2012, DHCLG 2019b). Instead, cumulative effects are referred to at several points within the text. For example, in relation to the consideration of the impact of planning proposal on transport the Framework states that proposals should only be refused on highways' grounds where there would be unacceptable impact on road safety and "the residual cumulative impact on the road network would be severe" (DHCLG 2019 p32). Of particular interest to the case study in this thesis is the NPPF example on minerals. This states that planning authorities should avoid adverse impacts taking account of "the cumulative effect of multiple impacts from individual sites and/or from a number of sites in a locality" (DCLG 2012, p34 and DHCLG 2019b, p59). So, whilst making no dedicated provision for cumulative effects the Framework does appreciate that multiple development sites in a locality could give rise to an accumulation of effects, beyond the individual projects. Overall, on cumulative effects the NPPF essentially seeks to remind planning authorities of the potential for cumulative effects.

One area of planning practice where detailed guidance is given on cumulative effects is for Nationally Significant Infrastructure Projects (NSIP) (PINS 2019). Although often large these are still individual projects. As such these fall under EIA regulations (IP-EIA 2017). However, for NSIP the legal definition of cumulative effects is expanded beyond that in the Directive. This includes “the direct effects and any indirect, secondary, cumulative, transboundary, short-term, medium- term and long-term, permanent and temporary, positive and negative effects of the development” (Ref IP-EIA 2017, schedule 4(5)). The NSIP guide on cumulative effects assessment advocates the identification of a ‘temporal and spatial zone of influence’ (ZOI) around developments. Within this ZOI developers need to identify other developments creating significant effects. This includes specifying the other projects, the environmental aspect or effect and the interaction. However, this process falls far short of the wide-ranging cumulative effects described in the literature (see section 2.2 and 2.4). Despite the fuller definition, for NSIP, all that is required, for cumulative effects that give rise to “interactions” which create significant cumulative effects, is that assessment of these is required (PINS 2019, p04). The cumulative effects may be both temporal and spatially separated or there may be other ways of mitigating cumulative effects. This suggests that the likely level of cumulative effects, arising with NSI projects, may be quite low. One area where the guidance suggest cumulative effects may arise is with transport (Ref ibid).

For energy NSIPs, the Energy National Policy Statement (E-NPS) says environmental statements should consider how effects of a proposal might “combine and interact” with other developments (DECC 2011b, p47). The E-NPS requires national decisionmakers to consider “how the accumulation of, and interrelationship between, effects might affect the environment, economy and community as a whole, even though they may be acceptable when considered on an individual basis” (ibid, p47). Since this appears to be the only clear guidance within planning regulation on cumulative effects, this zone of influence and effects ‘interactions’ is relevant to research objective RO2 and will be applied to the consideration of planning for dispersed energy and the case study, in this thesis (see Chapter 4 - Methodology).

Given the lack of guidance on cumulative effects, the question arises as to why there is little explicit dedicated guidance on cumulative effects within the UK planning system. This contrasts with Canada and several other jurisdictions (see Section 2.1.2). In the UK there is a plethora of guidance on many detailed issues (DHCLG 2019c), but why are cumulative effects given so little attention? The answer perhaps lies in the mindset, and the fundamental principles of planning in the UK. By its very nature the planning system does not consider individual projects in isolation. Planning takes a broad perspective on all proposals. Within 'development planning' the aim is to coordinate and organise all new development activity recognising extant land use. This goes beyond merely coordinating multiple provision for any one type of activity (Davies 1999). For example, development planning seeks to provide for many housing sites to provide for a town and city's needs. The regulatory provisions expect planning authorities to include policies in Local Plans that assess cumulative effects and ensure that effects from 'successive developments' are acceptable (DCLG 2014). Local Plans should set "a vision and a framework for future development of the area" for future decisions on proposals (DHCLG 2020a, p1). This may involve allocation of sites (ibid, p2).

The UK planning system takes a fundamentally different approach to the approaches applied in other jurisdictions on the way cumulative effects are considered. Through EIA and SEA many jurisdictions are reliant upon the legislative instrument that require environmental assessment. These are bound, arguably even confined, by the terms of definition and extent of coverage set out in the EIA and SEA procedure, so that the approach in other jurisdictions suffers from the limitations on application and interpretation of statutes and procedure. This particularly affects cumulative effects (see section 2.2 and 2.4). The UK planning system, however, with its broader approach, including development planning and control, inherently considers cumulative effects. Indeed, it may be more appropriate to describe these as accumulated effects. Within the UK system, assessment of accumulated effects is an integral part of planning practice. It also means that consideration of accumulated effects is not confined by specific regulatory terms on cumulative effects, such as population, biodiversity, land, water, air, and climate (Council Directive 85/337/EEC - Article 3(1)). For example, the EU EIA regulation makes no specific mention of traffic (ibid). Traffic appears to be only potentially included as an 'indirect' effect. Whereas with UK planning system, traffic is likely to be an automatic consideration since it is a 'material consideration'.

Overall, the UK planning system appears to offer a more comprehensive and effective way of taking account of accumulated effects than is provided by EIA, CEA and SEA. Rather than being confined to strict limitations on the definition and potential for project based cumulative effects (which can only arise in specified circumstances)(PINS 2019) the UK planning system's development planning process is able to consider and weigh the potential for wider accumulated or aggregate effects of a series of developments.

3.3 Positive Planning for Dispersed Energy – The Example of UK Offshore Wind

In the UK there is one type of dispersed energy development which has experienced a coordinated positive planning approach. This has been offshore wind development. Given the unique nature of this it useful to consider what spatial planning methodology (see RO2) was applied and what the institutional arrangements are, which facilitated this. This subsection first scrutinises the planning approach applied, from a technical or methodological perspective, and then considers the institutional circumstances.

In 2019 UK offshore wind energy generated 32 TWh of power, equivalent to 10% of the UK's total electricity generation and sufficient for 30% of UK homes. This energy was produced by 9.7GW of operational generation capacity (Crown Estates 2019). In 2020 the UK government set a target operational capacity for offshore wind energy of 40GW by 2030 (HMG 2020). This ambitious programme of future power generating capacity is being developed through auctioned rounds of leasing the seabed. Initially near-coast sites were developed. The next round of auctions, Round 4, will see sites offered at the limits of the UK's Exclusive Economic Zone (Crown Estates, 2019b). The rate of construction between 2010 and 2019 was around 1 GW per year. The contracted programme for 2020 to 2024 is expected to deliver 1.5 GW per year. The revised ambition, to 40 GW in 2030, requires 4 GW per year construction rate between 2025 and 2030 (Aurora 2020). Offshore wind energy costs have fallen substantially. Projects contracted in the 2015 auction round were priced at £140-£159/MWh. Projects coming on stream in the mid-2020s are contracted at around £37/MWh, "below the cost of new gas-fired generation" (CCC 2020c, p117). It is now envisaged that the UK will soon see "the world's first negative-subsidy offshore wind farm" (Jansen et al 2020, p614). The clarity on areas suitable for development and the offshore site selection, through a positive planning process, have contributed to the reduction in costs.

3.3.1 THE UK’S OFFSHORE WIND PLANNING PROCESS

To facilitate this offshore wind energy development programme, the planning process involved a “significant amount of spatial analysis and engagement on offshore wind resources and constraints at a strategic level” (Crown Estates 2019a). This consisted of a two-stage process aimed at selecting areas that offer the ‘best potential’ for wind energy development. The first stage entailed a generic identification of potential regions of the seabed that offered the possibility of benefit. The second stage provided ‘regional refinement’ through a four criteria model: the ‘technical resource model’ defined areas within a set depth (initially 50m but later 60m), below a set wave action tolerance and with suitable bedrock; the ‘exclusion model’ sieved out hard constraints, such as existing infrastructure or habitat designations, that prevent development; the ‘restriction modelling’ identified soft criteria that discourage development; and to complete the process the remaining areas were subject to ‘characterisation’ by detailed review (Crown Estates 2019b). In the background to this spatial modelling process a broad target range for the volume of required generation capacity was set. An appreciation of the potential energy conversion and therefore the required sea area extent was identified (Crown Estates 2019). The auction process also identifies potential developers who have proven track record together with financial and technical capability to deliver large-scale offshore wind farms. The planning process includes consideration and arrangements for delivery of power transmission lines. The area selection process took account of the need to access the existing onshore power transmission network and the capacity of the extant system to carry energy from concentrations of offshore generation (ibid). Overall, this offshore wind energy development programme can be described as a holistic positive planning process, in alignment with this thesis’s research ambition and research objective RO2.

3.3.2 OFFSHORE INSTITUTIONAL ARRANGEMENTS

The institutional arrangements for offshore wind development offer a demonstration of the desideratum for effective planning of dispersed energy. There is little doubt that planning for offshore wind development has been and seems continued to be a success (Crown Estates 2020). Institutionally the offshore wind positive planning approach can be seen to have five key components. Firstly, the planning was conducted by a single agency. This enabled a consistent strategic approach to be taken across the whole UK offshore exclusive economic zone (Crown Estates 2020). Secondly, the lead planning agency engaged with key industry stakeholder to account of the technical perspective of potential development. It was due to technical input that the sieving was extended from 50m water depth to 60m. The technical input included peer review of the planning inputs and process. Thirdly, the planning process was criteria led. The determining criteria were identified early in the planning process. Weighting these criteria enables differentiation between the varying importance of criteria, which went well beyond the hard and soft categorisation. The criteria included regulatory barriers, physical features and technical construction and operational capability. The access to transmission, both off and onshore, played an important role. Fourthly, the planning process required a substantial level of spatial analysis. It is this process, applying criteria modelling, which identified the areas best suited for development. This spatial analysis applied the criteria and technical constraints to clearly identify zones, or sites, for development (Crown Estates 2019, Crown Estates 2019a, Crown Estates 2019b). Fifthly, the planning was undertaken within a wider “long term industrial strategy” (Whitmarsh 2020, p3) with sustained policy and political commitment (Hundleby 2016, BEIS 2020e, Bosch et al 2019). The planning process, to identify and consent suitable sites, can therefore be seen to driven by an ‘imperative to deliver’ the programme of offshore wind energy construction.

This broader industrial strategy programme encompassed establishing new arrangements for offshore transmission operation and delivery (Ofgem 2020a), together with framing the Contract for Difference funding auctions in ways sympathetic to offshore wind development (Durakovic 2020). The programme has sustained political commitment over twenty years (Grantham Institute 2020). The broad programme represents a clear attempt to develop a collaborative programme with industry. Government set a clear policy goal of major offshore wind development. It organised regulatory arrangement to suit development and built a funding regime designed to reduce financial risk for developers. As part of this compact industry undertook to organise the supply chain and to contribute to industry wide efficiency, whilst retaining open market competition, to drive down the cost of construction and produce energy at or below existing market prices (BEIS 2020e). This is contrary to usual competitive behaviour. The result appears likely to produce downward pricing pressure on the UK wholesale electricity market over the medium and long term (Bosch et al 2019).

The planning process for UK offshore wind energy demonstrates a potential for delivering dispersed energy through a positive planning approach. It sets a potential template for the research ambition of this thesis (see section 1.5.1). This thesis seeks to apply a similar approach to support planning for dispersed energy onshore. It seeks to identify the factors that require to be considered (RO1), develop a methodology for holistic development planning approach for dispersed energy (RO2) and apply the constructive use of actual rather than proxy data for effects (RO3).

3.4 Study Area

Having reviewed the general context for dispersed energy planning in the UK, this Chapter now moves into its second part. This focuses on the context for the exemplar case study and, in considering a methodology for planning for dispersed energy (RO2), the context for a possible plan for the development of the dispersed energy of shale gas. This is dealt with by setting out details on the case study area, then considering the recent experience in practice of shale gas development (SGD) in the study area and finally by looking at the published estimates of SGD in the study area.

This first section in this part considers the geological and geographic context of the case study area.

3.4.1 SUBSURFACE CONTEXT

The Bowland Basin is the largest resource for shale gas onshore in the UK (BGS 2020). This basin is therefore selected as the case study area for this thesis. The Basin, shown in Figure 3.3, extends across Northern England. It incorporates the East Midland Oil Province, the West Lancashire Basin, the Cheshire Basin and most of the North-East England Province. Detailed study of the basin has shown that there are two principal shale units (Andrews 2013), the Upper Bowland and the Lower Bowland. In large parts these overlap. The Upper Unit covers 8,636 km^2 whilst the Lower unit covers 12,319 km^2, with 7,206 km^2 of overlap.

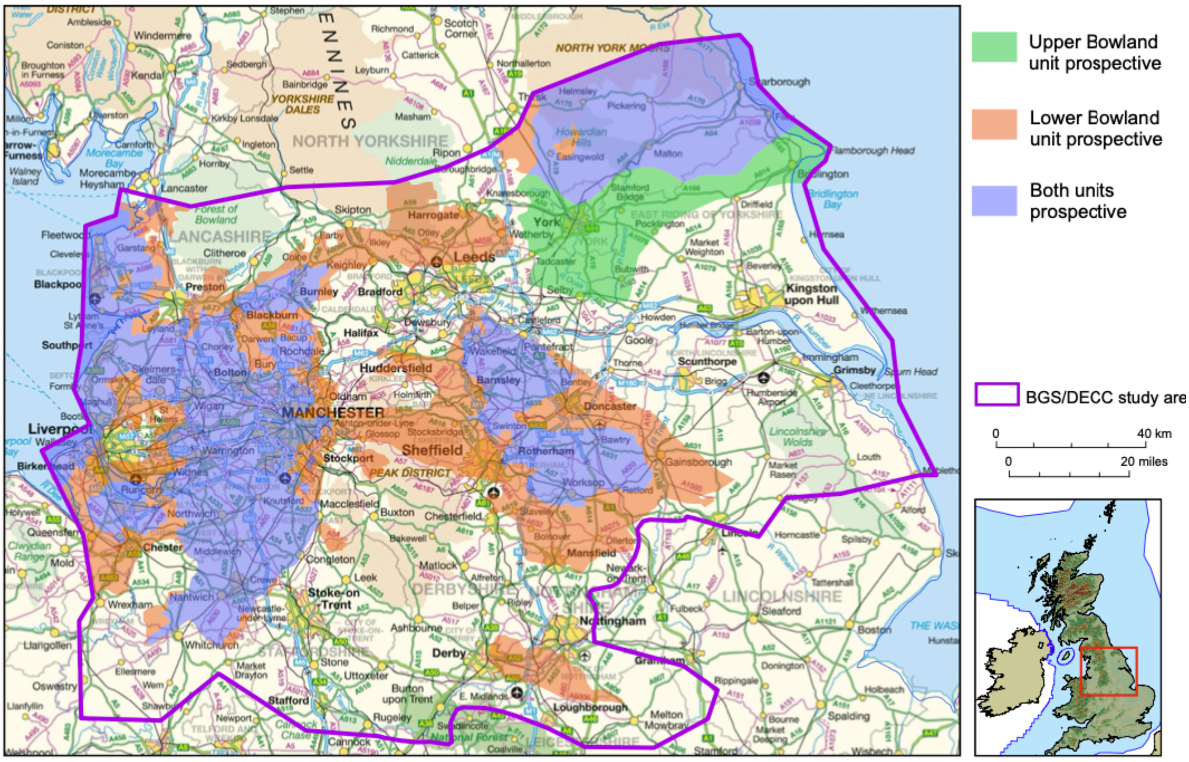


Figure 3.3: Bowland Shale Gas Prospectivity Areas in Northern England, UK

Source: Andrews 2013, Figure 44. © Crown Copyright

As part of his study Andrews identified the disposition, depth, thickness and total organic carbon (TOC) of the shale resource, thereby assessing the overall gas prospectivity of the Bowland basin. Both the Upper and Lower Units are significantly faulted and variable in both depth and thickness. The shale units are thought to vary in depth from 1,500 metres to 6,000 metres. The average typical depth of the shale is 3,000 metres (Andrews 2013). Figure 3.4 shows the variability of the depth and thickness of both Shale Units, together with the disposition of the thickness of gas-mature Lower Unit. The deep blue shown in the middle of the upper diagram, between the locations marked ‘Gainsborough 2’ and ‘Kirk Smeaton 1’, relates to the thick deep orange areas shown on the right side of the of the middle cross-section. The cross sections suggest that the Lower unit has greater volume than the Upper. The Andrews (2013) estimates of the total gas-in-place is given in Table 3.2. This estimate takes account of the probability of producing gas, by estimating P10, P50 and P90 (where P equals probability, ergo P90 represents a 90% probability or chance of occurring).

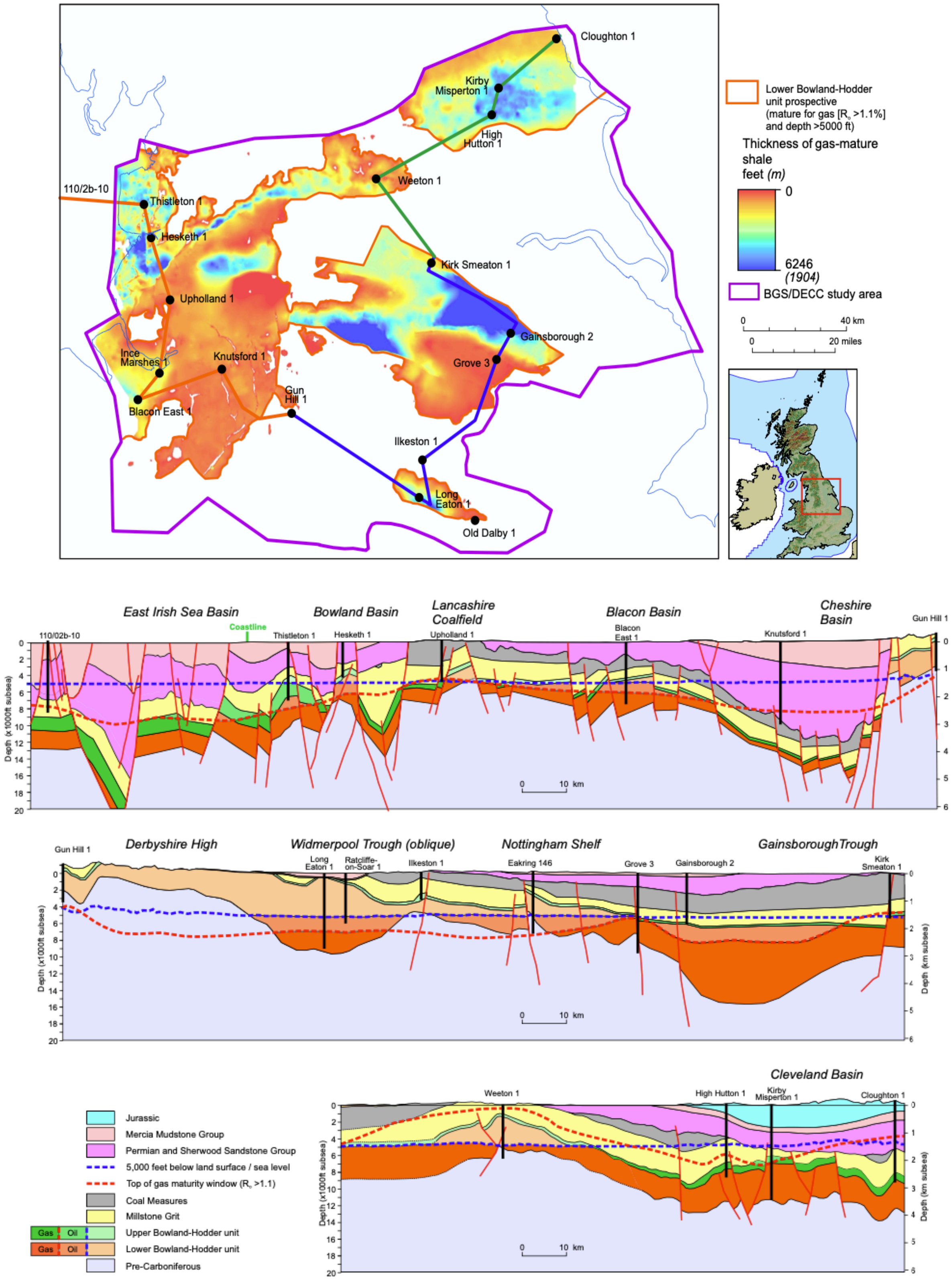


Figure 3.4: Fence Diagram Schematic Cross section of the Bowland Shale

Notes: The upper panel shows the variable thickness of the Upper Shale Unit. The orange, blue and green 'fence' line in the upper panel show the position of the cross sections shown in the lower panel. The three fence line colours relate to the three cross-sections. The lower panel shows the variability and disruption of both Upper (bright green) and Lower (bright red) Shale Units. The red angular downward lines represent faults. The black straight vertical lines represent data from boreholes. **Source:** Andrews 2013, Figures 40 and 42).

Table 3.2: Estimated of Gas-in-Place for the Bowland Shale Units

Area	Total gas-in-place estimates (tcf) Low (P90)	Central (P50)	High (P10)	Total gas-in-place estimates (tcm) Low (P90)	Central (P50)	High (P10)
Upper Unit	164	264	447	4.6	7.5	12.7
Lower Unit	658	1,065	1,834	18.6	30.2	51.9
Total	822	1,329	2,281	23.3	37.6	61.6

Source: Andrews 2013, p46.

On the basis of these estimates, at a 10% recovery rate (i.e., recovering 10% of the gas estimated) the P50 central estimate of resource gas-in-place (1329 tcf) is equivalent to circa 45 years supply of UK consumption at 2017 levels (DUKES 2020b). This estimate does not take into account any difficulty of accessing and extracting the gas. Clarke et al., while expressing the need for caution in estimating, describes the Bowland resource as “enormous” and in line with Andrews’ estimates (Clarke, et al., 2018, p. 316). A later study, looking at the remaining TOC of borehole samples from two locations, questions Andrews’ estimate on the scope for hydrocarbon created and instead suggest the “recoverable reserves of less than 10 years of current UK gas consumption” (Whitelaw et al 2019, p. 1). Although, questions have been raised on the appropriateness of Whitelaw’s conclusion given the depleted samples used (Hennissen, 2019).

Whilst these laboratory sample and desk studies show there is considerable variation in the estimates of recoverable gas, findings from very early exploratory drilling suggest that the industry is optimistic on the reservoir’s gas potential. Cuadrilla, based on flow tests after drilling near Blackpool Lancashire in the western Bowland, reported there are indications of a “rich reservoir of recoverable high quality natural gas present” (Cuadrilla 2019). Ineos, based on core samples from Tinkers Lane Nottinghamshire in the eastern Bowland, “found very high concentrations of gas, comparable (and in some of the tests higher) than the average levels in the Barnett shale in Texas” (Ineos 2019).

The orientation of the maximum horizontal in-situ stress (SHmax) is an important operational consideration for shale gas development, as this sets the orientation of shale gas laterals. Due to the focus on the Bowland basin additional analysis has identified the orientation of tectonic stress for the area. Two studies have considered this (Kingdon et al 2016, Fellgett et al 2017). Figure 3.5 shows the consensus on the orientation of maximum horizontal in-situ stress

(SHmax) across Northern England and the results of earlier studies. Whilst there is some minor local variation the analysis demonstrates the mean orientation of maximum horizontal in-situ stress (SHmax) is 150.9° with a standard circular standard deviation of 13.1°.

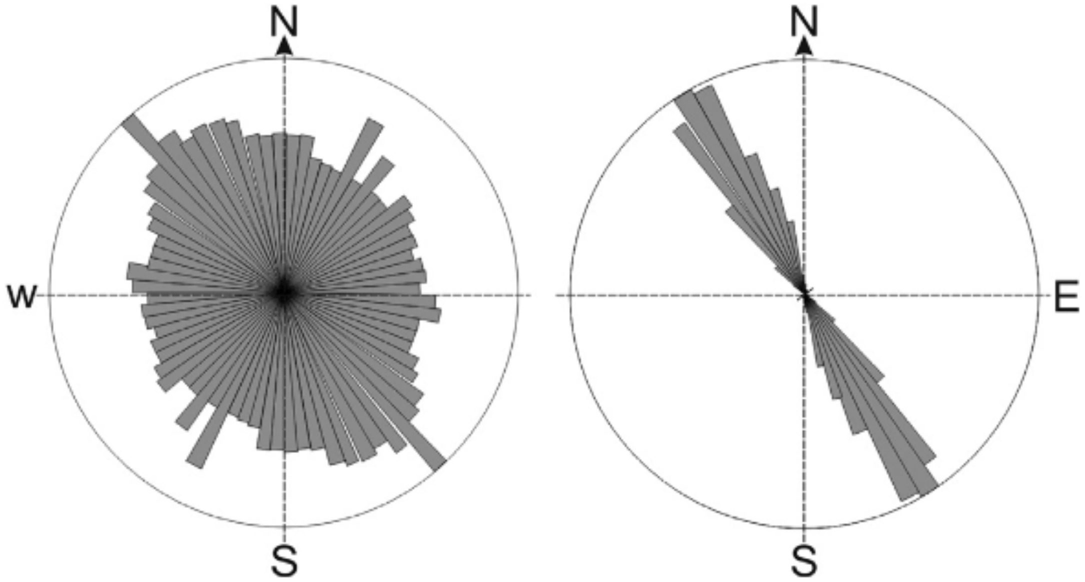


Figure 3.5: Orientation of Maximum Horizontal In-Situ Stress (SHmax) in the Bowland Basin

Notes: The left panel shows the results of analysis by Evans & Brereton in 1990. This shows the mean orientation of S_{Hmax} as 149.87° with a circular standard deviation of 66.9°. The right panel shows the results of analysis by Kingdon et al in 2016. This shows a more precise result with the mean orientation of S_{Hmax} as 150.9°-330.9° with a circular standard deviation of 13.1°. **Source:** Kingdon 2016, Figure 8.

3.4.2 SURFACE CONTEXT

The Bowland basin appears to have the largest resource and is therefore under the greatest pressure for development, in the UK. It is a large area which covers a mixed geographical region with areas of urbanisation, rural areas and upland scenic areas. Figure 3.6 shows a map of Northern England including cities, urban areas and nationally valued scenic areas. The central spine, from the Peak District northwards through and beyond the Yorkshire Dales, is an upland area known as The Pennines. Assuming shale gas development would avoid upland and national scenic areas the main areas for development lie in the lower areas east and west of the Pennine spine. However, these areas are occupied by significant human population and

Figure 3.6: Map of Northern England showing Cities, Major Urban and Scenic Areas
Key: Yellow dots = Cities and selected towns. Purple = Urban areas. Beige = National Parks. Green= Areas of Outstanding Natural Beauty. **Source:** Ordnance Survey. © Crown Copyright

existing land use activity. Figure 3.7 shows the combined Bowland shale units against residential land use coverage.

The Bowland Basin is representative of the geography and population density found in other shale areas in the UK, Western Europe and some areas of the US. These are often seen as problematic for shale development due to the potential interaction with the resident population (Sovacool 2014). The study of the potential for shale gas development across the Bowland basin is therefore of broader relevance to shale development in other UK and European areas, and the US.

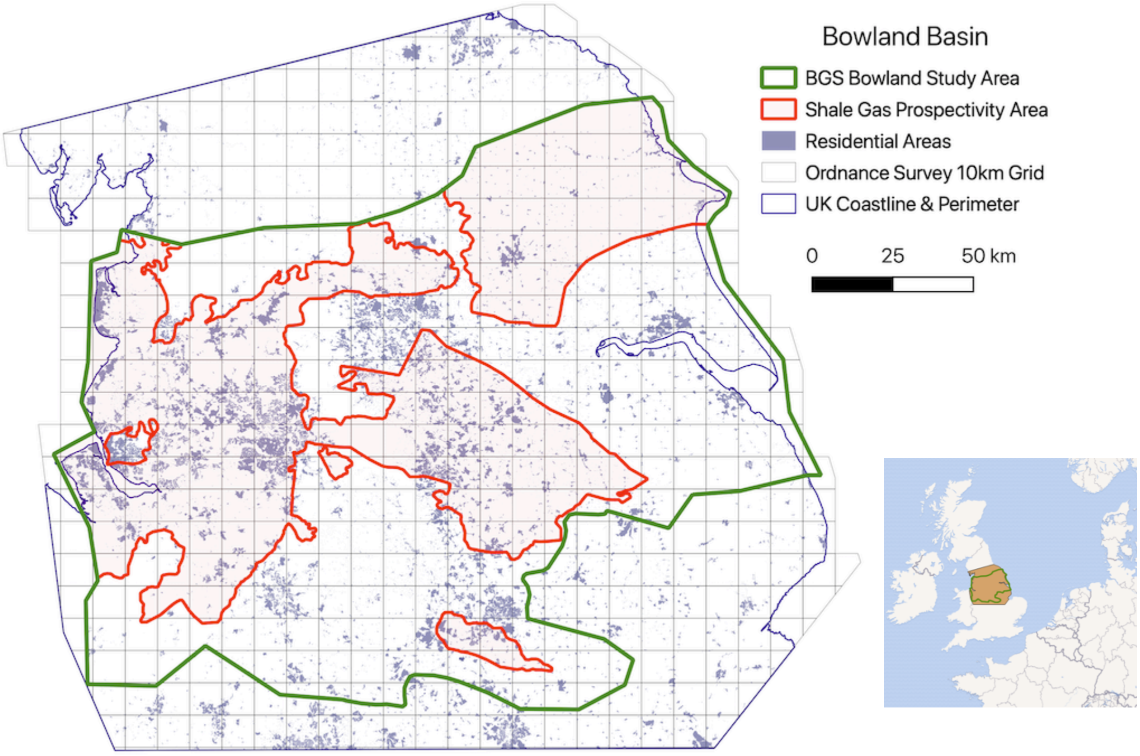


Figure 3.7: Bowland Basin Study Area Together with Residential Areas
Sources: BGS Bowland Basin and Shale Gas Prospectivity Areas (Andrews, 2013), Residential Areas (Open Street Map, 2018), UK Coastline and Ordnance Survey 10km Grid (Edina, 2019b), Inset map (Open Street Map, 2018).

The disposition of the geological shale resource has already been established by the Andrews study (2013). The case study area has a high standard of mapping (Ordnance Survey). There is therefore a strong source of data for analytical purposes. The Bowland basin has also been the area of greatest onshore fracking activity and an important focal point of the fracking controversy in the UK. Given the uncertainty in the estimates for recovery of gas resource, and only initial industry discoveries, it appears too early to consider the economic viability of shale gas development for the Bowland basin. Whilst this is a crucial question it is outside the scope of this thesis. Consideration within this thesis will therefore be based on the disposition of shale identified by Andrews (2013) and assumes a constant gas prospectivity evenly across the identified shale areas.

3.5 Experience of Bowland Basin Shale Gas Development in Practice: 2014 to 2019.

Having set out the geological and geographic characteristics of the case study area, this section now turns to the recent real-world context of decision on shale gas development in practice (between 2014 and 2019). It does this in two subsections. The first reviews the real-world development decisions on shale gas development proposals in the Bowland basin. The second details what environmental effects have been considered within the planning judgements on these recent proposals and what weight was reached with each effect.

3.5.1 BOWLAND SHALE GAS DEVELOPMENT ACTIVITY: 2014 TO 2019

This section identifies proposals for shale gas development (SGD) in the Bowland basin since the lifting of the first moratorium on fracking in 2013. It considers all of the new site-specific proposals for SGD-related activity in the UK since the 2011 Preese Hall events up to early 2020. Ten shale gas related proposals, located in six local planning authorities (PA) areas, were put forward and considered by the planning system between 2013 and 2020. The details of the cases are set out in Table 3.3. Only four of the proposals included hydraulic fracturing. All other proposals are concerned with some form of pre-fracturing exploration. The locations of the sites in the Bowland basin are shown in Figure 3.8.

3.5.2 MATERIAL AND SIGNIFICANT ENVIRONMENTAL EFFECTS OF SHALE GAS DEVELOPMENTS

When making recommendations to their councils, planning officers undertake a detailed assessment of the proposal. This includes consulting with statutory and non-statutory bodies such as other regulators. Proposals are advertised in the local area and community representations are reported. Overall, the planning officers are using their professional expertise and judgement to advise the councils. In reaching their conclusions officers and the council have a legal duty to weigh the balance of the planning merits of each proposal. This include identifying and considering both the positive and negative effects of the proposal. This is relevant to the environmental effects considered in this thesis. As part of the process of preparing for the thesis case study these officers’ reports were collected and reviewed, Planning Committee meetings on the proposals and any subsequent planning appeal public inquiries were observed (by either in person attendance or viewing online).

Table 3.3: Shale Gas Development Activity in the Bowland basin: 2014 to 2021

Site	Site Code	Planning Authority	Proposal	Site Type	EIA Details	App Date	Officer Advice	Council Decisions	Council Decision Date	Appeal Decision	Comment
Preston New Road	PN	Lancashire	Drill vertical & horizontal well & test HF	New	Full EIA	6/14	Approve	Refuse	6/15	Approve	Developed. HFC suspended following seismic events
Roseacre Wood	RW	Lancashire	Drill vertical & horizontal well & test HF	New	Full EIA	6/14	Refuse	Refuse	6/15	Refuse	
Kirby Misperton	Km	N Yorkshire	Test HF existing vertical well	Existing	Full EIA	7/15	Approve	Approve	6/16		HFC withheld following financial issues
Misson	Mi	Notts	Drill vertically & horizontally well	New	Full EIA	10/15	Approve	Approve	10/16		Under development
Tinkers Lane	TL	Notts	Drill vertically & horizontally well	New	Full EIA	5/16	Approve	Approve	3/17		Completed
Marsh Lane	ML	Derbyshire	Drill vertical well	New	None	5/17	Approve	Refuse	12/17	Approve	No activity
Harthill	Hh	Rotherham	Drill vertical well	New	None	5/17	Refuse	Refuse	1/18	Approve	No activity
Portside	Ps	Cheshire W & Chester	Drill stem test existing vertical well	Existing	None	7/17	Approve	Refuse	1/18	U/C	Awaiting appeal decision
Woodsetts	Wo	Rotherham	Drill vertical well	New	None	10/17 6/18	Refuse Approve	Refuse Refuse	3/18 9/18	U/C	Awaiting appeal decision
Altcar Moss	AM	Lancashire	Drill vertical & horizontal well & test HF	New	None	7/19	n/a	n/a			Application withdrawn after request to review seismic assessment.

Notes: U/C = under consideration. HFC = Hydraulic Fracturing Consent. App Date = Application date. Two identical application were made for Woodsetts. The second followed approval on appeal of Harthill, overturning the officer's advice. EIAs are required for these proposals but undertaken by some developers on a voluntary basis. **Source:** author's fieldwork.

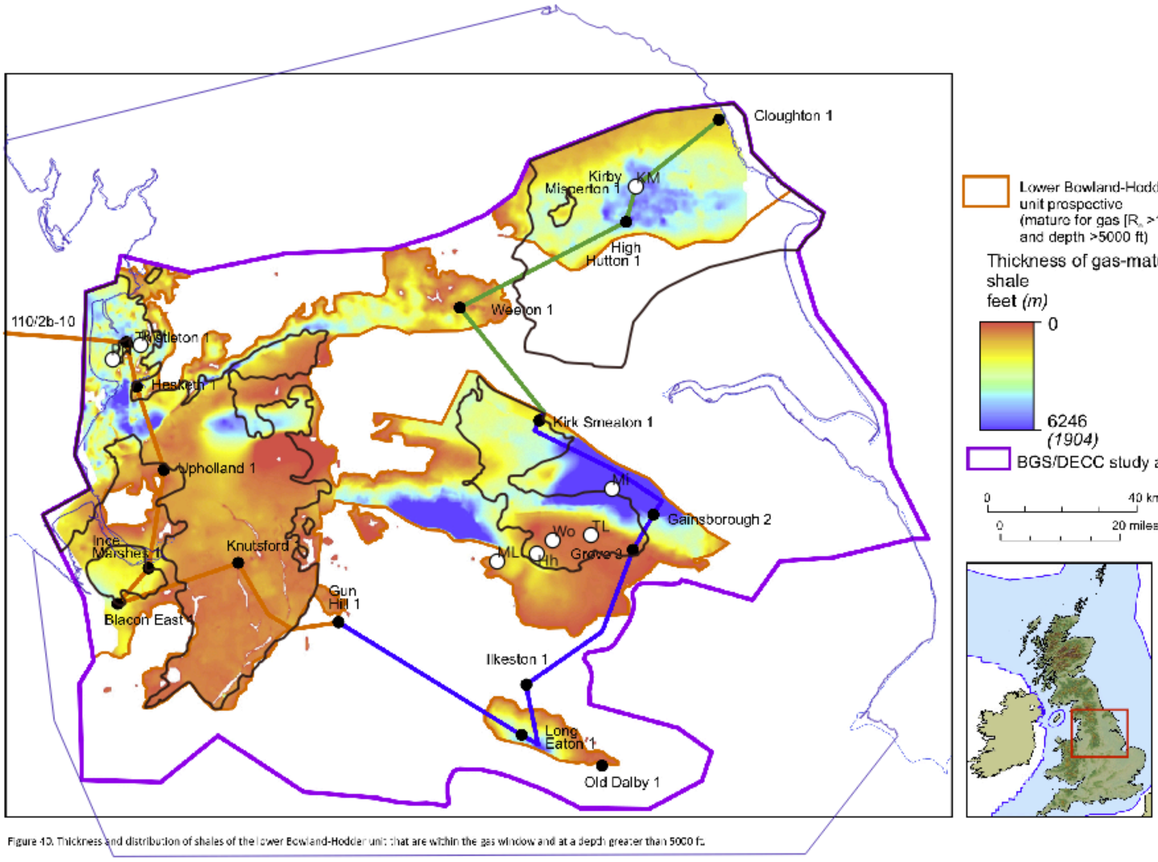


Figure 3.8: Shale Gas Development Sites Locations between 2014 and 2020

Key: White Dots = Sites of SGD activity during the period from 2014 to 2019. **Notes:** Sites are shown over the background of the variable thickness of the Upper Shale Unit (from Andrews 2013, Figure 40). The black line shows the boundary of the Lower Shale Unit. **Source:** Andrews 2013 and author's fieldwork.

Table 3.4 shows each planning authorities officers' assessment of each proposal. Every environmental effect considered by each authority is shown with either a '0' or an 'X'. Where the cell is blank the planning officers did not consider that the effect was sufficiently 'material' to investigate and report to their council. Where a 0 is shown the planning officers considered the effect material but concluded that it did not constitute a significant influence on the determination of the proposal. Where a X is shown the planning officers concluded that the effect constituted a significant material consideration which should be influential to the decision on the proposal. The planning officers found that most potential effects were not significant. Only in one case did they find an effect which should prevent the proposal from being approved (RW). For one authority (Rotherham) the planning officers initially rejected proposals but eventually concluded that any effects were insufficient to prevent proposals (Hh & Wo) being approved. Overwhelmingly, officers' judgement confirmed the assessment

Table 3.4: Planning Officers' Assessment of the Principal Effects for Each SGD Case

Effect	PNR	RW	KM	Mi	TL	ML *a	Hh *a	Ws	Ps	AM	Total
Air Pollution	0	0	0	0	0	0	0	0		U/c	0
Climate Change	0	0	0	0	0	0				U/c	0
Ecology / Wildlife	0	0	0	0	0	0	0	0	0	U/c	0
Ground Water	0	0	0	0	0		0			U/c	0
Noise	0	0	0	0	0	0	0	0	0	U/c	0
Public Health	0	0	0			0	0	0		U/c	0
Seismicity	0	0	0	0	0					U/c	0
Surface Water	0	0	0	0			0			U/c	0
Traffic	0	X	0	0	0	0	0	0	0	U/c	1
Visual Amenity	0	0	0	0	0	0	0		0	U/c	0
Waste Treatment	0	0								U/c	0
Water Demand	0	0				0				U/c	0
Total	0	1	0	0	0	0	0	0			
Final Outcome	App	Ref	App	App	App	App	App	U/c	U/c	U/c	

Key: 0 = No significant effect found. X = Significant effect found. Blank white space(i.e. no 0 or X) = No effect identified. App = Approved. Ref = Refused. U/c = Still Under Consideration. **Notes:** ^{*a} = Planning Officers position in relation to appeal.

of significant environmental effect found by EIAs (where these were carried out – see Table 3.3). The only exception, and the only fundamental difference with EIA findings, was in relation to the traffic impact of the Roseacre Wood proposal (RW). During the RW EIA the developer's consultants found that, while significant, the effects of traffic could be mitigated with sufficient traffic management measures. The planning officers, guided by the local Highways Engineers, found that the volume and type of traffic on lengthy rural roads was likely to lead to adverse public highway safety effects.

Understandably planning case officers are considering the effects that arise for the location where the proposals are made. The locations for the SGD sites were chosen by the developers. For this thesis it is instructive to understand what effects might arise in different locations. Particularly, what effects need to be considered as influential on the acceptability of locations for SGD under the planning system. To appraise what effects might influence the suitability of other locations generally the planning officers' assessments of material planning consideration have been appraised. These have been considered both collectively and individually by reviewing planning officers' report for each case. Each planning officer's report and public presentation at the Planning Committee or Public Inquiry was considered to assess what spatial area might potentially be affected by each effect. Table 3.5 collates the findings of this appraisal. Of the twelve effects identified by planning officers as potentially needing consideration the planning officers reported that only three have locally material effects likely to be influential determinants on SGD location. These are traffic, noise and visual amenity/ landscape. All other effects were found, by the planning officers, to either merit low weighting in the planning balance, mitigable or regulated by other regimes. The planning officers found the effect of traffic is dependent upon local roads configuration around sites. Noise might adversely affect residents in close proximity to SGD sites, although all the sites proposed (Table 3.3) were beyond any undue noise effect. The impact of the visual amenity is dependent upon the landscape setting of the site, but again for all the proposed sites (Table 3.3) no compelling effects was found.

3.6 Public Estimates of Bowland Basin Shale Gas Development

Before completing this section, it is useful to briefly review the various published estimates of activity needed to develop the shale units in the Bowland basin. In the public discourse and debate on the merits of shale gas development in the UK there is conjecture on the potential effects. Many agents appreciate that without some understanding of the number of sites required any inference on the likely scale of effects or benefits is supposition. As a consequence, several agents have made estimates or predictions over the likely level or required number of sites for SGD. In part these feed into the controversy and storylines (Bomberg 2017). It is instructive to critique these estimates, particularly to understand what techniques, methodology and metrics have been used in their estimates. This section deals with non-academic estimates. Academic estimates are referred to in Section 2.3.3. Several studies investigate the economic value of UK SGD (Task Force 2015, Regeneris 2011, Taylor 2013, Ernst & Young 2014) and industrial resources estimates are also made (EIA 2015). Table 3.6 sets out a brief summary of these studies. The focus here is on studies which consider the number of sites and the spatial distribution of sites. The methods used to estimate the level of activity is of chief interest.

Table 3.5: Summary of Weight Applied to Material Effects in the Planning Balance by Planning Officers

Effect	PO view of Planning Merit	Planning Officers' Assessment	Within Scope of Planning	Other Involved Regulator
Air pollution	Low, generic emissions	Use of diesel-powered machinery is not unusual activity for general emission.	Yes	EA
		Specific regulatory controls over venting and flaring.	No	OGA
Climate change	Low, only site effects relevant	Production of gas is within the national policy. Effect arises in use of the fuel, not at the site.	Yes	
Ecology & Wildlife	Low due to separation	Only arises in some location. Is mitigable by adequate separation distance.	Yes	
Ground water contamination	Low due to protection	Large vertical separation distance. Regulatory control over injected chemicals.	No	EA & HSE
Noise	**Locally Significant**	**Primary mitigation is by a suitable separation distance from noise sensitive property.**	**Yes**	
Public Health	Low due to evidence	No proven pathway to adversely affect public health whilst overall risk of emission is low.	Yes	
Seismicity	Low due regulatory scope	Known effects are low magnitude and unlikely to impact receptors. Regulated by the traffic light system to be below 0.5 M_L.	No	OGA
Surface water contamination	Low due to protective measures	Mitigation through physical barriers, collection & treatment of run off with regulation of waste into watercourses.	Yes	EA
Traffic	**Locally Significant**	**Effects vary depending on site location.**	**Yes**	
Visual Amenity	**Locally Significant**	**Excluded from high value scenic areas. Localised impact depending on local circumstances of site.**	**Yes**	
Waste	Low due scope	Appropriate treatment required for all waste, most likely to be off-site.	No	EA
Water Demand	Low due regulatory scope	High but not excessive water use, with the ability to cease use if resource is seasonally stressed.	No	EA

Key: PA = Planning Authorities, PO = planning officers, EA = Environment Agency, OGA = Oil and gas Authority

Table 3.6: Published Economic & Resource Studies on Shale Gas Development

Estimator	Description & Comment	Spatial Component or Estimate
Regeneris (2011)	Aspatial economics and commercial roll out study. The study provides useful indications of scheduling and build out scenarios.	Lancashire
Taylor (2013)	Economic, aspatial, modelling. Estimates include: truck movement by activity per pad; characterises pad development components; timing; gas production and economic worth. Estimates of gas production are based US data on	Hypothetical national network of 100 pads with scenarios of 10 well pad with 10 lateral, and 10 pads with 10 verticals well accessing 40 laterals. No detail on pad coverage or separation, although this may be deductible (see text).
US EIA (2015)	Basin resource estimate including some geological analysis.	Basins based study
Ernst & Young (2014)	Economic and supply chain study, using SGD activity based on Taylor 2013.	Up to 4,000 wells (but based on Taylor = 100 pads with 10 vertical wells and 4 laterals each). Like Taylor, this equates to one hundred pads.

Source: Regeneris 2011, Taylor 2013, EIA 2015, Ernst & Young 2014**.**

Table 3.7 sets out the various published estimates made for the potential number of sites for SGD. With the notable exception of the Tyndall study, these studies consistently fail to equate the number of pads to area of shale covered. None of the studies acknowledge any possible adjustability in the area coverage from pads or fluctuations in pad density. Accordingly, pad coverage is apparently always presumed to be static. One of the most influential early studies is Taylor (2013). This is an aspatial model which derives the volume of gas produced per lateral from a US study. The modelling projects a “hypothetical national development of 100 10-well pads of 40 laterals” (ibid, p127). The laterals per well and wells per pad are an assumption. In terms of coverage Taylor simple states these will be ‘scattered’. The key link to any spatial scale is through a constant of ‘estimated ultimate recover per lateral’ (ibid, table 33). The is derived from Baihly et al (2010). Their paper compares production trends, in five main US basins, to identify ‘estimated ultimate recoveries’ of gas. The analysis compares gas flow per month over the life of wells. It records that major improvement in gas production rates from wells “related to a step change in lateral lengths” (Baihly et al 2010, p10). In several basins they report doubling of lateral lengths to 1,500m, in two cases in one year (ibid). If these are the laterals that Taylor (2013) is applying, then it is

Table 3.7: Published Estimates and Modelling Scenarios of the Number of Shale Gas Development Sites

Estimator	Number of Sites	Method Used & Comment
AMEC (2013)-SEA	Between 30 and 120 sites, each having between 6 and 24 wells.	Activity scenarios required to consider the consequence of the licensing round.
Ricardo-AEA (2014)	Three scenarios: 12,478, 3,095 & 580 wells, without indication of spatial coverage.	Models illustrative scenarios of industry growth, rather than forecast. Summarises development stages.
Rowley (2018)	6,000 for English shale areas.	Unstated
Tyndall (2011)	500 pads with 6 wells each covering some 400km^2 of shale. Equates to 0.8km^2 shale coverage per pad.	Reverse engineered from GHG and gas production volume, based on US comparisons. Prepared before Andrews Bowland prospectivity study.
Jones (2018)	Scenarios estimates a requirement for 2,760, 1010 & 680 pads.	Estimates scale of SGD activity to replace imported gas.
UKOOG	10 pads per 100km^2 block	Suggested pad density

Notes: While Jones (2018) is an academic, his estimate is not peer reviewed and was prepared for Friends of the Earth. **Source:** DECC 2013, AMEC 2013, Ricardo 2014, Rowley 2018, Wood et al 2011 (Tyndall), Jones 2018, UKOOG 2018.

possible to derive the area coverage from each pad she is expecting. Putting aside Taylor's rather odd multiple stacked laterals (which require a consistent 4 by 500m thickness of shale) the coverage from a pad is an area of shale 3km long (2 x 1.5km) by 1.666km wide (5 laterals with 0.33km lateral separation). This equates to an area of shale covered by one SGD site of 5 square kilometres or 20 pads per 100km^2.

As the second SEA for the fourteenth licensing round has shown, any assessment of effects of SGD needs to be based on some expectation on the level of activity (AMEC 2013). Rowley, for example, provides no basis for his prediction of 6,000 sites (Rowley 2018). The study by Jones also derives an estimated number of pads from a predicted produced gas volume. He critiques Taylor suggesting that “multiple laterally-drilled wells are not typical in the US” (Jones 2018, p10). Rather than Taylor's forty laterals per pad, Jones's estimate is based on six laterals per pad (ibid, p10). Consequently, Jones's central estimate requires over one thousand sites. Presuming that overall environmental effects are commensurate to the number of pads, that compares unfavourably with Taylor's one hundred hypothetical sites. Whilst Taylor's vertically stacked multi-laterals appear odd, six laterals per pad now looks exceedingly conservative. Super-pads, with many wells, appear to be viable (see Appendix F). Taylor's forty laterals per pad (although not vertically stacked) now looks achievable. Like many others, Jones also gives no details on predicted spatial coverage.

A consistent impediment throughout the published non-academic studies is the aspatial nature of the estimates. Viewed from a spatial planning perspective this is especially problematic. To understand what effects and consequences might arise, were shale gas development to take place, some rigorous estimate of the possible number of sites is required. As well as the scale of the possible development ideally any estimate would also consider the regions local context where the shales are found. This thesis seeks to address this important gap. It takes on this considerable challenge to make the first attempt to estimate or model the scale of activity required were the Bowland basin to by fully developed.

3.7 The Context and Its Bearing on the Thesis Question

This concluding section of the Chapter draws together the observations on the context for dispersed energy, which have a particular bearing or relevance to the thesis research question, together with a reprise of the main deficiencies of academic literature (from Chapter 2). It therefore seeks to show where this thesis fits into existing research and practice. It highlights the author's assessment of where both the practice, of decision making on dispersed energy development, and the academic literature, on analytical techniques and for guiding the spatial planning for dispersed energy, appear to fall short in providing a coherent approach for the '*development of a dispersed energy system which balances the necessary construction of energy facilities, sufficient for demand, with minimal local and global environmental effects and at minimum cost to consumers*' (Section 1.5.1 – research aim and purpose). This section therefore provides a starting point for the research to seek to achieve the research objectives: of identifying the factors that need to be considered (RO1), in the development of spatial planning methodology for the holistic development of dispersed energy (RO2), applied to actual, rather than proxy, environmental effects and data (RO3). This section first addresses the practice deficiencies and then the gaps in literature.

It is clear from the prior section (3.6) that the published studies have thrown only limited light on the potential effects of shale gas development. Overwhelmingly these have looked at the macro scale of economic viability, economic value and the potential volume of gas. Few if any have considered local environmental effects of shale gas development. Section 3.5 has shown that, in practice, there has been no systematic consideration of what effects might accumulate if SGD activity was widespread across the Bowland basin. For both practice and academic study, it seems difficult to be able to start to quantify what the local effects of SGD would be without some estimation as to how many sites would be needed and how far apart sites in the Bowland basin would need to be. This thesis seeks to address these questions by quantifying the potential environmental effects of shale gas development across the Bowland basin, were it to go ahead.

Earlier this chapter has shown the broader context in the planning sphere on dispersed energy development (Section 3.1). While there are goals for delivery of net zero emission and various programs on specific sectors of activity this is largely aspatial and doesn’t appear to adequately take account of spatial considerations. The soft-space attempts to develop regional dispersed energy strategies appear ineffective and insubstantial. The UK planning system appears to have the capability to developing a positive coherent ‘development planning’ approach to dispersed energy but this has not been applied. With the notable exception of offshore wind energy development, instead, all onshore dispersed energy development, including both shale gas but also other dispersed energy types, have been made on a project-by-project basis. These decisions have been taken in the development control part of the planning system (Section 3.2.1). This might be called piecemeal or project-based decision-making. No doubt each authority seeks to be consistent with proposals in its own area. Contrasting the experience in practice, which the literature appears to mainly follow, this thesis seeks to examine whether a regional, supra-local or basin-wide perspective could apply a spatially planned approach to dispersed energy, and shale gas development in particular. This thesis seeks to establish what the appropriate factors need to be considered (RO1) and to develop a technique or methodology for the development of dispersed energy (RO2).

In terms of meeting the aim of developing sufficient dispersed energy facilities to meet need while minimising local environmental effects at least cost to consumers the academic literature seems also to have shortfalls. Onshore the only evident positive approach to planning for dispersed energy in the UK was in Wales, described by Cowell (2010). This and Gonzales et al’s research in Ireland (2016) seems to suggest there is a lack of coherency to the positive planning approaches adopted for conscious attempt to plan positively for dispersed energy. This suggests the need for a new or at least revised or reinvigorated methodology for dispersed energy development. However, it is notable that both Cowell and Gonzales's reports of planning for dispersed energy show that these relate purely to the planning perspective which takes into account local environmental effects, but that these do not take account of wider issues such as the transportation of energy to consumers and the technical/ engineering challenges of exploiting the primary resource. Under RO1, this thesis seeks to bind together all of these aspects of technological, resource, demand, transport and local environmental effects, to be considered in a spatial planning methodology (RO2).

Toke (2011) and Jay (2010) both suggest that the UK planning approach has the capability to develop and apply a coherent methodology for dispersed energy development. Toke (2011) recognises that offshore criteria-based planning methodologies have been effective in leading to a sustained program for wind energy developments. Jay (2010) recognises the value of a future-orientated thinking rather than incremental project-based decision making. Strachan (2011) takes this further, by recognising the cross-disciplinary nature of energy systems together with need to consider these in their spatial circumstances through modelling tools. But this potential, of the UK planning approach, needs to be taken forward into delivery. This thesis takes this challenge forward by seeking to evolve a criteria-based approach which seeks to develop a spatial planning methodology for dispersed energy (RO2).

To do this it is felt necessary to move beyond the obvious deficiencies of the use of proxy or surrogate data on effects and receptors, deployed by Braban & Parry 2000, Simao et al 2009, Baseer et al 2017, and Harper et al 2019, to use actual data for the measurement of environmental effects and real receptors. This reflect the importance, and the academic benefit, of moving forward from an analytical technique used simply for reporting purposes to an analytical technique which is conceived of to be used in decision-making, in spatial planning. If research is to contribute to spatial planning for dispersed energy, both in academia and in practice, it needs to be based on constructive use of actual data rather than proxy data (RO3). The methodology in the next chapter will seek to formulate a methodology for a coherent approach to spatial planning of dispersed energy facilities.

4. Methodology

This Chapter seeks to develop and trial a planning process for dispersed energy. As Research Objective 2 (see Section 1.5.1) sets out, the development of a methodology is itself part of the research value of this thesis. The trial methodology should be developed with a reasonably feasible spatial area, to minimise complexities of scale, but covering a sufficiently large area to be a meaningful exemplar. From a plan for one type of dispersed energy wider implication and value of the plan can be ascertained.

The dispersed energy considered in this exemplar is shale gas development. It is a distinct form of dispersed energy so the boundaries around the energy type are conveniently definable. The resource exists at a significant scale but not countrywide. Thus, the spatial area under investigation is beyond local and large-scale, but not so extensive that unnecessary complexities arise. The energy resource exists at a regional scale, meaning the planning process usefully covers multiple local planning authority areas. This also means the research is not confined to one type of location with specific geographical character and planning circumstances. Several other forms of dispersed energy were considered (see section 1.6.2) but overall shale gas offered the most appropriate form of discrete dispersed energy for this research.

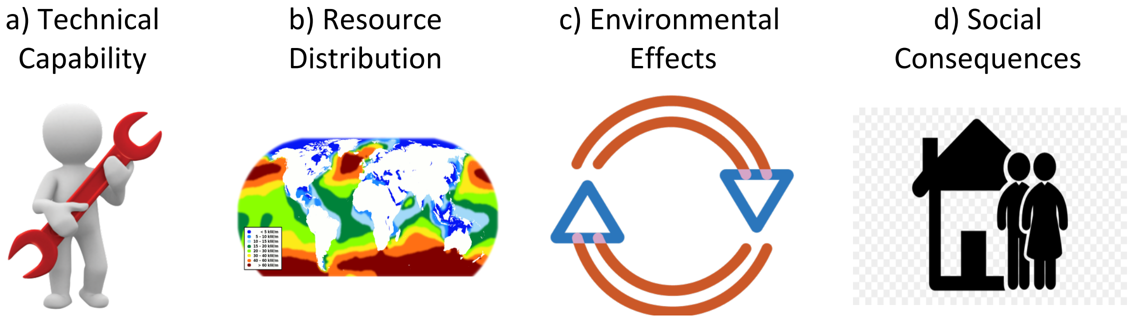
The chapter sets out how the methodology was developed. It initially considers what a generic methodology for any form dispersed energy planning might consist of. What needs to be covered and how the planning can be approached. It then turns to consider how that methodology can be applied to the shale gas case study. The methodology for dispersed energy planning, both in general and for the case study, involves several complex processes. To assist with explaining this, particularly for the shale gas exemplar, the explanation has been split over this chapter and Appendices B to F. This chapter provides an overview of the methodology and details on the critical stages of planning for shale gas development (SGD). The Appendices provide greater detail of some of the other aspects. These cover the technical or engineering aspect of shale gas development, modelling parameters and supporting modelling processes. The reader could approach this by digesting the synopsis provided by this Chapter and then reviewing the Appendices for greater detail.

Sections 1 and 2 of this Chapter give an overview of the generic process for dispersed energy planning including important prerequisites. The subsequent sections then focus on the case study. Section 3 introduces the case study area and explains why this was selected. Section 4 briefly looks back to the Context Chapter to reprise the local environmental effects selected for the case study. Section 5 sets out the assumptions for the shale gas dispersed energy case study planning process and explains why certain factors are excluded. Section 6 sets out how the generic process is adapted to the case study exemplar. An important part of any development planning preparation is to consider alternatives and Section 7 explains how this is applied for the case study. Sections 8 to 11 then explain the methodology for the shale gas exemplar, initially detailing the technical factors in Section 8 and then explaining how the local environmental effects are considered in Section 9. This includes how the interaction between technical capability and the resulting environmental effects are managed or handled. As might be expected, in any sophisticated plan preparation, this process shows that local environmental effects are asymmetrical. For example, not all environmental effects arise radially around a site. This means that different environmental effects need to be contended with in different ways. Since planning for one environmental effect (traffic) is particularly complex Section 10 goes into detail to explains how this effect is dealt with. Having laid out the key elements that the planning process needs to consider, Section 11 then summarises how the core modelling is run. The Literature Review and Context Chapters highlighted the importance of overall accumulated environmental effects (Sections 2.1.2, 2.3.1, 3.2.4 and 3.3) and particularly that cumulative effects are often omitted from project-based decision-making. In the earlier chapters it was suggested (Section 2.3.1) that these could be modelled to demonstrate that cumulative effects are dealt with more effectively when decision-making is coordinated in a development plan.

Appendices B to F provide supporting guidance explaining the operation of the model and how the final modelling approach was developed. Because each form of dispersed energy requires different land use/ take and profiles of impacts through time (e.g., construction vs operating traffic) it is important to have a sound understanding of the technical basis of the modelling. Appendix B summarises the petroleum engineering process for the production of gas from shale. It also explains other technical elements such as deploying horizontal laterals and the concentration of boreholes to access an area of shale from a central pad. Appendix C explains the modelling technique of using a base block to conceptualise and engineer the core technical development of an area of shale. It then goes on to explain how this base block is transposed to deploy the assessment throughout the basin. Appendix D summarises the key steps in the model calculation process. This could be used as a high-level set of instructions for the calculation methodology. It lays out the thirty-nine steps which summarises the computation within the planning model. Appendix E sets out the sources of data used in the modelling and explains the data choices made. Appendix F sets out how specific detailed challenges in the modelling were addressed. These detailed explanations are referenced in this Chapter.

4.1 What Ingredients Need to be Included in Generic Planning for Dispersed Energy

The methodology first considers a generic dispersed energy planning process, which could apply to any form of dispersed energy. This section investigates what needs to be considered within a plan for dispersed energy. These are grouped in to four categories. Firstly, there are distinct technical considerations which need to be understood to deploy any dispersed energy. For example, the level of solar radiation and the ability of solar panels to convert the energy. Secondly, given that there is a spatial dimension to the planning process the spatial factors need to be understood. For geothermal, compressed air storage and shale gas this includes the subsurface geology. For all dispersed energy the surface geography needs to be included in the spatial factors. Thirdly, any dispersed energy development is likely to produce some form of environmental effects, but these will obviously vary by energy type. Finally, consideration needs to be applied to the impact on the community and societal concerns. This category needs to consider the social effects of the dispersed energy. These four ingredients for dispersed energy planning are shown in Figure 4.1. The four-ingredient analysis appears to be unique and original to this thesis. It has been developed out of analysis of the potential consideration for planning for a range of dispersed energy types with identification of common elements. This section now scopes out what needs to be taken into account for each category.


a) Technical Capability

b) Resource Distribution

c) Environmental Effects

d) Social Consequences

Figure 4.1: The Four Ingredients for Dispersed Energy Planning

Commentary: The ingredients start and end with human choice, whilst within this is the systems geospatial state of the resource and the environmental effects produced. It is human capability that initiates the development process and decides the tolerable level of social and environmental consequence, that are key to the development choices. The central ingredients, of resource distribution and environmental effects, are viewed as system mechanisms.

For the technical category there is a clear need to understand the technical and engineering requirements and capability of each energy type. For example, for wind energy the engineering capability of turbines to convert the wind energy needs to be understood together with an appreciation of different turbine specifications (variability of swept area of blades against power output). Each energy type will have distinct technological requirements, at the construction and operational/ energy production phases. To effectively exploit each type of dispersed energy a detailed understanding of these technical requirements is needed. This requires understanding of what the engineering requirement are for the development or exploitation of the resource. For solar energy this may be very simple, related to the energy potential of the area covered, the resulting solar radiation and the conversion efficiency of the panels (recognising orientation, azimuth and latitude). For other energy types the exploitation requirements may be convoluted, particularly for the subsurface energy resources where complex engineering is involved to access the resource.

As has been identified in the Introduction Chapter 1 it is the spatial dimension which distinguishes dispersed energy. There are two possible components to this. Firstly some, probably most, dispersed energy is locationally tied, or it can be dependent upon a specific location. The latter applies to all geological based energy such as shale, geothermal and CAS. Whilst for solar energy and possibly wind energy it might be assumed that location is not as important, a spatial area energy potential applies. Solar panels cannot overlap whilst wind turbines clusters have optimal separation requirements. The second component is the spatial coverage required. Given the energy density of each type, very extensive spatial coverage may be needed to produce sufficient energy to meet the production volume requirements. Applying the figures mentioned in the Introduction Chapter 1, onshore wind has a mean energy density of 3.8 MW per square kilometre, allowing for load factor (Table 1.1). To meet the UK peak demand for energy of 75GW means a land requirement of 19,737 square kilometres, or 8.2% of Great Britain's land area. The spatial component also needs to take of the location of the energy resource, such as the stronger winds in north-west Britain. The increased land requirements and resource location heightens the need for appropriate consideration within spatial planning. This may need to take account of both the surface geography and the subsurface geology.

The third category incorporates environmental effects. Every type of physical development produces some type of environmental effect. Wind and solar energy produce visual impacts either due to viewing turbines across the landscape or because solar panel replace the natural colours of flora with reflective industrial structures. Wind energy requires a lot of traffic movement during the construction phase but has relatively few movements for the operational stage, whereas the traffic requirement of biomass heat and power systems, bringing material to the production plant, remain high during the operational phase. For each dispersed energy type each potential environmental effect needs to be identified and understood. The spatial spread and coverage of these effects might extend the environmental footprint beyond the spatial boundaries of the energy development. To plan for each dispersed energy these environmental footprints need to be identified and considered.

The social category comes into play because these environmental footprints may adversely affect humans. The social category also includes the human choice to protect certain types of environments, flora and fauna. Such effects are seen as undesirable and, under good planning principles, need to be avoided. For example, a dispersed energy technology may produce unacceptable noise at a set distance. This could require a separation distance from human habitation areas. As well as acting as an environmental envelope limit this would also form an exclusion area from human settlements.

Overall, these four factors create a hierarchy of ingredients which form the basis for identifying what needs to be considered in a dispersed energy plan. Satisfactory balancing of these ingredients is crucial to the effectiveness of the plan.

4.2 How to Go About Preparing a Generic Planning Approach for Dispersed Energy

Having established the scope of the ingredients that need to be recognised in a plan for dispersed energy, the next step is to identify the planning process needed to develop a plan. This section looks at the development planning process deployed within the planning system and recognises the environmental impact assessment processes. Given the challenges in these fields, consideration is also given to wide academic techniques for developing and assessing plan options. This section concludes by setting out how the planning process for dispersed energy will be approached in the case study research.

Within the UK planning system, the development planning process appropriately lays great emphasis on the need to take a wide collaborative approach to development planning (PAS 2020). A duty to cooperate is a requirement where plans cover multi authority areas. Collaboration is also required by planning authorities with other agencies and interested bodies. For example, the transport component of any plan needs to be coordinated with transport agencies, whilst for minerals planning local industry trade bodies assist with identifying need. Most development plans involve collaboration with several consultees. This is good planning practice and helps to build a sound foundation of information for the plan. It also implicitly builds a consultative approach. In the later stages of plan-making consultation is thrown open to the wider public. This provides opportunities for the neighbourhoods, parishes and communities, which are being planned for, to have an understanding and input into the plan. In the UK planning system, the planning process concludes by an ‘examination in public’ where each aspect of the plan is inspected. This seeks to assess whether the plan “has been prepared in accordance with legal and procedural requirements and if it is sound” (PINS 2020a). Whilst the requirements are judged against set criteria the question over whether a plan is sound represents a qualitative assessment of the plan.

Unavoidably for this thesis these collaborative, consultative, examination and public participation processes cannot be included. The plan for dispersed energy is therefore representative of the core of the planning process, the preparation of a plan which is outlined in the next section.

4.2.1 THE PAUCITY OF PLANNING SYSTEM METHODOLOGY – TIME TO GO BACK TO BASICS

The obvious place to start to develop a planning methodology for a dispersed energy plan is to apply the development planning process deployed in the UK planning system. The formal guidance on planning making says “plans set out a vision and a framework for the future development of the area, addressing needs and opportunities in relation to housing, the economy, community facilities and infrastructure – as well as a basis for conserving and enhancing the natural and historic environment, mitigating and adapting to climate change, and achieving well designed places” (DHCLG 2020). The guidance sets out the legal requirements to prepare plans and keep them up to date, so that they can be used to determine decisions on planning applications. This is known as a ‘plan-led’ system. Previously development plans included ‘structure plans’, typically at the county level, and ‘local plans’ at the district, neighbourhood or area level. In many ways the ‘plan-led’ approach was not necessarily concerned with the development planning process (Davies 1999). It was intended to restrain inappropriate discretionary decisions by planning authorities, from sometimes arbitrary and occasionally corrupt decisions, on planning applications (Allmendinger 1996, Booth 2014). Much of the guidance on development plans confirms the legal requirements around the preparation, examination and adoption of plans. Perhaps surprisingly the guidance does not set out *how* plans are to be prepared.

In the absence of government guidance, the other possibility for what a development planning process should cover is Environmental Impact Assessment (EIA). The EIA process has been applied in the UK though the Planning Acts. This EIA process provides some insight into a possible approach for planning for dispersed energy. Two key stages of the EIA process appear to offer value to the process of preparing a plan for dispersed energy. The selection of environmental effects, at the scoping stage, is a useful element. Since not every conceivable effect could be considered, it is useful to focus planning and assessment on those environmental effects which are most likely to be influential in development decisions. The

EIA stage of predicting potential significant effects and considering whether and how these can be mitigated also appears beneficial (Glasson et al 2012).

A third possible source of guidance on a planning process for dispersed energy comes from Strategic Environmental Assessment (SEA). Whereas EIA is project-based SEA applies to programmes and policy development. It is therefore more appropriate than EIA for a wide area planning approach for dispersed energy. SEA is seen as “a decision aiding tool rather than a decision-making process” (Dalal-Clayton & Sadler 2008, p104). In this sense SEA is better suited to a plan preparation process, since a plan is intended to demonstrate how decisions should be made for dispersed energy. However, it is notable that the SEA is intended to be applied to a prior prepared programme. It is an appraisal tool to be applied once the programme is established, prior to implementation. It therefore does not provide relevant guidance on how to prepare a plan or programme.

In each of their own ways the three potential areas for guidance on how to prepare a plan for dispersed energy fall short of giving practical guidance. The guidance on development planning mostly covers the legal requirements around plan approval. The EIA is focused on individual projects rather than offering the required wider-scale perspective. SEA is intended for post-plan or programme appraisal. In many ways there is a paucity of guidance of how plans are prepared. The process of preparing development plans within the planning system relies on the professional expertise of the planners concerned. For the research here a similar approach is adopted, that relies on the author’s planning expertise as a Chartered Town Planner. One key feature of the guidance on development planning process which is adopted here is that the plan should be ‘evidence based’ (DHCLG 2020).

4.2.2 THE PLAN PREPARATION PROCESS

Using professional expertise and the relevant guidance the following planning process for dispersed energy plan-making applied in this Chapter, is set out in Box 4.1.

Box 4.1: General Principles for the Dispersed Energy Planning

1. Identify resource type potential, including any development constraints and technical development requirements. This needs to include movement or transmission of the energy.
2. Gather information on the location of the resource relative to its circumstances. This is likely to include topography, geographical features, residential settlements, road networks and barriers arising from development constraints. For geological resources this needs to include the subsurface features.
3. Define a suitable area for a plan. Identify any out-of-area requirements (such as energy transmission) and whether the plan boundary is sufficient or whether out-of-area requirements need separate consideration.
4. Understand the technology and engineering requirement for the development of the resource.
5. Identify the initial likely environmental effects. To avoid attempting to consider every possible effect, the potentially significant environmental effects need to be selected so that consideration can be focused on these more important effects. This is similar to scoping in EIA.
6. Assess the development potential of the resource. For the selected environmental effects predict the potential significant effects and the likely potential impact on receptors. This is similar to identifying significance in EIA.
7. Identify and consider alternative plan strategies.
8. Consider what mitigation measures can be applied including considering alternatives.
9. Predict the effects arising across the chosen plan area, including considering alternative forms and scale of development.
10. Optimise the planning scenarios so that environmental effects are minimised, if not avoided. If possible, find the trade-off options.

The planning approach outlined here may require iteration to find the optimal position where the most suitable trade-off can be found. The planning process is likely to be applied through some system of modelling or trialling alternative strategies. This is likely to take account of the surface geography, for geological resources the subsurface, the technical development engineering of resource and the potential environmental effects envelope. Where these effects impinge upon the residential settlements and human activity, there needs to be consideration of social factors (Figure 4.1).

4.2.3 CONSISTENCY, MODEL RULES AND OPTIMISATION

The dispersed energy planning process applied here is developed through modelling (Section 1.6.2) to simulate the consequences and effects that could arise with a full-scale exploitation of dispersed energy. “Models are a simplification of reality” (Schrojenstein-Lantman et al 2011). For the case study the simulation is of the Bowland Basin shale gas development (SGD). This is a form of agent-based modelling, or rather activity-based modelling (Schrojenstein-Lantman et al 2004). As with all agent-based models there are two key components: “a map of the study area, and a model with agents that represent human decision-making” (ibid p43). For the modelling here the map has three dimensions, to allow for consideration of the subsurface disposition of the shale unit as well as the two dimensions of the surface geography. The area used in the model is Northern England. The modelling takes account of the residential land use and road network as well as the disposition of the resource. The model assumes that SGD sites can be placed anywhere within the Bowland basin: that there are no barriers, other than those specified within the model, on the location of SGD activity. In this model there is only one actor or decisionmaker, who is seeking to mastermind the full-scale development of shale gas in the Bowland basin. That actor might be seen as government, or government agent or a master SGD developer or master planner. The decision-maker makes all decisions regarding the development and judges which factor are relevant to the choices. This is a modelling simplification since in real world planning for shale gas development decisions would be far more complex and involve many decision agents.

As with all modelling there is a need to achieve consistency. This requires a common set of self-imposed rules which determine how the development may take place. These rules persist throughout the model. As will be seen (in Section 4.6), the model evolves in complexity through ‘levels’. These reflect the dispersed energy planning ingredients outlined earlier (Section 4.2). The rules for the model therefore evolve with each level so that further complexity can be added. The rules established in lower levels persist into upper levels. A constant rule throughout is that the model is seeking to optimise the development of shale gas. This means that the model seeks to develop the shale in the most efficient way possible. It seeks to use the minimum effort, the least materials necessary and seeks to avoid or at least minimise adverse environmental effects. The scope of environmental effects considered in the model is defined and explicit (Appendix F).

4.3 The Case study Area: Why and How to Use Bowland Basin Test Area?

The Bowland basin has been selected as the study area for this thesis (Section 3.6). It appears to have the largest shale resource in the UK (Andrews 2013) and would therefore face the greatest pressure for development. It is a large area which covers a mixed geographical region with areas of urbanisation, rural areas and upland scenic areas. The disposition of the geological shale resource has already been established by the Andrews (2013) study. As with much of the UK, the area has a high standard surface and geological mapping. The Bowland basin has been the area of considerable onshore SGD activity to-date (at 2020) and an important focal point of the fracking controversy in the UK (Section 3.7). The extent of the Bowland basin together with its regional context in northern England and north-western Europe is shown in Figure 4.2.

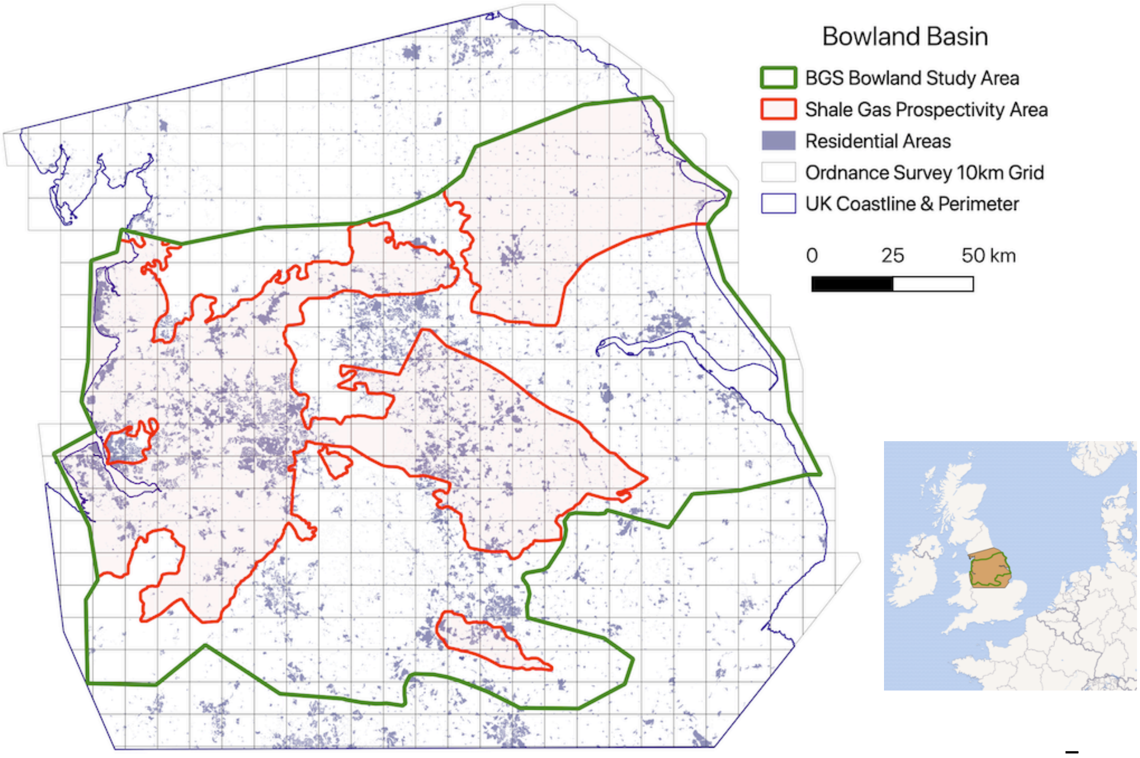


Figure 4.2: Bowland Basin Study and Shale Area

Source: Bowland shale (from Andrews, 2013), Residential Areas (Open Street Map, 2018), UK Coastline and Ordnance Survey 10km Grid (Edina, 2019b) across Northern England, with Inset map (Open Street Map, 2018).

The Bowland Basin is representative of the geography and population density found in other shale areas in the UK, Western Europe and some areas of the US. Population density is often seen as problematic for shale development due to the potential interaction with the resident population (Bazilian et al 2013, Sovacool 2014). A strategic approach to resource development can also be applied to environmental effects in less densely populated areas. The study of the Bowland basin and consideration of a strategic approach in this study therefore has a broader relevance to shale development in other UK and European areas, the US and even globally, as well as to other dispersed energy development.

Since 2013 licence blocks for onshore hydrocarbon development have been based on the Ordnance Survey 10km national grid (OGA 2020) (Edina 2020). Whilst licenses issued after 2014 recognise extant licenses from previous licensing rounds, the modelling here is simplified by basing study on the 10km national grid. Drilling is restricted in high value scenic areas such as National Parks, Areas of Outstanding Natural Beauty and potable groundwater Source Protection Zones (Zone 1). The modelling therefore excludes these areas (Figure 4.3). Modelling is carried out where shale gas resource has been identified from the Andrews study. It is applied to all OS national grid blocks, outside of restricted areas, where there is at least 70% area cover of shale units remaining. This results in 96 blocks being analysed in the case study (Appendix H). Figure 4.3 shows the Bowland shale units, the scenic areas, source protection zone (zone 1) and the OS National Grid together with the 96 blocks meeting the 70% shale coverage criteria. The researcher's choice of setting a 70% threshold is made to minimise arithmetical complexity in the modelling calculations. In real world development a developer may make a similar choice based on economic criteria. The study blocks are identified in the format 'aann' (e.g., SD32) where the alphabetics (aa) specifies a 100km national grid block, whilst the numeric (nn) indicates a 10km^2 block within the 100km block with an x-y reference (x for the Easting and y for the Northing) (Appendix C).

The unit of study for the assessment, based on 10km^2 blocks from the Ordnance Survey 10km national grid, provides a useful basis for studying the planning of SGD and measuring accumulated effects. They provide an appropriate scale for consideration of local issues, such as traffic and noise, whilst also facilitating comparison between blocks with different types of geographic character, land use and levels of urbanisation. As Figure 4.3 shows, the 96 selected 10km^2 study blocks cover most of the available Bowland shale units.

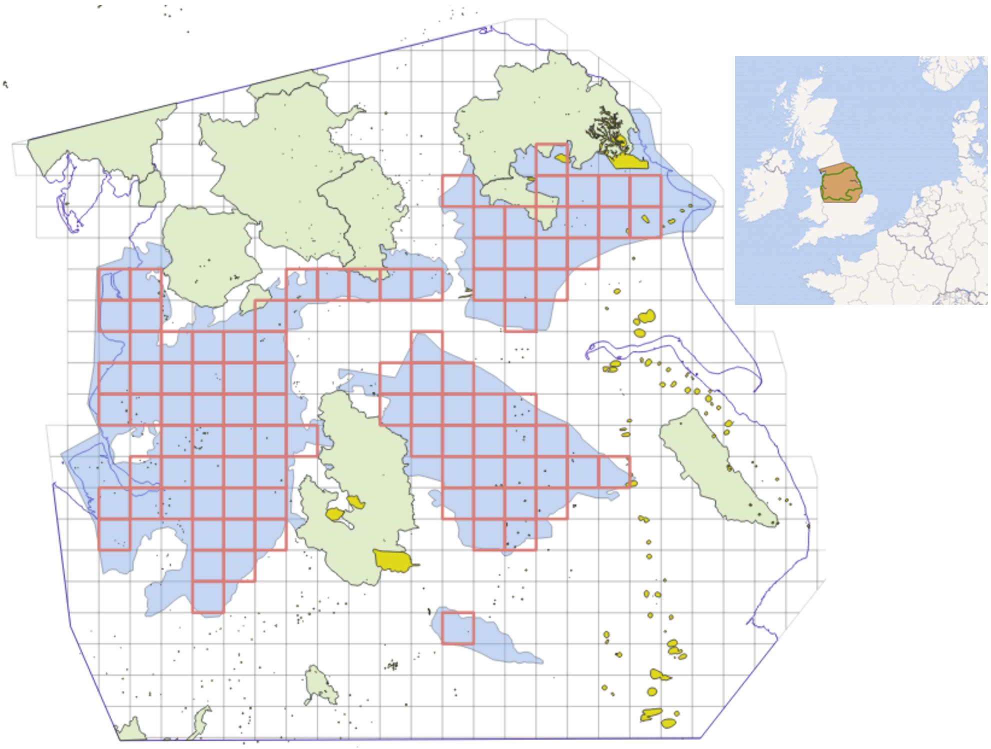


Figure 4.3: Bowland Shale, Exclusion Areas and Blocks Selected for Study

Key: Blue = Combined Bowland Shale Units. Light green = National Parks & Areas of Outstanding Natural Beauty. Yellow = Source protection zone one. Blue lines = UK coastline and study area perimeter. Grey grid lines = OS 10km national grid. Red block squares = Study Blocks (96). Inset map – Bowland study area in the NW Europe. **Source:** Bowland Study Area and Shale Gas Unit from Andrews (2013), Exclusion Areas from National Parks UK (2019), UK Coastline and National Grid from Ordnance Survey (2019b), inset map from Open Street Map (2020).

4.4 Identifying the Key Local Environmental Effects of SGD for Assessment.

Within a planning process and modelling of environmental effects for research purposes, it is not possible to take account of every possible effect in every situation. In real-world planning there is also the need to identify what the important or key effects are. For example, a key effect of renewable wind energy development is likely to be the visual effect of the turbines, which may be in position for 25 years, and how this relates to the landscape situation.

Chapter 3 provided detail on the twelve potential environmental effects which planning authorities considering SGD proposals examined within their assessments (Section 3.7.2). Table 3.4 lists the environmental effects considered by them. Most of these effects were found, by the local planning authorities, to be not significant (Section 3.7). Table 4.1 gives details on these environmental effects, identifies whether the effect arises locally or not and whether the effect was found to be significant to the planning consideration.

Table 4.1: Identification of Key Effects for Modelling

Effect	Zone of Influence	Significance & Mitigation	Key Effect, Influential in SGD Siting
Air Pollution	Local	Not Significant	No
Climate Change	National	Not significant	No
Ecology / Wildlife	Local	Not significant	No
Ground Water	Local	Mitigatable	No
Noise	**Local**	**Significant**	**Yes**
Public Health	Uncertain	Not Significant	No
Seismicity	Local	Not significant	No
Surface Water	Local	Mitigatable	No
Traffic	**Local**	**Significant**	**Yes**
Visual Amenity	**Local**	**Significant**	**Yes**
Waste Treatment	Regional	Not Significant	No
Water Demand	Regional	Not Significant	No

Analysis (summarised in Table 3.5) of these potential effects shows that only three effects were found to be likely to be locally significant by the local planning authority (LPA) assessments. These are: noise, traffic and visual amenity (in bold in Table 4.1). These three effects are taken to be the key effects to be assessed in the modelling.

Seismicity, while potentially likely to have local effects, was found by planning authorities not to be significant. This is because it falls outside of the ‘material considerations’ which they legally consider (Section 3.2.1). Seismicity is thus outside LPA’s remit. While it may be appropriate to consider seismicity as a local environmental effect within the modelling in this thesis, there is considerable uncertainty over predicting the extent and circumstances under which seismicity effects arise (BEIS 2019d). Consequently, it is not possible to incorporate seismicity into the modelling at this time.

4.5 Broad Scope – the Assumptions of and Exclusions from the Model

The case study research is undertaken by modelling (Section 1.6.2). Epstein (2008) suggests that it is important to make assumptions behind models and the scope of models explicit. This section therefore sets out what the model covers, what is excluded, and the underlying assumptions applied to the modelling.

The following issues and factors are excluded from the model:

- Gas pipelines: The UK has an extensive gas infrastructure including both nationwide trunk and local distribution networks. Most of the Bowland shale area lies within a few kilometres of the gas network suggesting that the requirement to ship any gas produced from SGD is reasonably straight forward. However, as the detailed location of the gas distribution network is not known this makes modelling connects between shale gas production pads and the gas network problematic. Thus, modelling of connections between shale gas production pads and the gas network has not been conducted in this research.
- Water supply: The Bowland basin has an extensive water supply pipe network. For the one active SGD site (Table 3.3 - PNR) water supply has been provided from the local water distribution network (Arup 2014). Given the volumes of water required hydraulic fracturing it is likely that for shale gas production sites water will be supplied by pipe. In the model water is assumed to be supplied by pipe but works associated with this is excluded from the model due to the lack of easily accessible data on the water distribution network.
- Wastewater: The level of waste is dependent upon the level of water injected, the proportion of flowback and produced water as well as the level of recycling of wastewater for further reinjection. All of these factors are dependent upon local circumstances and are very difficult to predict for research purposes. Removal of wastewater is excluded from the model as the level of wastewater is uncertain, highly dependent on the local geology and therefore problematic to predict. It is likely that wastewater would be transported away by tanker but projecting wastewater volumes is unreliable. The other options for developers are to recycle wastewater or to lay a wastewater extraction pipe to a convenient collection point, at the same time water supply and /or gas export pipes are laid. Given these uncertainties the transport of wastewater is excluded from modelling.
- Other potential environmental effects: The potential effects of air pollution, climate change, ecology, ground water contamination, public health, seismicity and surface water contamination are excluded from modelling. These potential effects have been shown not to be influential in decision-making on SGD (Section 3.7) and are thus excluded from modelling.

- Economic viability: whilst the financial viability of SGD will significantly affect the scale of activity this is beyond the scope of the model and this research. Whilst economic viability is normally excluded from 'material considerations' for planning permissions development planning would seek to establish the viability of planning for dispersed energy and the likely chances of a plan being delivered. However, given the considerable uncertainty around shale gas development economic viability is excluded from modelling.
- Timing and Sequencing: It would be possible to develop as Gantt chart for the sequencing of SGD activity; however, detailed time analysis is excluded from the model. Timing is discussed in relation to cumulative effects (Section 5.4). This exclusion is due to limits on time available for the research.
- Other surface features: The modelling does not take account of all surface ground features which might obstruct or inhibit SGD. Features such as water courses, railway lines, public open space and restricted access areas are excluded. Topography is also excluded. The surface modelling therefore only takes account of public roads, residential land use and statutory SGD restriction areas. This exclusion is due to complexity that these features create and the limit on time available within this study.

The modelling is based on the following assumptions:

- The shale units identified by Andrews are taken as the disposition of the shale gas bearing subunits. The modelling is based on the Andrews (2013) two-dimensional cover only. The shale unit depth is assumed to be consistently 3,000m with a standard thickness equivalent to the vertical extent of the model hydraulic fracturing zone. In part this assumption is made because more refined data on the shale unit is not available (Harvey 2019). The shale subunit is assumed to parallel to the surface as well as having consistent porosity and permeability. Therefore, the shale unit is assumed to provide a consistent flow of gas per unit of surface area covered. Andrews (2103) identifies two shale units, the upper and lower Bowland-Hodder shales. However, for modelling purposes these are combined into a single unit with the area coverage derived from merging both. Effectively this assumption assumes that all of the implications of geological heterogeneity can be dealt with by the petroleum engineers within operators and that areal unit of shale will deliver gas consistently.

- Modelling assumes a consistent application of a five stage SGD process, consisting of: site preparation, vertical and lateral borehole drilling, hydraulic fracturing, gas production, and concluding with capping boreholes and site remediation. A description of the five stage SGD process is set out in Appendix B.
- The model makes assumptions regard the efficiency and effectiveness of drilling activity and hydraulic fracturing. It assumes a linear relationship between the distance drilled, for both vertical and horizontal boreholes, and the materials used. This presumes that the geology is homogenous. The materials used, include drilling muds, casings, cements and drill strings, are proportional to the length of boreholes. It also assumes a linear relationship between the length of boreholes production sections, referred to as laterals, and the materials used in hydraulic fracturing.
- Whilst time analysis is excluded, the model assumes that one drilling rig and one set of hydraulic fracture pumps is used for all pads within each 100m2 block (at any given pad density). This means that the rig and pump sets, together with associated equipment, have to be transported from one pad to the next. The rig and pump sets are assumed to require a consistent number of vehicles to transport each.
- Modelling is based on the OS national grid and assumes that licenses are issued for 10 km^2 license blocks. Data is taken from Ordnance Survey for the 10km national grid, the road network and coastlines. Open Street Maps (OSM) is used for residential land use areas. This data is assumed to be reliable and consistent. The OSM data does not include individual residential properties such as farms or isolated dwellings. Treatment of the road network is discussed in Section 4.10.
- The traffic analysis includes various load factors for the size of vehicles and their carrying capacity. This data is given in the modelling and assumed to be consistent. Details of vehicle carrying capacity are discussed in Section 4.10.
- Boreholes are assumed to consist of two straight sections, connecting the pad to the heel, and the heel to the toe. The heel is the point where a borehole turns, typically through 90 degrees, from the vertical or near vertical to the horizontal (to start its run laterally through the shale rocks). The toe is the end of the borehole (and the lateral). In practice boreholes bend at the heel through a large, graduated arc to allow the bore to change direction. For modelling purpose, direct lines are used for borehole

calculations (from pad to bore heel and from heel to the bore toe). Figure 4.4 illustrates the assumed geometry of a shale gas borehole, showing the Pad, the Heel and the Toe.

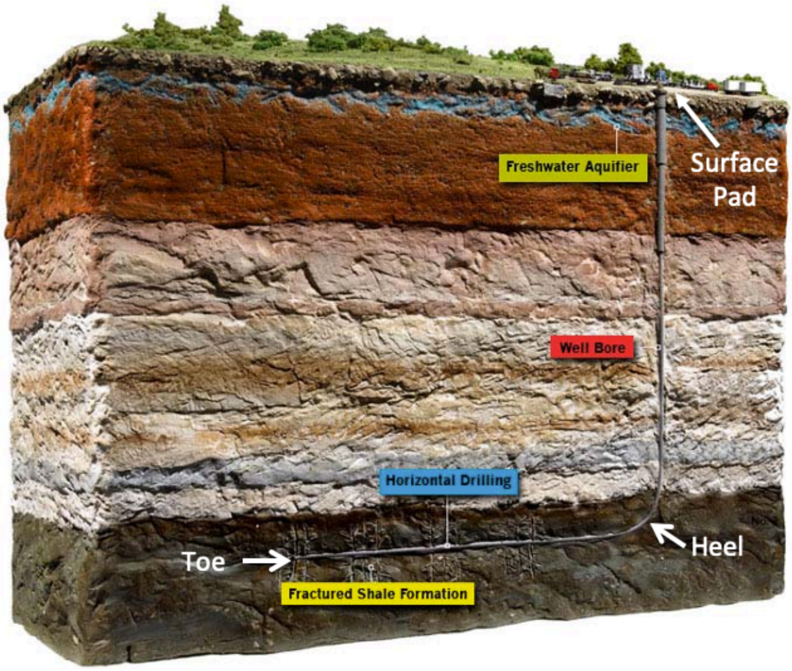


Figure 4.4: Simple Shale Gas Development Borehole.

Commentary: The figure shows a simplified geometry for a shale gas borehole. The bore initially decends down from the Surface Pad, towards the Heel. At the Heel the bore turns to run horizontally through the target shale formation, to terminate at the Toe. The productive section of the borehole, from which shale gas is extracted, is the horizontal section between the Heel and the Toe. This section is referred to as the ‘Lateral’. In the example shown the bore runs vertically from the Pad to the Heel. While this is the shortest point between the Pad and the Heel, it is technically possible for this section of the borehole to be angled. This enable pads to be located away from the point directly above the Heel. For the purposes of modelling the bore is assumed to be two straight lines connecting the Pad to the Heel and the Heel to the Toe. **Source:** BEIS 2019e, with author annotation.

4.6 Applying the Four Ingredients to the Shale Gas Case Study as a Four-Level Model

To address the complexities of potential basin-wide development of the Bowland shale gas resource the model is developed through four levels: petroleum engineering, surface geography, subsurface geology and the social dimension. These levels reflect the four ingredients referred to in section 4.1: the first level being the simplest, with the fourth level being the most complex. By breaking the model down into levels, it is possible to address the practical issues of the surface road network, the subsurface geology and the social effects, by considering these separately at the appropriate level.

As the model builds additional factors are added to the model. At lower levels of the model the excluded factors are either entirely absent or handled in an idealised way. For example, no account of social factor is taken in levels one to three and there is no consideration of possible effects on the human population. Table 4.2 shows the treatment of factors at each level. Figure 4.5 illustrates the concept of the four-level model.

Table 4.2: Treatment of Factors within the Evolution of the Model

	Treatment of factors of:			
Level	**Engineering**	**Geography**	**Geology**	**Social**
1: Engineering -	✓	I	I	A
2: Geography -	✓	✓	I	A
3: Geology -	✓	✓	✓	A
4: Social -	✓	✓	✓	✓

Key: ✓= Taken into account, I = Idealised, A = Absent.

The focus of the first level is on understanding the petroleum engineering requirement to produce shale gas. Analysis considers the number of laterals or fracking zones covered from each pad, the consequent length of laterals, and the vertical or diagonal (near vertical) boreholes required to reach each lateral heel. Strictly speaking there is no need to assess the traffic, noise or visual amenity at the engineering level. However, given the importance of traffic to the overall assessment of environmental effects of SGD it is instructive to at least conceptualise what the traffic effects at the engineering level would be. Further details are given in Appendix F.1.2.

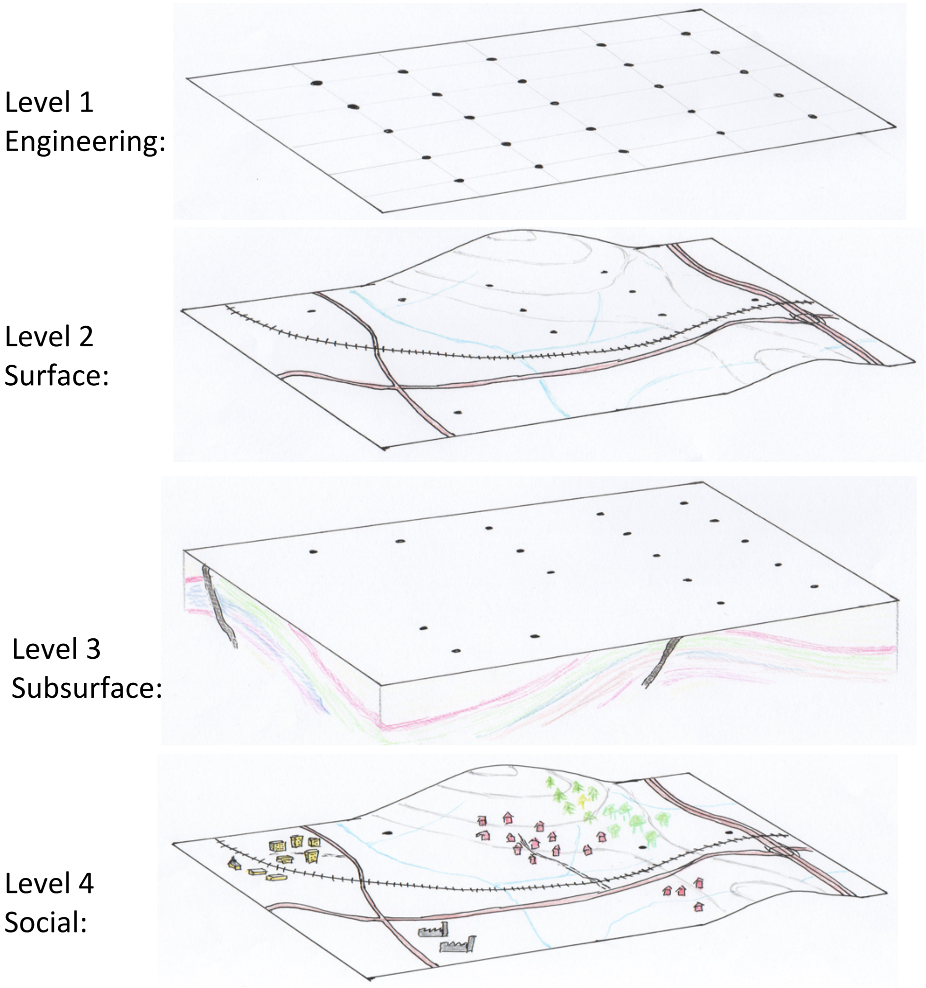


Figure 4.5: Four Level Model to Simplify Shale Gas Development Examination.

Commentary: The figure shows the four levels of engineering, surface geography, subsurface geology and social level. For engineering level only representative pads and the connecting idealised roads are visible. Roads within the block are assumed to be Local Road. Roads around the perimeter are assumed to be Major Roads. For the surface level features, such as the roads network, are shown. For the subsurface level the geology is accounted for. For social level residential property is visible as well as roads and topographical features. The levels work cumulatively.

4.7 Planning for Alternatives: Pad Density – What is it and Why is it Important?

In planning for dispersed energy, it is useful to consider alternative forms of development or scenarios. In the case of SGD, the alternative scenarios arise from different scales of development. Petroleum engineering experience of extending area coverage from a single pad is growing all the time (see Appendix B). In simple terms, the scale is the area of shale unit covered from a pad. This is a function of the length of the lateral borehole and the width of the facture zone. For example, a 1km long lateral with a 500m fracture zone could drain gas from an area of 0.5 km^2. If each pad had one lateral with these parameters to fully cover a 10 km by 10 km license block, ten 1km laterals are required to cover the north-south axis, referred to the X dimension (10/1=10), whilst twenty 500m fracture zones are required to cover the east-west axis, referred to as the Y dimension (10/0.5=20). Thus, to fully cover the 100km^2 area two hundred pads are required (10 x 20).

More laterals can be drilled from a single pad the lower the overall number of pads required to access the full resource of each block. It is possible to drill laterals in two opposite directions from one pad. This brings the number of pads in the above worked example down to one hundred. However, it is also possible to drill boreholes down at an angle, rather than vertically from the surface (as shown in Figure 4.4), to reach lateral heels and fracture zones some distance horizontally away from a pad (Hyne 2001). Boreholes have been drilled out over 11.5km (Allen et al 1997) suggesting it is possible to have laterals with heels several kilometres horizontally from a pad. If the reach of multiple near vertical boreholes could extend to cover five laterals and laterals were drilled in each direction, giving ten laterals from a single pad, then the number of pads required in the worked example reduces to twenty pads to cover the 100km^2 area. Figure 4.6 illustrates examples of area coverage of a single and multiple pads. Appendix B provides further explanation of this.

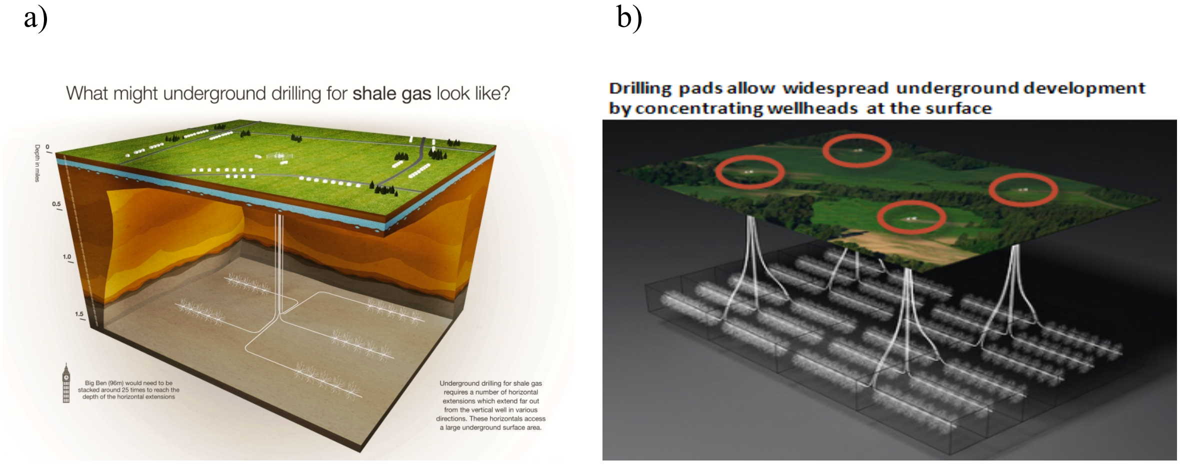


Figure 4.6: 3D Organisation of Boreholes to Cover an Area of Shale.
a) One pad is shown; b) A series of pads is shown.

Source: EIA 2012. **Notes:** Boreholes are shown in white. Observe the consistent alignment of lateral boreholes in the same direction. In both images the fuzzy area around the laterals shows the fracture zone. Panel b) shows extended coverage across a large area of shale, with the red rings highlighting the location of pads on the surface.

This worked example, of twenty pads covering 100 km^2, provides one possible scale of SGD across an area or basin. Proposals and activity by industry, in the UK and US, show that there are other possible scales of SGD. One industry player in the UK appears to suggest a scale of development for the Bowland basin of thirty pads per 100 km^2 (Ineos 2017). The same developer has also suggested ten pads per 100 km^2 (Hollingrake undated). In one case in the US laterals have been drilled out to 8.3km (Nieto 2016), suggesting that it might be possible to cover the whole of a 100 km^2 license block by multiple bores and laterals from a single central pad. In the US such pads, known as super or mega-pads, are envisaged to have up to 64 wells with potentially 6.4km laterals in each direction on one pad of 4 hectares (Litvak 2018)(see Appendix B and Figure B.3). To cater for this engineering uncertainty the modelling in this thesis needs to take account of these varying scales of possible development: modelling the extremes (one and thirty pads per block) and intermediate scales of SGD (two, four and ten pads per 100 km^2). These various scales of potential SGD activity are hereafter referred to as ‘pad density’ or densities. The modelling is applied at 1, 2, 4, 10 and 30 pads per 100 km^2 block. Pad density is hereafter is often referred to as ‘ppb’ or pads per 100 km^2 block. These five engineering scales provide alternative development scenarios for assessing whether the local environmental effects vary, due to changes in pad density, for planning purposes.

4.8 Modelling the Technical Ingredient.

For each form of dispersed energy, the technical ingredient of exploiting the energy sources needs to be understood and accounted for. For shale gas development the technical ingredient covers petroleum engineering of the shale unit (at Level 1). This section provides: a resume of the petroleum engineering production process applied in the modelling (Section 4.8.1); how the locations of fracture zones, laterals and pads are determined (Section 4.8.2); how fracture zones, laterals and pads are adjusted to take account of the geology in the Bowland basin (Section 4.8.3); and how the model is adjusted to take account of partial shale coverage within a block (Section 4.8.4).

4.8.1 SUMMARY OF THE SHALE GAS PRODUCTION PROCESS

The modelling here applies a simulation of the shale gas development following a five-step production process which is largely standard in the hydrocarbon industry (Hyne 2001, Arup 2014, Azar & Robello-Samuel 2007). Further details on this process are set out in Appendix B. In summary, the process consists of:

- Construction: Site preparation (stripping back topsoil and levelling), erecting security fencing, laying a geotechnical membrane across the site, laying and compacting an aggregate work base, forming bunds for surface water handling around the perimeter and preparing the concrete cellar(s) for the drilling platform.
- Drilling: Applies the industry conventional process for hydrocarbon wells, with rotary drilling, using drilling mud as a lubricant and to control the well pressure. Creation of four cemented-in steel casings (conductor, surface, intermediate and production) (Devereux, 1998; Society of Petroleum Engineers, 2019). For shale wells the borehole is initially drilled down to reach the target depth, but then curves to intersect and track horizontally along the target shale reservoir horizon (the in-shale section referred to as 'laterals'), to maximise the amount of contact between the borehole and the reservoir (see Figure 4.4). This is known as horizontal drilling, although the shales in the UK are not always in horizontal layers and the lateral will follow the layering. To provide area coverage laterals are horizontally aligned in parallel.
- Hydraulic fracturing: Current techniques of injecting fracture fluid at high pressure to create a fracture zone around the lateral borehole, known as hydraulic fracturing (Donaldson, et al 2013, King 2012, Zendehboudi & Bahadori 2017). For modelling purposes, I assume a horizontal fracture zone (and therefore separation between laterals) and the presumed thickness of the shale vertically, of 333m. To maximise the fracturing efficiency laterals are aligned perpendicular to in-situ maximum horizontal stress (S_{Hmax})(Tang et al 2019). For modelling purposes, a basin-wide universal orientation of maximum horizontal in-situ stress (S_{Hmax}) is applied at 150-330 degrees (Kingdon et al 2016, Fellgett et al 2017) (see section 3.4.1 and Figure 3.5).

- Production: Gas is exported from a pad via a pipeline. Pipeline works are excluded from modelling due to poor data availability.
- Site Remediation: After the production phase remediation includes capping boreholes, site clearance, removing all materials and reinstating the site to its to prior condition.

4.8.2 FRACTURE ZONES, LATERALS AND PAD ORGANISATION ACROSS A 10KM^2 BLOCK

As set out in section 4.3, the unit of study for the assessment is a 100km^2 block, based on the Ordnance Survey 10km national grid. Ninety-six of the 10km^2 blocks are selected for study (Figure 4.2). These cover most of the Bowland Shale units. For plan preparation and modelling purposes, it is assumed that any development of shale resource would exploit each block in the most effective and efficient way possible. This section sets out the how this is achieved, for modelling purposes, and the rationale behind this.

Figure 4.6 shows a 3D cutaway theoretical plan of boreholes and lateral coverage for an area of SGD. Figure 4.7 shows a conceptualised typical plan form layout of laterals from a pad (NB. Figure 4.7 specifications are not representative of the pad densities used in the modelling). Since the vertical dimension is omitted, in Figure 4.7, the vertical sections of the wellbore are not evident.

The size of the fracture zone is dependent upon the hydraulic pressure used during fracturing and the mechanical strength of the shale. Data from the US suggests that the typical horizontal size of fracture zones extend out from each direction from the lateral to around 150m (Warpinski et al 2012). This gives an overall fracture zone for each lateral of around 300m. For modelling purposes, a total fracture zone width of 333.3m is used, with the lateral lying centrally. Whilst approximating to field experience, a fracture zone of this size provides a comfortable fit within a 10km2 block. Thus, with fracture zones at 0.33km and with laterals aligned to the sides of the 10km2 licenced block, each block would require thirty laterals and fracture zones running across it (10km/0.33km=30) to maximise the volume of rock that is drained. The resulting pattern of parallel laterals within a block is illustrated in Figure 4.8.

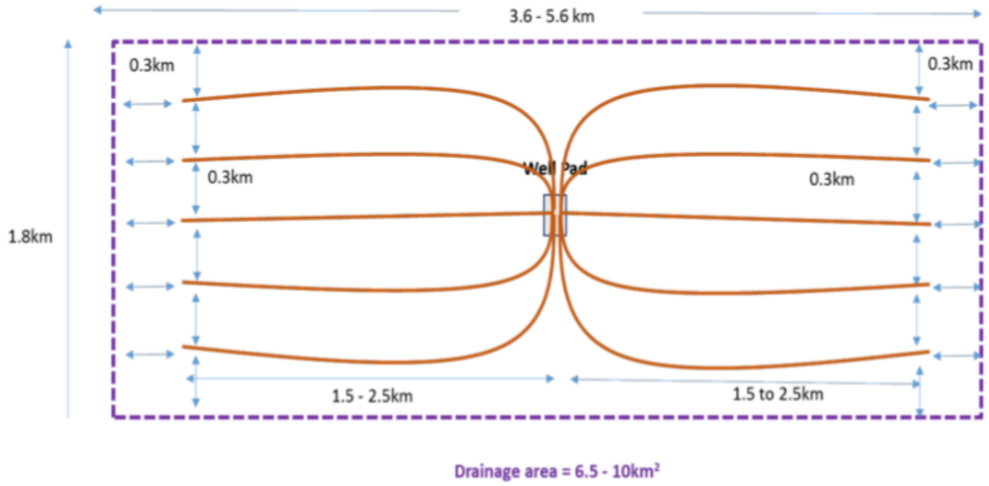


Figure 4.7: Two-Dimensional Organisation of Laterals from a Pad

Key: Brown = laterals. Purple box = Area of shale covered by the pad, known as the 'fracture zone'. **Notes:** Laterals are perpendicular to the maximum horizontal in-situ stress (S_{HMax}) to maximise the efficiency of hydraulic fracturing. The above diagram, showing laterals orientated east-west is based on maximum in-situ stress (S_{HMax}) being north-south. For modelling purposes all laterals have an assumed separation of 333.3m, whilst the number and length of laterals on each pad varies according to the pad density. If viewed in 3D form with a vertical dimension, from the surface to the shale strata 3,000m below, the wellbores would descend directly below the well pad to the heel of the lateral. **Source:** UKOOG 2019.

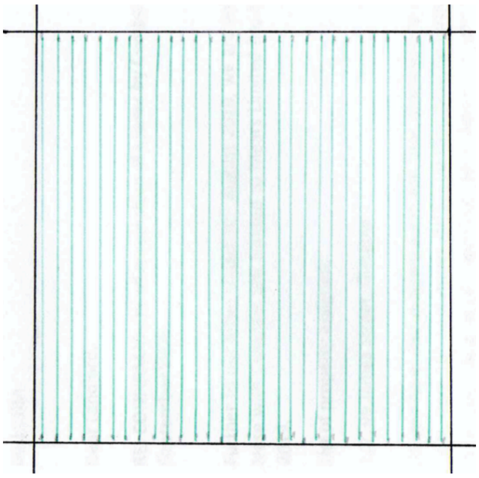
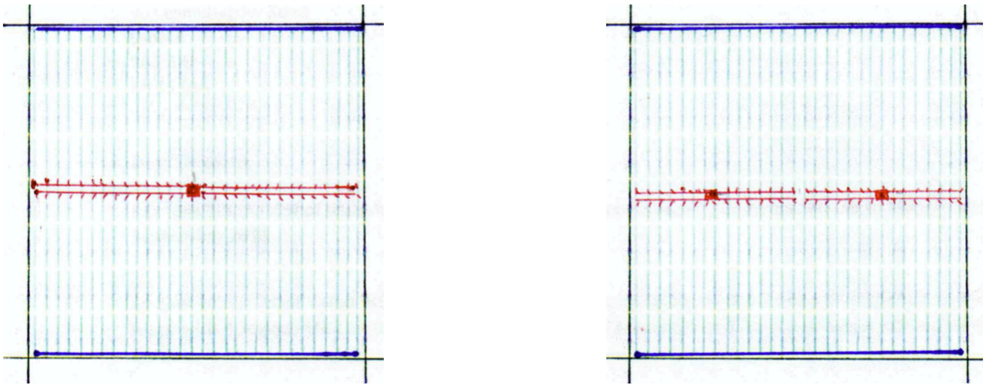


Figure 4.8: 2D Area Plan of Laterals across a 10km^2 Block

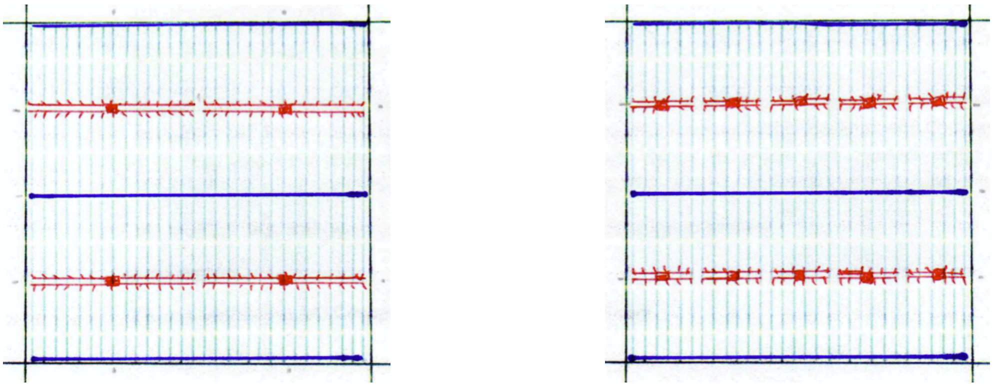
Key: Black = OS 10km National Grid and Licence Block. Green line = Laterals. **Notes:** Laterals are orientated perpendicular to the maximum horizontal in-situ stress (S_{Hmax}), which is assumed to be aligned east-west, with 0.33km parallel separation between laterals.

Having set the fracture zone and laterals that optimise the exploitation of the target gas bearing shale in a 100km2 block for modelling, the next requirement is to position pads, or SGD sites, at the surface to access these cross-block laterals. This is a process of tessellation to optimise and balance coverage with a consistent pattern (Senechal 1993). Following the broad pattern of boreholes to access laterals, illustrated in Figure 4.6, each pad is likely to access several fracture zones. The laterals across the 10km block need to be subdivided into lengths to be accessed from a pad. For example, at 30 pads per block, a pad would reach laterals of 1.66km in length, in three adjoining pairs of fracture zones (one in each direction) for each pad, with three pairs of laterals served from each pad (Figure 4.9). Applying a mean coordinate to achieve the shortest combined connection from the lateral heels to an appropriate pad, the pad is sited over the centre of the central fracture zone (for 30ppb). This requires the near vertical borehole to reach across 333m to the lateral on the centre line of the adjoining fracture zones. Where there are more than three fracture zones associated with each pad (for lower pad densities) this reach across will be in multiples of 333m. Figure 4.9 shows a schematic area plan, for each studied pad density, of the configuration of laterals and pads sited centrally to optimise the coverage from each pad. Overlaying this is a tessellated pattern of consistent rectangular shale coverage. The unproductive cross reaching borehole, to connect to the heel, are shown (in red). Table 4.3 sets out the data parameters of the consequent coverage of laterals for each pad density.

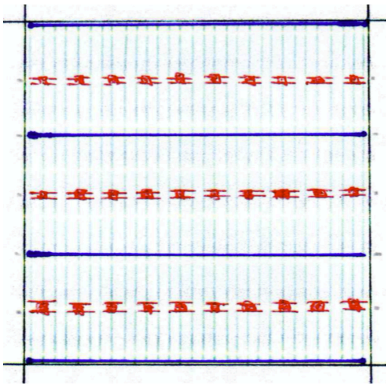
Applying the parameters from Table 4.3 and the pattern of shale coverage to equalise the access to laterals the resulting pattern of surface pads, for each pad density, is shown in Figure 4.10. To summarise, the surface position of pads is determined by the position of the laterals (serving fracture zones), the subdivision of cross-block laterals into sections, the resulting position of the heel, with the mean coordinate of the heels positioning the pad centrally for the group of fracture zones served. The full grid reference position of all pads, for pad densities, is given in Box F.1 in Appendix F.



1 ppb 2 ppb



4 ppb 10 ppb



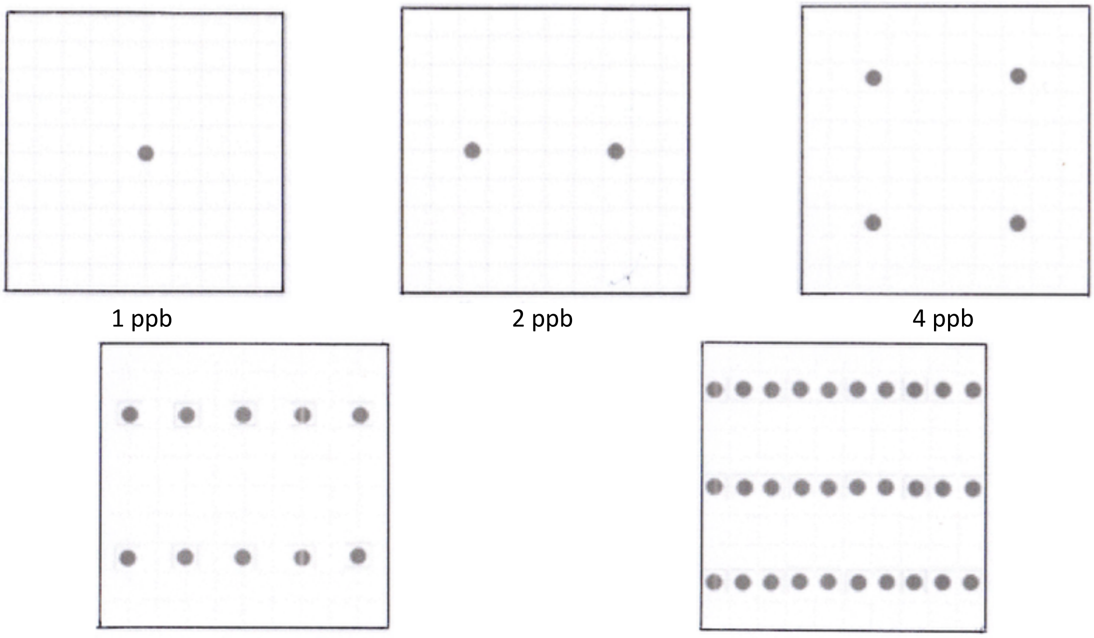
30 ppb

Figure 4.9: 2D Area Plan of Equalised Pad Coverage and Laterals across a 10km^2 Block, for each Pad Density

Key: Black = OS 10km National Grid and Licence Block boundary. Green line = Laterals, orientated perpendicular to the maximum horizontal in-situ stress (S_{Hmax}), which is aligned east-west, with 0.33km parallel separation between laterals. Blue line = line of the toes for each set of laterals resulting from subdivision of laterals into appropriate lengths, for each pad density. Red line = connection of fracture zones with unproductive boreholes sections reaching across to laterals. Red dots = the resulting centralised location for pads. The position of pads is calculated as the mean of coordinates of served heels.

Table 4.3: Parameters for Laterals Coverage for Pads

Parameters	**30 ppb**	**10 ppb**	**4 ppb**	**2 ppb**	**1 ppb**
Number of Laterals across Block	30	30	30	30	30
Number of Pads per Block	30	10	4	2	1
Area Coverage per Pad km^2	3.33	10	25	50	100
Number of Columns of Pads	3	2	2	1	1
Number of Pads per Row	10	5	2	2	1
Accessed Lateral Length-km	1.66	2.5	2.5	5	5
Fracture Zones/ Laterals per Pad	3	6	15	15	30
Boreholes per Pad per Direction	3	6	15	15	30
Total Number of Boreholes per Pad	6	12	30	30	60
Total Lateral Length per Block (Pads x Boreholes x borehole length) – km	300	300	300	300	300
Fracture Zone Width – km	0.333	0.333	0.333	0.333	0.333
Total Area Coverage – km^2	100	100	100	100	100



1 ppb

2 ppb

4 ppb

10 ppb

30 ppb

Figure 4.10: Pad Organisation for Each Pad Density within a 10km^2 Block.

Notes: Show the location of pads, as used for Levels 1 and 2. The patterns of pads, for each density, represent the most efficient organisation. The maximum in-situ stress (S_{HMax}) is orientated East-West.

All the parameters used in the modelling are consistent across all pad densities, with one exception: the quantity of work required for each pad varies with pad density. Table 4.4 shows the number and length of boreholes which are required at each pad, for each density. Data from recent real-world UK SGD proposals (Section 3.5.1) shows an average pad land area size of approximately 1 hectare per pad. This is taken as the minimum land area required for any pad. A visit to the PNR site (see Table 3.3) shows that there is considerable scope to drill and operate far more than one or two boreholes from a pad of one hectare (Cuadrilla 2018). However, given the varying level of activity required for the various pad densities this standard size is unlikely to be adequate for lower densities, where much greater work is required. To accommodate the increased work activity on pads for lower pad densities the land area used for each pad is adjusted for modelling purposes. The assumed land area required for each pad, for each pad density, is given in Table 4.5.

Table 4.4: Required Activity at Pads, for each Pad Density

Parameters	**30 ppb**	**10 ppb**	**4 ppb**	**2 ppb**	**1 ppb**
Number of Boreholes per pad	6	12	30	30	60
Length of each lateral - km	1.66	2.5	2.5	5	5
Total Length of laterals per pad - km	10	30	75	150	300
Average horizontal cross reach to heel -km.	0.22	0.83	0.83	2.5	2.5
Vertical Depth to Shale Unit -km	3	3	3	3	3
Average length of near vertical boreholes - km	3.0	3.1	3.1	3.9	3.9
Total Length of near Vertical Boreholes per pad - km	18.0	37.4	93.4	117.1	234.3
Total Borehole Length per Pad – km	28	67	168	267	534
Notional Drilling Time @ 333m/day - days	84	202	505	802	1604

Table 4.5: Assumed Area Pad Size, for each Pad Density

Parameters	**30 ppb**	**10 ppb**	**4 ppb**	**2 ppb**	**1 ppb**
Number of Boreholes per pad	6	12	30	30	60
Total Borehole Length per Pad – km	28	67	168	267	534
Assumed Area Size of Each Pad – hectares	1	1	2	3	5

4.8.3 Adjusting for Maximum Horizontal In-Situ Stress

The above explanation of fracture zones, laterals and pad organisation is premised on the basis that fracture zones align perfectly to sides of a National Grid 100km^2 block. This presumes that the maximum horizontal in-situ stress (S_{Hmax}) of the shale is orientated east-west. As explained in Section 3.4.1 (and shown in Figure 3.5) this is not the case for the UK. For the Bowland basin the general direction of maximum horizontal in-situ stress (S_{Hmax}) is orientated 150.9-330.9 degrees, with a circular standard deviation of 13.1 degrees (Kingdon et al 2016). To accommodate this in the modelling the fracture zones and laterals need to be reorientated to accommodate the direction of stress in the shale (rather than to the block boundaries). For modelling purposes, the maximum horizontal in-situ stress (S_{Hmax}) is assumed to be orientated at 150–330 degrees. Consequently, laterals are sited perpendicular to this, at 60 – 240 degrees (Tang et al 2019). The consequence is that the fracture zones do not fit comfortably into the 100 km^2 blocks. Figure 4.11 illustrates the reorientated fracture zones and laterals within a standard or base study block.

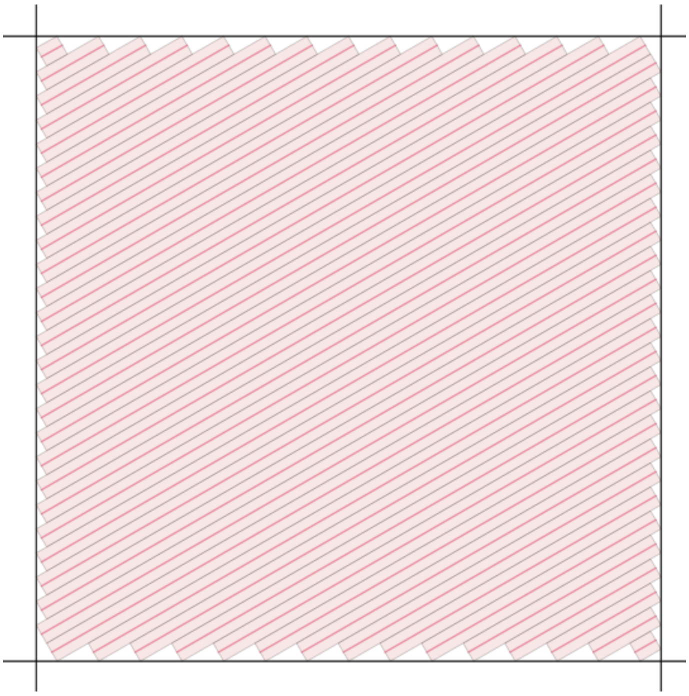


Figure 4.11: Laterals Orientated at 60-230 Degrees and Shortened Fracture Zones across a Block

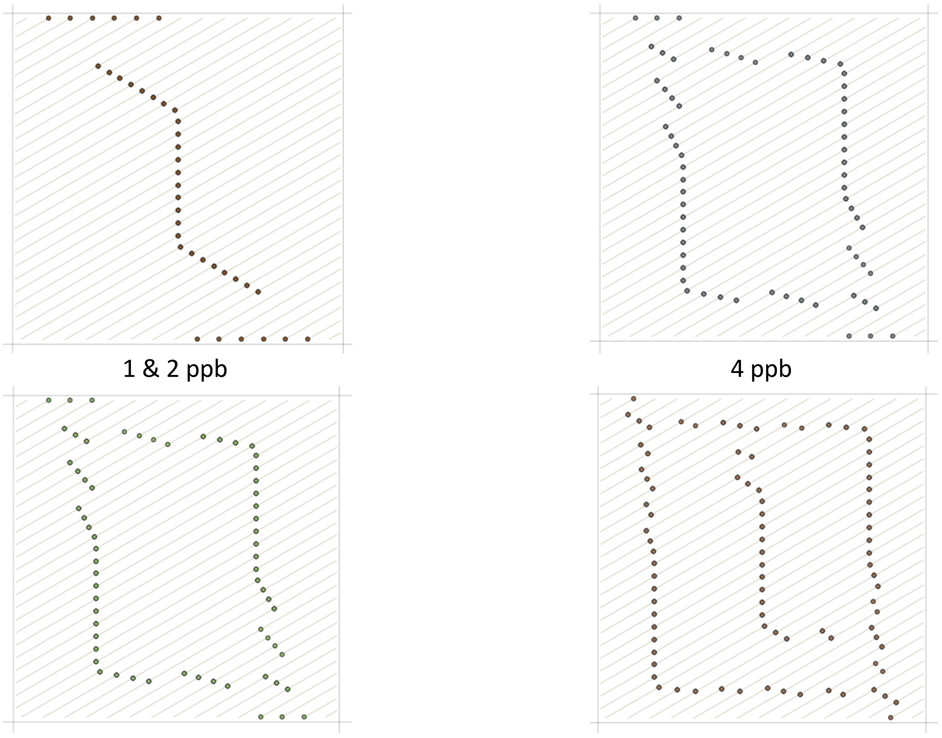
Key: Black Lines = OS 10km^2 Licence Block Boundary. Red Lines = Cross-block Laterals. Pink Area surrounded by Grey Lines= Fracture Zones. **Notes:** Laterals at a 60-240-degree orientation, shortened at the edge to avoid overlapping the Licenced Block. The consequent fracture zones are also shortened at the edge of the Licenced Block.

As well as the sides of the fracture zones not fitting comfortably against the block boundaries, the ends of the cross-block fracture zones at the block perimeter would extend beyond the boundaries of the licensed block. To avoid operators exceeding the license block perimeter, the laterals and fracture zones need to be shortened. The cross-block laterals need to be shortened to the point where the fracture zone does not exceed the license block perimeter. This shortening process is explained in detail in Appendix section F.3.1 and Figure F.5.

With the fracture zones and laterals realigned the earlier pads patterns serving these are dislocated. The consequence of simply rotating the pad alignment to follow the rotation of the laterals, to 60-240 degrees, is discussed in detail in Section F.3 of Appendix F. A simple pad rotation does not provide cover for the shale within the block. A more sophisticated approach to repositioning the pads is required. The technique applied is referred to 'cross-block lateral subdivision'. Essentially, laterals are subdivided into sections of appropriate length, based on the maximum feasible length of lateral sections for each pad density (Appendix section F.3.3). The positions for heels to access each lateral section is then determined. Pads are then positioned to optimise the access to the heels.

Figure 4.12 shows the resulting position of heels optimised for accessing the reposition laterals. The heels within the blocks often, though not always, represent the position of two heels (one for each direction of the lateral). Some heels, particularly those along the north and south block perimeter, only serve one lateral.

As a consequence of the lateral repositioning the parameters for the length of the laterals, the near vertical bores reaching down to the heels and the pad locations all need to be adjusted. For some laterals, particularly those running across the central body of the block, this means that the operating length of lateral sections generally needs to be increased (over those given in Table 4.4). The longest length of lengthways combined laterals, which run across the whole block, increase in length from 10km (when oriented due east-west) to 11.35km (when orientated at 60-240 degrees). This is a 13.5% increase.



1 & 2 ppb

4 ppb

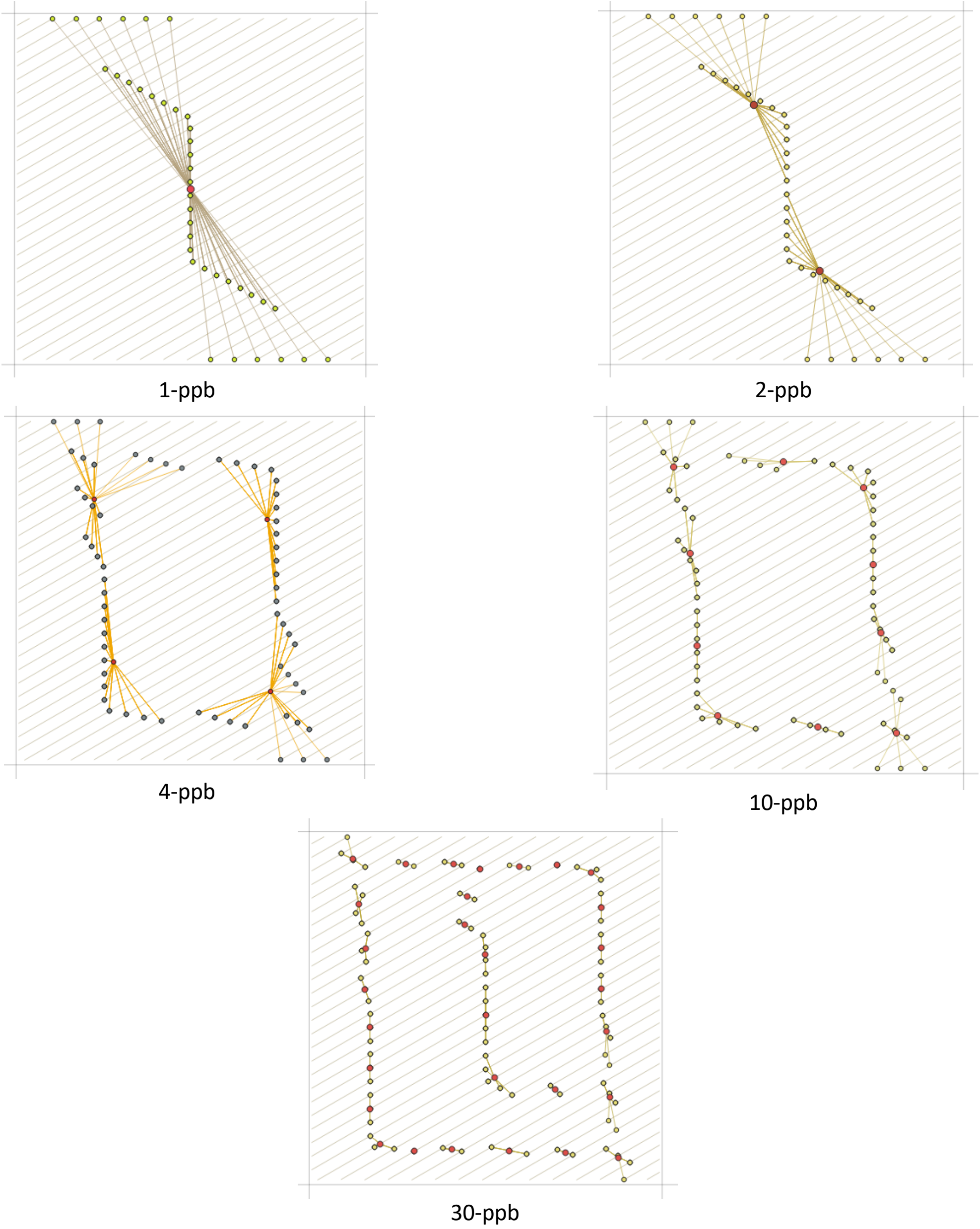
10 ppb

30 ppb

Figure 4.12: Lateral Heels Reorientated to Adjust for Maximum Horizontal Stress.

Key: Black Lines = OS 10km^2 Licence Block Boundary. Lines with Black with Dots at Ends = The heel and subdivided lateral sections.

The modelling assumes that the number of pads per block, for each pad density, is retained. The length of the bore from the pad to the heels is also likely to vary as a consequence of the realignment of the fracture zones. With the relocation of the heels the pattern and location of pads also needs to change. The pads need to be relocated to optimise the access to the heels. Figure 4.13 illustrates the repositioning of pads (for each pad density) to optimise the access to the heels and the laterals, when applying ‘cross-block lateral subdivision’. Determining the position of pads is achieved by gathering heels into groups based on the spatial optimum of the aggregate average horizontal distance, for the given number of pads and number of heels, for each pad density. Once the optimum pad locations are established it is possible to calculate the length of the near vertical bores to connect the pads to the heels. Figure 4.13 illustrates, in plan form, the position of heels (taken from Figure 4.12), the position of pads serving each group of heels and the boreholes that connect the pads to heels (for each pad density). The pad to heel bores need to be long for low pad density and are short for the highest pad density. The single laterals in the extreme north west and south east of a block require very extensive cross reaching bores whilst the productive lateral length is very short. In these extremes the laterals are assumed to be unviable. Where the ratio of lateral to unproductive bore is below 16.6% these have therefore been removed from subsequent modelling.



1-ppb

2-ppb

4-ppb

10-ppb

30-ppb

Figure 4.13: Notional Pads Positions, Lateral Section Heels and Cross-Reach Near-Vertical Borehole Pattern for Geol-land Base Blocks, for all Pad Densities, having Adjusted for Maximum Horizontal Stress Orientated at 150-330 Degrees.

Key: Grey Lines = OS 10km^2 Block. Beige Lines = Laterals (orientated at 60-240 degrees). Yellow Dots = Heels of Lateral Sections. Red Dots = Optimised Pad Positions. Orange Lines = Cross-reaching near vertical boreholes, connecting pads and heels. **Notes:** Note that the shortest laterals 1, in the northwest, and 40, in the south-east, are not connected due to lack of viability.

4.8.4 ADJUSTING FOR PARTIAL SHALE COVERAGE OF A BLOCK

The above explanation applies where there is full coverage of shale within a block. Blocks selected for the case study have at least 70% shale coverage (see Section 4.3). Details on shale coverage for each study block are provided in Appendix H (shale tab). Thirty-six blocks do not have full coverage (37.5% of the 96 study blocks) and further adjustment is needed to fracture zones, lateral and pads locations to accommodate this. The process for this adjustment essentially consists of seeking to locate pads where the access to the remaining fracture zones and laterals is optimised. This is set out in detail in Appendix Section F.3.5.

The modelling of the technical provision for shale gas development thus takes into account: the coverage of shale, the alignment of maximum horizontal in-situ stress (S_{Hmax}), the resulting optimal disposition of laterals and the extent of fracture zones, the derived position of heels and the resulting most advantageous location of pads, for each pad density. The technical analysis produces an optimum location for the pads for each pad density, to fully exploit the shale resource. The technical analysis produces the ideal or preferred pad locations from the perspective of optimum subsurface exploitation. The next section discusses the consequence for local environmental effects and how the model is adjusted to recognise these.

4.9 Modelling the Consequent Local Environmental Effects

Choices over shale gas development sites do not rest exclusively on the resource exploitation but will also recognise the local environmental effects or a developer risks an application for planning permission being refused. Reflecting this, the positive development planning process needs to identify potential local environmental effects and contend with these to avoid or at least minimise the effect on receptors. Three key local environmental effects of SGD have been identified (noise, visual amenity and traffic - see section 4.4) and need to be considered in detail in the modelling.

4.9.1 THE ASYMMETRY OF EFFECTS, THEIR IMPACT ON THE MODEL AND THE MODEL DEVELOPMENT

The three key environmental effects of noise, traffic and visual amenity have different types of local impacts. Noise has been shown to have a radial effect where the level of noise declines broadly pro rata with distance from an SGD pad (Appendix Figure F.16). The impact of SGD on visual amenity is also likely to decline with distance as a receptor is further away from the pad. Traffic, however, has a different form of impact. The traffic required to transport SGD plant and materials is likely to travel on a predefined (and approved) route from the major roads network to the pad. The whole of the predefined route will be affected by all SGD traffic. So, impacts could arise a considerable distance away from an SGD pad. If a route is, say, eastwards from a pad then other directions will not be adversely affected by the route. As well as being linear, along all of the selected route, the effects of SGD traffic is unidirectional from the SGD site. The three key environmental effects therefore diverge in their significance and differ in their impact.

The modelling of each key environmental effect therefore needs to be different for each of these three effects, reflecting this asymmetry. The noise and visual effects only arise when residential areas are involved. Mitigating for noise and visual effects is achieved by establishing exclusion of pad siting away from residential areas by providing a suitable ‘setback’ or ‘buffer zones’ around residential areas. Residential areas with surrounding noise and visual amenity buffer areas are illustrated in Figure 4.14. The buffer area around residential areas avoid noise effects spilling over from pads into residential areas. Pads need to locate outside the residential area and their buffers. The result is the designation of areas where shale gas development is not appropriate and other areas where it is possible. For modelling purposes areas outside this, where shale gas development is possible are identified as ‘developable zones’. The buffer size around residential areas (and thus the extent of developable zones) are varied according to pad density to take account of the duration of SGD production activity. Lower pad densities will have longer operating periods (Table 4.4). For modelling purposes, to recognise the longer duration of noise and visual amenity the extent of the buffer around residential areas is increased (for lower pad density).

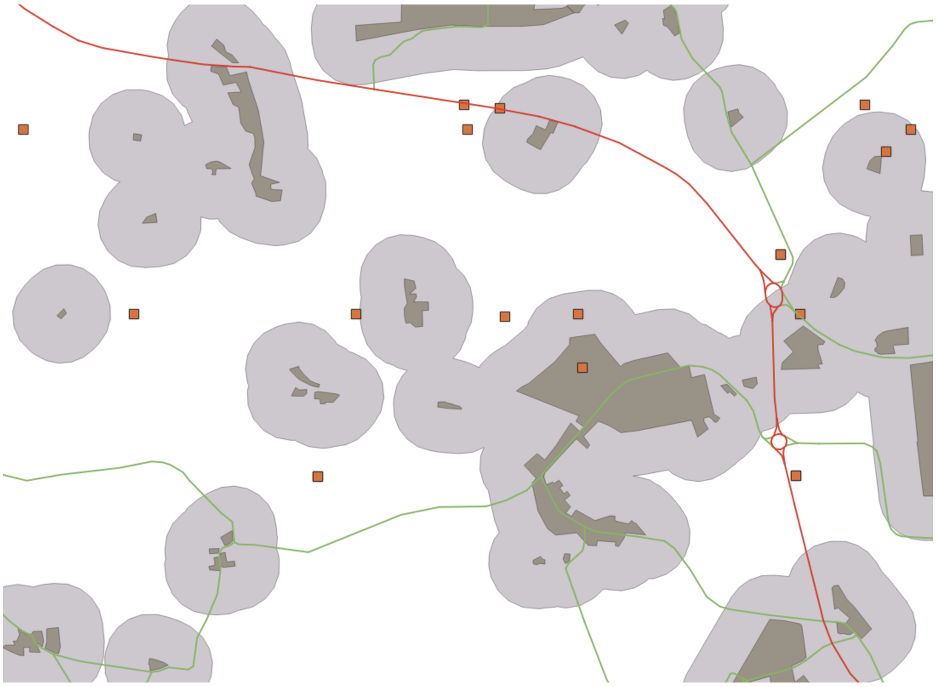


Figure 4.14: Pads, Residential Areas and Setback Zones

Key: Orange Square = Pads randomly distributed over an area. Dark Grey Area = Residential land use areas. Light Grey Area = Buffer or setback zones around residential Area. Red Lines = Major Roads. Green Lines= Local Roads. White area = Developable zone. **Notes:** While several pads are situated in the developable zone, some pads fall with residential areas or buffer zones. These would not be permitted as they do not lie within developable zones.

4.9.2 DEVELOPABLE ZONES, DEVELOPMENT TRACTS AND THE ITERATION OF PAD RELOCATION

The preferred pad locations, identified in Section 4.8, are not the only possible location for SGD pads. Pads could be moved from the preferred location to reduce or avoid causing local environmental effects. If the preferred location for a pad was in a residential area, for example, the pad could be relocated or not developed. A key part of the planning process is to find an acceptable balance between the technical capability of developing the shale resource and avoiding significant local environmental effects. The SGD planning process needs to find an acceptable trade-off which recognise three factors: the fixed extent of developable zones (outside residential buffers); the extent of technical flexibility to locate pads away from their preferred location (whilst still accessing an economically acceptable amount of the resource); and the potential effects of traffic. Whilst the first of the these is spatially fixed (because the residential areas exist), the second and third factors have a degree of spatial flexibility. The modelling needs to find some way of reconciling these three factors to enable SGD to take place by utilising this flexibility. Once these three factors can be defined, quantified and applied spatially within the modelling it should be possible to develop criteria for planning choices for shale gas development.

In practice whilst there is some flexibility for the location of pads (away from their preferred location) there is an engineering limitation to this. Effectively there is a definable area around the preferred pad location where the pads could be located. This area, which is likely to be covered by a radius around the preferred pad location, is referred to as a 'development tract'. Figure 4.15 illustrates the concept of combining of developable zones and development tracts to find the landing zones where pads can be located.

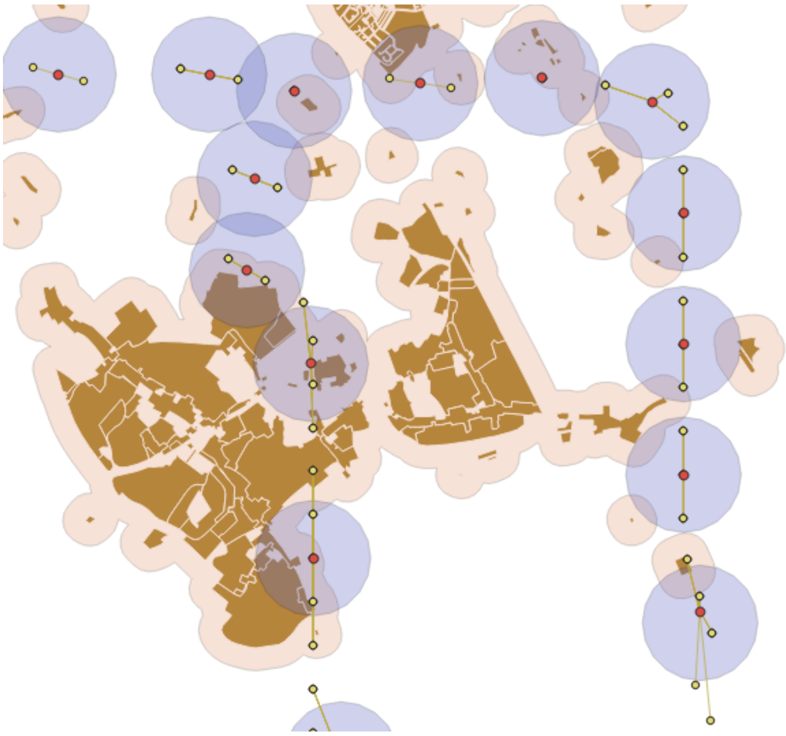


Figure 4.15: Concept of Combining Developable Zones and Development Tracts.

Key: Brown Area = Residential areas. Beige Area = Buffer around residential areas. White Area (including areas with blue only) = Developable zones (outside residential areas buffer). Yellow Dots = Heel of laterals. Red Dots = Preferred or nominal Pad Positions (nPP) serving a group of heels. Orange Lines = Cross-reaching near vertical boreholes connecting heels to pads. Blue areas = Development tract around the nPP. **Notes:** nPPs not within developable zones can be relocated to them, thus avoiding residential areas and buffer zones, as long as these are within the nPP's development tract. In the example all nPPs can be found a location (within their development tract) in the developable zone. In extensive urban areas this is problematic and often no suitable pad points can be found, resulting in a loss of access to the shale unit served by the nPP.

Three different approaches to deciding the extent of development tracts were considered for the model. The first was based on the notion that pads could <u>not</u> be located away from their preferred location. Pads were viewed as fixed and allowed to connect to the road network via an access track. The access track connected the pad to the nearest point on the road network. Where pads fell within a residential area or the surrounding noise buffer (thus outside developable zones) the pad could not be developed. This results in a significant loss of accessible shale coverage across the basin. The second approach applied a notional horizontal limit based on the distance to furthest heel from the preferred pad location, for each group (after reorientation for S_{Hmax}). While this approach seemed suitable for high pad densities, for the lowest pads densities this effectively meant that pads could theoretically be located almost anywhere within a block. For the third approach the second approach was adapted to improve the balance between densities. The horizontal limit was set as one positive standard deviation of the distance from the pad (nPP) to furthest heel for all group (after reorientation for S_{Hmax}), averaged across a block (with full shale coverage). This approach provided consistency across all pad densities: the distance is proportionate to the horizontal spread of the heels served by a pad.

The modelling used the third approach as it provides flexibility for siting pads, to facilitate access to heel and fracture zones, while being commensurate to the various scales of pad density. Development tracts are centred on preferred pad location. Pads could be located anywhere within the tract. The extent of ‘development tracts’ varies with pad density in proportion to the horizon spread of heels within pad groups: for higher pad densities pads have smaller tracts. These provide a reasonable flexibility in locating pads whilst maintaining a reasonable level of viability for the effort required to exploit the shale resource.

Where the development tracts did not overlap with any part of the road network, access tracks are used to connect to the nearest point on the nearest road. A one kilometre maximum was set for access tracks. Where there was no road within one kilometre of the development tract the pad was identified as inaccessible. Longer SGD tracks are used in the US, where the population density is far lower, however one kilometre is felt to be appropriate to the UK circumstances, where there are higher levels of habitation and more intensive land use.

This technical capability process defined firm boundaries for development tracts around preferred pad locations. The developable zones were sieved against development tracts to produce ‘areas suitable for development’. These are landing zones for possible final pad location. Figure 4.16 illustrates a flowchart of how landing zones are identified.

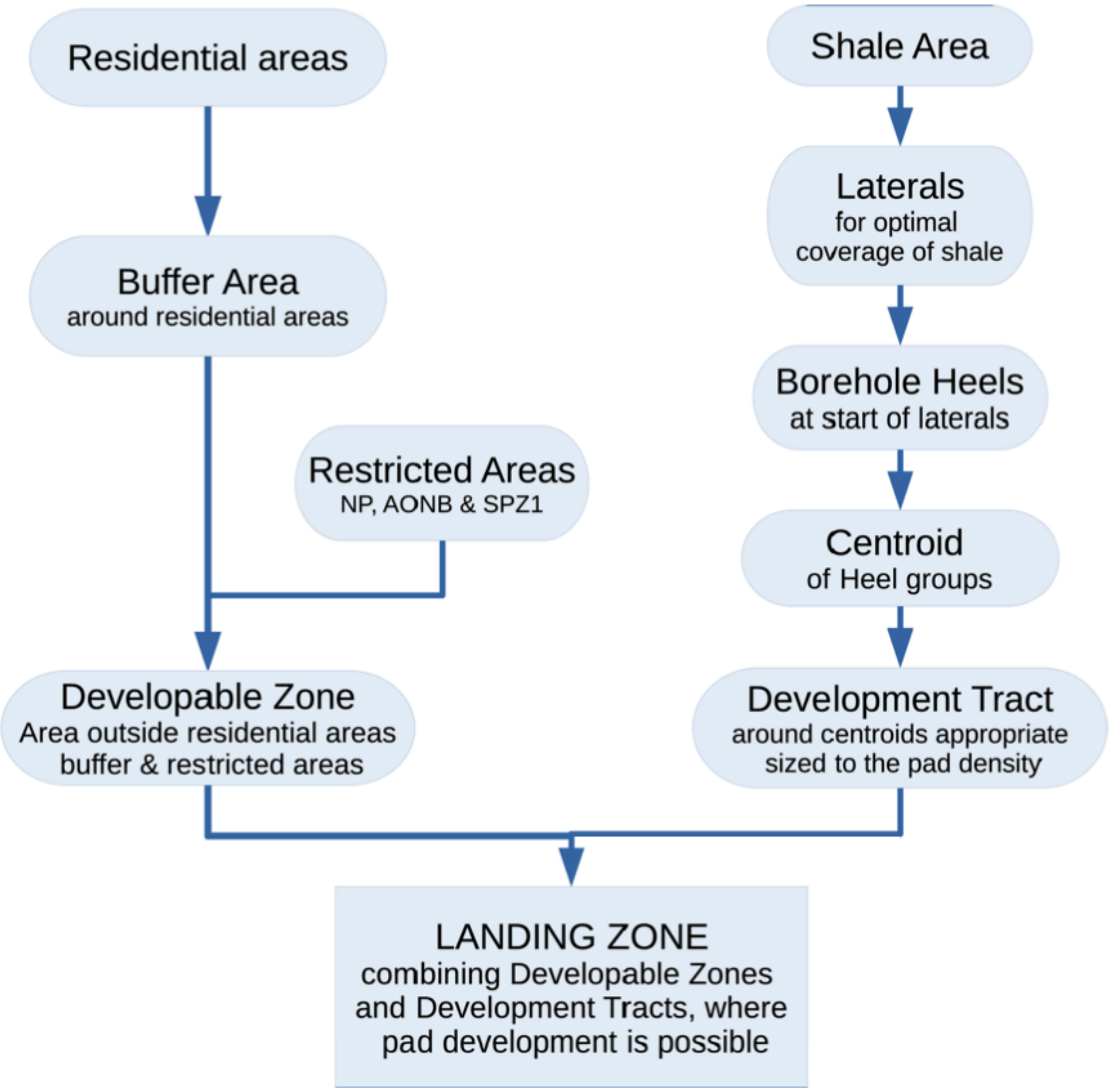


Figure 4.16: Flowchart for Identifying Landing Zones.

4.10 The Core Traffic Effects Assessment

The next stage in the modelling process is to find SGD sites within the 'areas suitable for shale gas development', which provide access for generated traffic. The choice of final site pad locations should be determined by the planning objective of seeking to minimise the local environmental effects of the required traffic.

Given the need to transport plant and material to pads, it seem inevitable that some level of traffic effect from SGD will arise. A key element in preparing a plan for shale gas development is identifying suitable planning criteria which minimises or avoids the potential traffic effect. This is not only a theoretical planning problem, but it also reflects the real-world planning decision making on shale gas development. As Section 3.5 sets out, traffic was the only planning factor which led to the refusal recent shale gas development proposals.

Whilst traffic effects will be considered on a project-by-project basis when applications for planning permission are proposed by developers, the positive development planning process needs to address the overall accumulated potential effect of traffic across the basin. Ideally the development plan would set out criteria or thresholds of levels of traffic effects acceptability as well as identifying planning policies which minimise basin-wide accumulated traffic effects. This section sets out how the traffic effect is assessed and explains the rationale for the choices involved in the modelling. It concludes by setting out the methodology for the calculation of traffic effect within the model and how this influences the final pad location choices.

4.10.1 THE TRAFFIC GENERATION VOLUME

The calculation of traffic effects level is derived from two components; (a) the amount or volume of traffic that is generated from each pad, and (b) the circumstances where a traffic effect arises. The volume of traffic is dependent upon the amount of materials used at each pad together with the requirement to move plant, such as drilling rigs and pump sets. The amount of materials required for a pad varies approximately in inverse proportion to pad density. Pads for lower pad densities require more materials to cover the larger shale areas they address; just as high pad densities divide the shale area to be drilled of 100km^2 block into smaller areas of coverage. Even if the materials used for one whole block across pad densities was the same, the traffic would be more dispersed with higher pad densities.

Once the amount of material required for a particular pad is known, the volume of traffic generated is determined by how many vehicles are required to transport the materials. This reflects the transport vehicles’ carrying or load capacity. In some cases, carrying capacity may be constrained by volume and sometimes by weight. For example, the steel casing required to line a borehole is required at different sizes for different types of casing (Deveraux 1998, Society of Petroleum Engineers 2019). Whilst all casing is transported in 9m lengths, at 506mm diameter the conductor casing can be carried sixteen pieces per load, due to size constraints (approx. load profile of 4 x 0.506m wide = 2.024m wide load, by 4 x 0.506m high = 2.024m high, gives capacity of 16 casings). Production casing, with a diameter of 0.2m could be carried ten across a flatbed truck and twenty high. However, at this number the weight of two hundred production casings would overload a standard 44 gross tonne truck. The load therefore has to be limited by weight.

For each pad, the amount of materials used is determined by the amount of work required on each pad. However, changes in pad location (from preferred to final pad positions) will change the amount of work and materials required, as the bores linking the pad to heels will change length. To calculate the material used the final pad positions need to be established. The final pad positions need to take account of the need to minimise traffic effect of SGD. Full details on how these two factors are combined and how the calculation of the volume of traffic is derived is set out in Section 4.11.4.

4.10.2 The Circumstances Where Traffic Effect Arises

The second, and more complex, component of assessing the traffic effects of SGD is the circumstances where a traffic effect of SGD arises. In practice, as shown in the recent cases of real-world SGD proposals (Section 3.5), the materials and plant used in developing pads can come from anywhere across the country. It is at least theoretically possible for pads to be located anywhere onshore that there is shale. However, the real-world cases demonstrate the self-evident maxim that all SGD traffic needs to use the existing roads network to get from the materials supply point, which could anywhere in the country, to the vicinity of a site. Often sites are situated next to a road. Where they are away from a road and access track connects the pad to a convenient point on the road network.

UK road network data used in the modelling is taken from Ordnance Survey (2017). This data shows that roads in the UK are organised into a ‘Highways Hierarchy’ reflecting their function and expected volume of traffic. Motorways and ‘trunk routes’ carrying long distance traffic, while ‘local roads’ carry local traffic and ‘access roads’ carrying traffic to individual properties (ibid). Motorways, carrying long distance traffic, have multiple lanes to carry substantial amounts of traffic, whilst access roads provide entry for light vehicles to only a few, even just one or two, properties.

Preliminary assessment and recent real-world cases (Section 3.5) shows that the adverse effect of SGD traffic, even in its most concentrated form, is not significant on motorways and trunk routes. The volume of any SGD traffic would be a small proportion of the overall existing traffic flow. Conversely, the volume of traffic from even the smallest SGD pad is likely to be entirely unsuitable for ‘local access roads’. SGD traffic on local roads is likely to result in an environmentally significant effect. The focus of modelling, regarding the circumstances where significant SGD traffic effects might arise, is therefore focused on these ‘local roads’.

Table 4.6 sets out the UK roads hierarchy and an assessment of the significance of the likely effect of SGD traffic together with of how each road type is used (or not used) within the modelling. The judgement of significance and use within modelling is based on the real-world decisions of recent SGD cases (Section 3.5). Having excluded motorways and the lowest level from the road hierarchy (Table 4.6 road functions 5-8), two levels of the roads hierarchy are considered in the modelling. These are ‘major roads’, which are referred to on OS 1:50,000 maps as “A Roads”, and ‘local roads’, which are identified by OS maps as “B Roads” and “C Roads” (Ordnance Survey 2017). For major roads the modelling assumes that SGD traffic can use these roads but that the environmental effect is not significant. For local roads the modelling assumes that SGD traffic can use these roads but assumes the environmental effect is significant. Figure 4.17 illustrates two contiguous example 100km^2 blocks, typical of blocks in the Bowland basin, with major and local roads.

Table 4.6: Road Hierarchy and Categorisation

Ordnance Survey Road Function	**Ordnance Survey Description**	**Environmental Effect of Volume SGD HGV Traffic**	**Categorisation for Modelling Purposes**
1- Motorway.	Multi-carriageway roads connecting important cities.	Not Significant	Excluded, due to restricted access
2- A Road.	Roads intended for large-scale transport links within or between areas.	Not Significant	Major Roads
3- B Road. 4- Minor Road.	Roads that provide interconnectivity to higher class roads.	Significant	Local Roads
5- Local Road. 6- Local Access Road. 7- Restricted Local Access Road. 8- Secondary Access Road.	Roads that provide access to land/ houses, generally, not intended for through traffic.	Highly Significant	Excluded, as unsuitable

Source: Road Function and Description from Ordnance Survey (2017), environmental effects of volume SGD HGV traffic from Chapter 3 and Arup (2014).

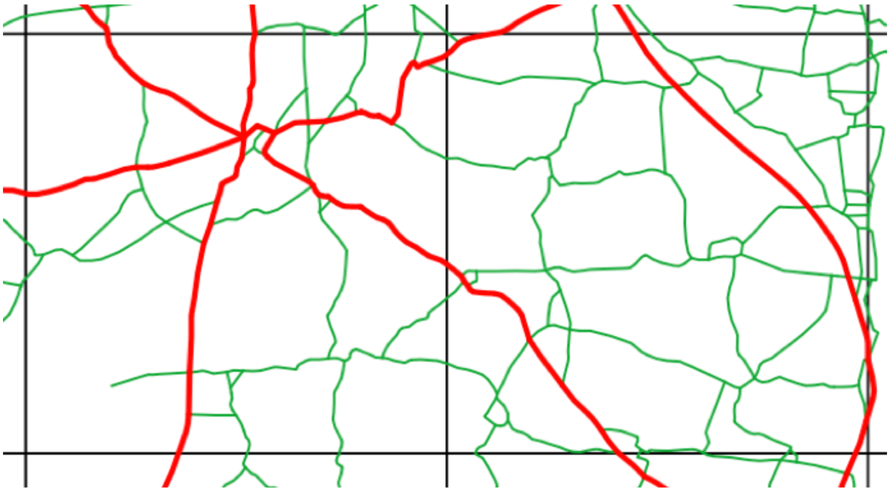


Figure 4.17: Major and Local Roads Example Used in Modelling

Key: Red Line = Major roads. Green Line = Local roads. Black lines = Ordnance Survey 10 km National Grid.

4.10.3 FINDING THE OPTIMAL ROUTE FOR SGD TRAFFIC

Having recognised that the roads hierarchy plays a crucial role in distinguishing between the significant and non-significant SGD traffic effects, the next question is how this distinction will be handled during modelling. In planning for SGD there is a preference to avoid or minimise adverse effects of traffic as much as possible. Since significant traffic effects only arise on 'local roads' minimising the use of local roads as much as possible is a key objective of planning for SGD. The modelling therefore seeks to optimise a trade-off between minimising SGD traffics' use of local roads while maximise the development of shale gas. This subsection explains the SGD traffic route selection process principles applied in the modelling to fulfil this objective.

SGD traffic has to connect each pad to the roads network at some point. The location used for SGD traffic to access the road network is referred to as the 'access point'. Once traffic is on the major roads network it is environmentally insignificant and able to travel anywhere in the country to transport materials and plant, without any local traffic effect (see Table 4.6). The modelling therefore initially seeks to site pads next to any major road, within the pad's development tract and in developable zones. The major road nearest to the preferred pad location (within the landing zone) is favoured since this minimises the length of bores on the pad.

Where access directly on major roads is not available (within the landing zone) local roads need to be used to gain access to the major roads network. To minimise potential adverse traffic effects the shortest possible route, between the access point and the major roads network, is favoured. Where there is both no major or local road within the pad's development tract and in development zones, an access track can be used. For modelling purposes, access tracks are limited to being no more than one kilometre long and must be a straight line from the pad to the nearest point on the nearest road, but not passing through a residential area. While the options for access tracks could be more flexible preliminary testing showed these parameters offered quantifiable modelling without undue complexity.

Figure 4.18 illustrates a hypothetical route connecting a pad to the major roads network using the shortest route. In this case an access track is used, connected to the nearest point on the nearest local road. The Pad (orange square) is connected to the nearest road by the access track (orange line). The shortest route on local roads is shown (in blue) with other local roads in the vicinity (in green) together with the nearest major road (in red). Putting all these steps together, the overall assessment of traffic effect within modelling therefore takes account of the local circumstances in the roads surrounding each pad by ensuring that SGD traffic uses the shortest possible route on local roads. This minimises, and mitigates, the overall significant effects of SGD traffic.

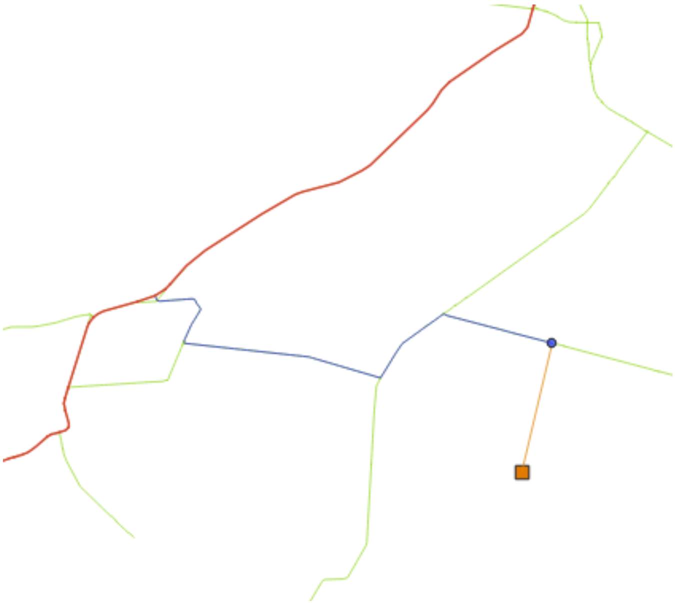


Figure 4.18: Shortest Route, showing Major Roads, Local Roads, Pad and Access Track.

Key: Major roads (red), Local roads (green), Pad (orange square), Access Track (that requires new construction - orange line) and the Shortest Route (blue) over Local roads to a Major road.

Minimisation of the traffic effects is arrived at by taking account of the number of loads required (Section 4.10.1) and minimising the distance travelled by vehicles on local roads (Section 4.10.2). This includes sophisticated siting choices which trade off viable access to the shale and access to the roads network. This modelling of the traffic effects is referred to as the 'core traffic assessment process'. Figure 4.19 summarises the steps and components of this process.

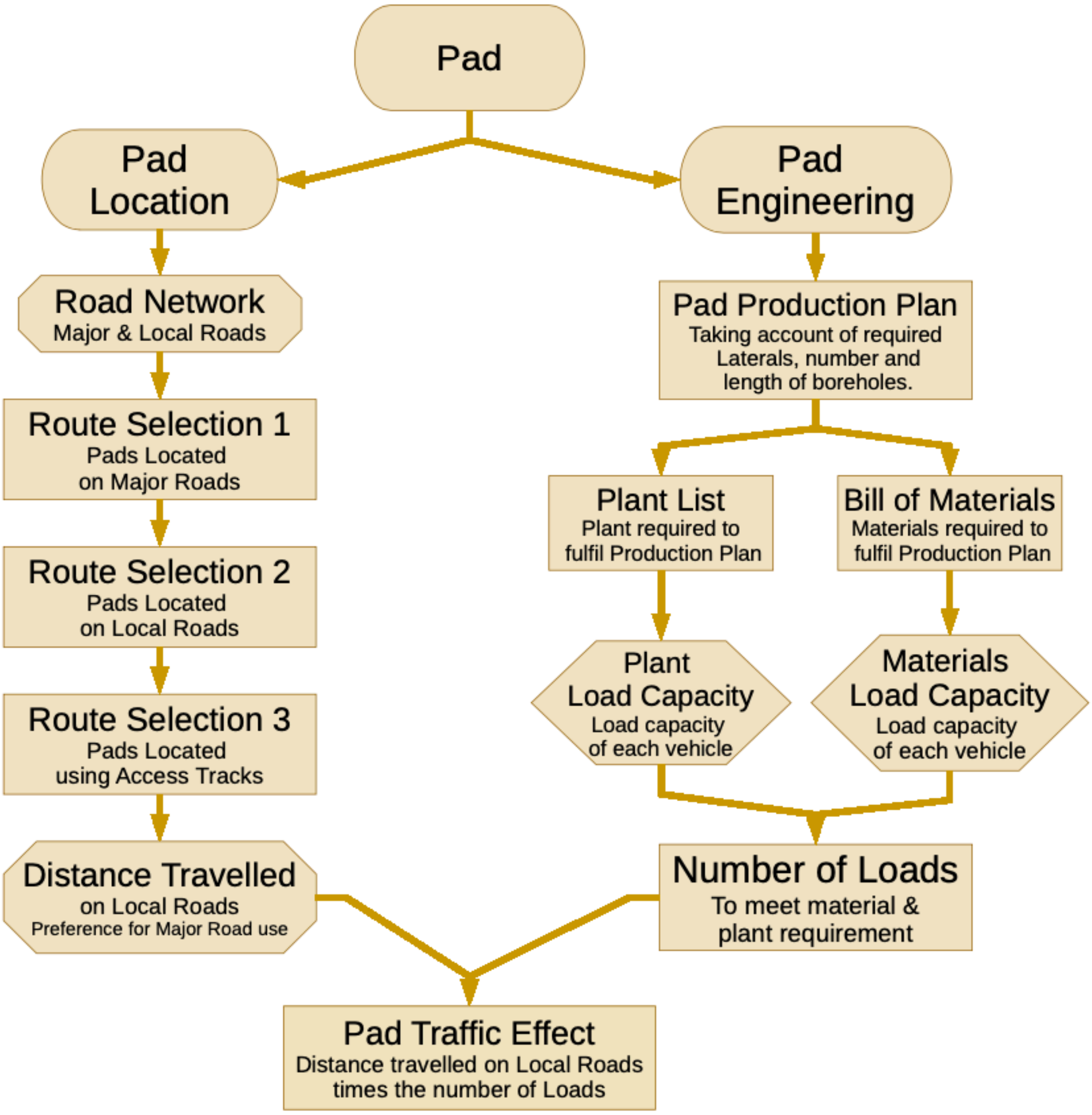


Figure 4.19: Core Traffic Assessment Process

Commentary: The figure shows the stages of the overall traffic assessment process: Once pad locations are known the length of laterals and borehole for each pad gives a bill of materials and plant list, this then applied to vehicle load capacities to calculate the number of loads required. The road network is used to find whether pads can be located on major roads, local roads or need to use access tracks. Where traffic requires to use local roads the shortest path on local roads Is selected. Applying the number of loads required to the shortest route distance on local roads, with return journeys give pad distance travelled for each pad.

4.11 How the Model is Run

The earlier sections have set out: how notional pad locations are determined to take account of subsurface engineering; the application of development tracts and developable zones to identify landing zones suitable for pads; and the modelling principles of the core traffic assessment. The remaining modelling requirement is to apply the principles of the traffic assessment to finalise pad locations. This concluding section, describing the modelling method, sets out how the model is run. The choice of the final pad locations should minimise the accumulated significant traffic effect.

In theory there is a possible trade-off between using the shortest route and reducing the amount of traffic from a pad (due to a lower volume of materials because, on some occasions, moving the pad location lowers the aggregate length of bores from the pad). Random sampling of this has shown that shortest distance is always the overriding factor in minimising the overall traffic effect. The modelling therefore proceeded on the basis of giving priority to the shortest distance from a pad access point to a major road junction. Figure 4.20 illustrates a simplified decision tree for locating pads together with the consequences.

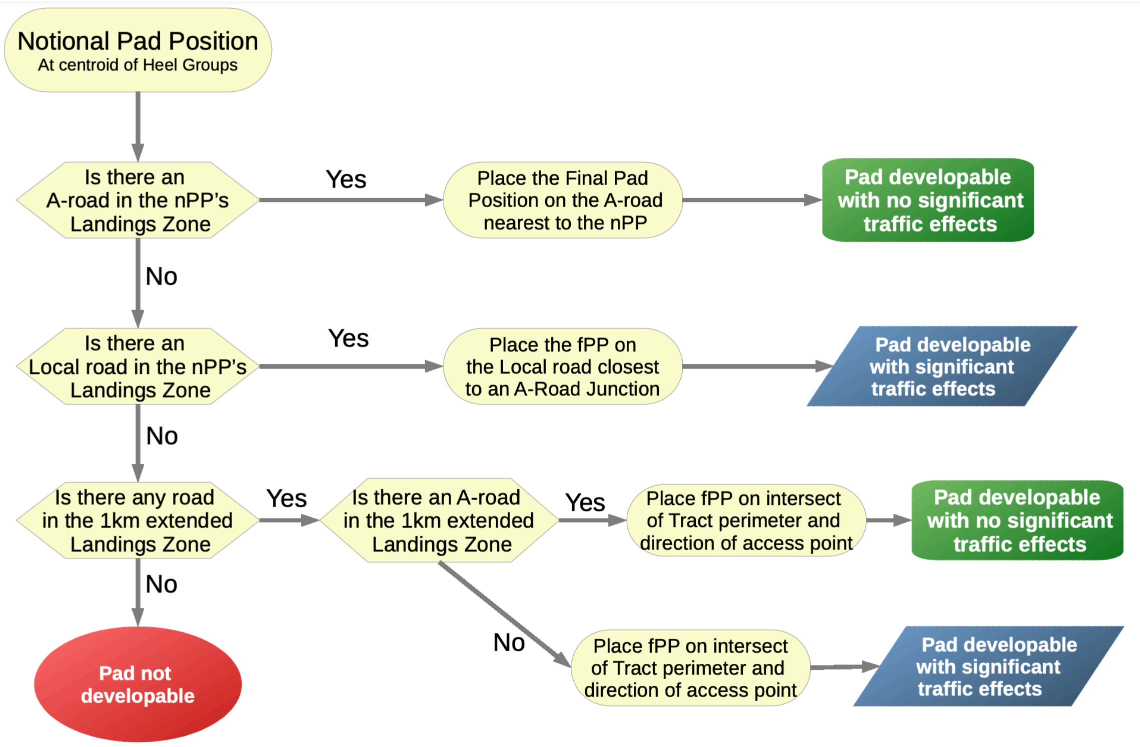


Figure 4.20: Summary Decision Tree for Identifying Final Pad Locations

NB: nPP refers to the notional or preferred pad position – at the centroid of the heel group. fPP refers to the final pad position – within the landing zone of developable zones and each pads development tract.

4.11.1 COMBINING DEVELOPABLE AREAS, DEVELOPMENT TRACTS AND THE SHORTEST ROUTE TO PRODUCE THE FINAL PAD LOCATIONS

To establish the optimum locations for each pad the following summary steps are applied:

1. All ‘local roads’ across the basin are divided to classify each section according to the distance along each road from a major road junction. Where two or more road junction are involved, the lowest distance is applied. (In practice the local roads are divided into 250m sections up to 6km, thereafter 500m sections up to 10km and 1,000m thereafter).
2. The road sections are then sieved against developable zones, to identify all local roads sections across the basin where pads could be located.
3. For each pad, all road parts (for both major and local roads) within the development tract and in developable zones are identified. These are referred to as ‘possible roads’.
4. For each pad the possible roads within its development tract are identified.
5. Where ‘possible roads’ within the development tract include major roads, the nearest point of the nearest major road to the preferred pad location (nPP) is identified as the ‘final pad location’ (fPP). The final pad location is also the pad’s the access point to the roads network.
6. For pads not covered by step 5, the road sections on local roads with the lowest distance within the pad’s development tract is identified.
7. For these pads the final pad location (fPP) is set. This is usually at the point where road section, with the shortest distance to a major road junction, intersects with the development tract boundary.
8. Where there are no local roads within a pad’s development tract a one-kilometre radial extension is added to the tract, to allow for an access track. Where the access track can be established by a straight line to a road (but not passing through a residential area) the final pad location (fPP) is set at the tract boundary, on the intersection of the straight line from the preferred pad location to the nearest point on the nearest road. Where a major road is available within the extended tract this is favoured, otherwise the access point is positioned on the local road with the shortest

distance to a major road junction. For these pads, the access point onto the roads network is separated from the fPP by the access track.

9. Where pads have no access to roads within their extended tract, the model concludes that these pads cannot be developed without undue significant local environmental effects. Most of these pads could be developed by setting aside the principle of excluding pad development from residential areas or their buffer zones. However, this would break the planning criteria and result in adverse local environmental effects.

4.11.2 COMPLETING THE MODELLING BY CALCULATING THE BASIN-WIDE TRAFFIC EFFECT

Knowing the finalised pad locations (fPP) enables the volume of traffic to be calculated, following the method described in section 4.10.1. The number and length of boreholes, the length of laterals and all other pad specification components which contribute to the amount of materials required is used to derive a ‘bill of materials’ needed to develop each pad. This ‘bill of materials’ is then applied through appropriate vehicle load factors (set out in Appendix G) to derive the number of vehicles required to develop each pad (specific to the location and the fracture zones served from the pad). This includes the additional materials required for any access tracks. In practice the traffic loads required for moving plant, such as rigs and hydraulic fracturing (HF) pump sets, is found to be not significant to the overall calculation of the traffic generated. Traffic movements for plant have therefore been excluded from the traffic effects assessment. Given the assumption that one rig and one hydraulic fracturing pump set is used for each block, this exclusion favours high pad density.

For each pad, the volume of traffic generated and the distance the traffic requires to travel on local roads is found through modelling. For pads that have direct access to a major road, no traffic effect arises. Pad locations with no access to the roads network, which cannot be developed are removed from the traffic effects assessment and the area of shale that they serve needs to be discounted from any calculation of the recoverable shale area. For each pad using local roads, the traffic effect is calculated by multiplying the number of vehicles generated by the distance travelled on the local roads. This computation also needs to recognise that each delivery of materials entails a two-way journey. For each pad a total distance travelled is produced. This is referred to as the ‘distance travelled on local roads’ (DToLR). This represents the predicted traffic effects of each pad’s development. It takes account of the accessibility of the site (on local roads) and the materials required to develop the pad (given the shale area it serves), having minimised the traffic effect of SGD across the basin.

For comparison purposes it is useful to consider the aggregate DToLR figure for each study block (for each pad density) in the light of the coverage of shale unit which is developable within each block. To understand the traffic effect this DToLR is analysed to consider the comparative performance of each pad density. Comparisons can also be made between pads located in urban, rural and suburban areas. It is also useful to analyse the DToLR against the road density in each block (where road density is the aggregate length of roads) for road types (major and local roads), within each block. This analysis provides useful insight into how and where the traffic effects arises and what criteria may usefully be applied to develop a basin-wide plan for shale gas development. If one type of pad density or road density or character produces less traffic effect, policies can be orientated to minimise the overall local environmental effects of the dispersed energy development. The detailed computational sequence of steps required to calculate the local environmental effects arising from SGD are set out in Appendix D.

For plan preparation purposes the model shows planning criteria on: (a) how to avoid noise and visual amenity effects; (b) where pads can best be sited; (c) what alternatives and planning scenario options are available; (d) how to minimise the traffic effect; (e) what the predicted traffic effect would be of each alternative planning approach; (f) what extent of shale unit can be covered in the production process, and (g) with a known recovery rate per hectare, what volume of gas can be produced for a known level of local environmental effects. By analysing the predicted environmental effects and gas produced against the circumstances of each block it is possible to draw planning observations on the relationship between SGD, local environmental effects and residential land cover or the relationship with existing road density. This modelling analysis can be applied to weigh other planning scenarios and options.

5. Results of the Modelling of Basin-Wide Development of Shale Gas in the Bowland Basin

This Chapter sets out the Results of the Modelling of the local environmental effects which arise when a positive planning approach is applied to basin-wide development of shale gas in the Bowland basin of Northern England. The focus of this research is to establish whether a positive planning for dispersed energy development can be achieved and whether this reduces the local environmental effects. As Chapter 3 set out, like most dispersed energy activity, shale gas development decisions are usually made on an incremental site by site basis.

Conducting the shale gas basin modelling requires extensive data, computation and time: some 217,830 files taking up approximately 363 gigabytes of data. This includes the assembly of base data, such as GIS location files, the development of the methodology (largely through computational experimentation) and the full computation of the finalised model. For the five pad densities in the 96 study blocks there are potentially up to 4,512 pads to be sited ({1+2+4+10+30}x 96). Each pad needs to be considered at every stage or level in the model. So, each pad needs to be assessed for engineering, subsurface, surface and social factors, giving approximately 13,500 pad locations to be assessed (47+{3x4,512})[3]. To assess the connectivity of the roads network 83,407 A-road and 213,905 local road sections were identified as being within the Bowland basin study area. These are extracted from the original Ordnance Survey source data. Each pad not located near an A-road needs to connect, via local

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[3] For the engineering level only the base block is calculated.

roads, to one of the 23,391 A-road junctions within the Bowland basin. Whilst the computation focused on road junctions within a 5km area around each study block, there are potentially several hundred alternative routes on local roads to link each pad access point to an A-road junctions. All these routes have to be assessed for every pad, sometimes repeating for alternative pad locations. Each of these need to be assessed to find the shortest route.

The selection of suitable pad locations is itself complex. For each pad, this includes:

a) Consideration of the need to gain access to as much of the resource (shale unit in this case study) as possible.

b) Taking account of the restriction on surface siting due to exclusion from residential areas and their noise exclusion buffer zones. And,

c) The need to optimise the vertical or near vertical bores as well as optimising the groupings of laterals to be served from each pad.

The considerable number of files and the large extent of the data in part arises because some steps in the methodology require multiple files for each study block. Several steps, consisting of 5-10 sub-processes can generate 480-960 files. This has to be applied to all of the 96 study blocks. A summary of the steps required in the model are set out in Chapter 4. Given the extensive computational processes involved details on the methodology are set out in the Appendices B to G.

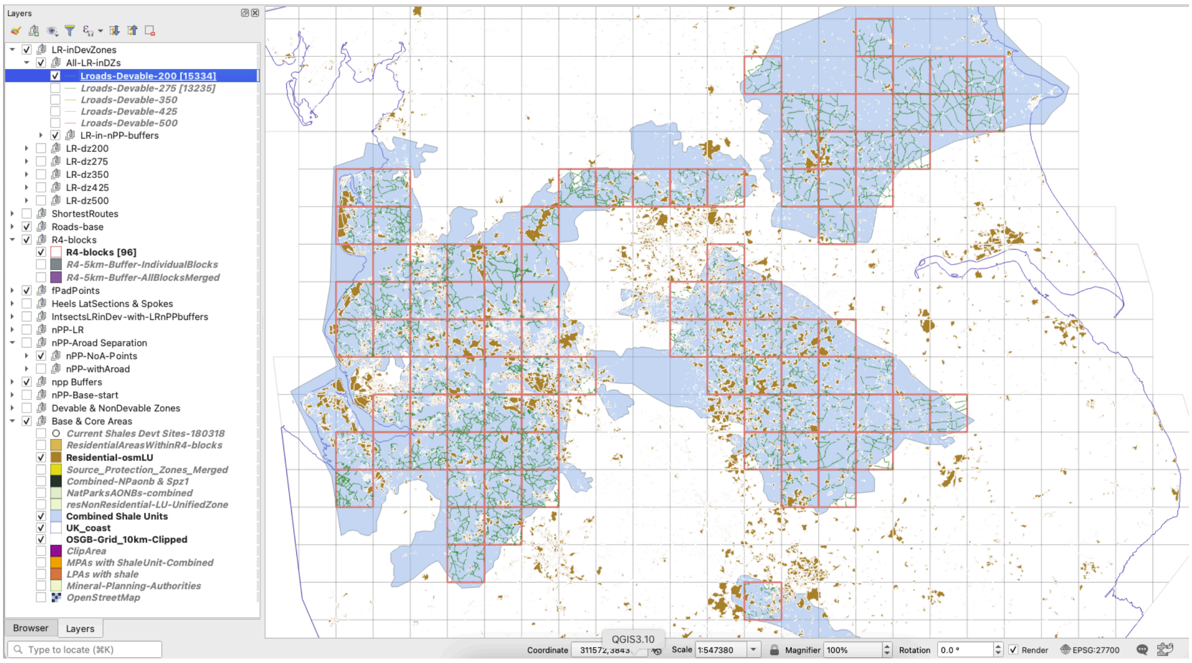
The results in this Chapter are structured into two main sections. The first, and by far the larger section, deals with the main modelling results, of the predicted local environmental effects arising from the spatial planning process. The second looks at the cumulative effects predicted by the modelling. The main modelling results are divided into three subsections. The first of these looks at what are called the Circumstantial Findings. This statistically describes extant situational parameters, or extant circumstances, of the basin, such as the extent of the shale unit, habitation and residential land use. These also includes data on road coverage within the basin and the statistical relationship found between road coverage and residential land use.

The second subsection provides information on the Operative Outcomes which arise from the model. The model assumes certain working parameters such as the extent of exclusions around residential areas inhibiting SGD, varying levels of tolerance of flexibility of siting pads and the resultant tolerable length of boreholes (for each pad density). The Operative Outcomes subsection describes these results and provides the findings of the intermediate stage of the modelling.

The third subsection provides the Analytical Results. These are the principal or main results of the modelling that show the comparative effect of traffic from SGD, arising for each pad density. The constituents of how these results are arrived at is also given. This subsection includes results data on the transport loading capability, the final pad positions, the resultant borehole lengths, how the various pads access the roads network and the extent of the shale unit accessed, for SGD for each pad density. The final accumulated traffic effect measure is compared across pad densities by stating how much traffic is generated per unit area of shale accessed. Assuming consistent gas recovery this is surrogate for the level of accumulated traffic arising per unit of energy produced. The final part of this subsection provides a summary of the main influential factors which determine the traffic effect results.

The Chapter closes with a summary of the results for cumulative effects and data on the number of planning authorities involved in planning decision making for SGD. The cumulative effects results provide an indication of whether a positive planned approach provides a better outcome for the cumulative effects over project-by-project decision making.

Given the very large volumes of data involved in these results this chapter is supported by extensive appendices. Within this chapter the results presented are for the Bowland Basin as a whole. These are aggregated from the results for each of the 96 study blocks. Appendices H, I and J provide the individual results for each study block. Appendix H provides the individual block results for the Circumstantial Findings, Appendix I covers the Operative Outcomes, while Appendix J provides the Analytical Results for each block. These appendices are digital, in spreadsheet format. The data in the three results appendices is passive (simple text). This information is available in .xlsm (Microsoft Excel Macro-enabled Workbook) format. During the research case study extensive spreadsheet calculations were carried out using LibreOffice v7.0 and earlier versions. The active spreadsheets, which are used to calculate the results as well as various stages of the study, are also presented. However, no explanation of these is offered. These active files use .ods format. This format is part of the Open Document Format specified by the UK government. Whilst the active files can be viewed in Microsoft Excel the presentation of the data is not assured. These active data files are best viewed in LibreOffice calc or OpenOffice calc. The study was conducted using spreadsheets with GIS software applied for spatial analysis. The GIS software used was Qgis v3.10 and earlier versions. The final working version of Qgis has over 230 layers. Earlier iterations of the modelling deployed over one thousand GIS vector layers. Whilst the working version is available to view, unfortunately the size of the associated data is too large to attach and include with this thesis. Figure 5.1 illustrates a screenshot of the GIS software used in the modelling.



- ☑ LR-inDevZones
  - ☑ All-LR-inDZs
    - ☑ Lroads-Devable-200 [15334]
    - ☐ Lroads-Devable-275 [13235]
    - ☐ Lroads-Devable-350
    - ☐ Lroads-Devable-425
    - ☐ Lroads-Devable-500
    - ☑ LR-in-nPP-buffers
  - ☐ LR-dz200
  - ☐ LR-dz275
  - ☐ LR-dz350
  - ☐ LR-dz425
  - ☐ LR-dz500
- ☐ ShortestRoutes
- ☑ Roads-base
- ☑ R4-blocks
  - ☑ R4-blocks [96]
  - ☐ R4-5km-Buffer-IndividualBlocks
  - ☐ R4-5km-Buffer-AllBlocksMerged
- ☑ fPadPoints
- ☐ Heels LatSections & Spokes
- ☐ IntsectsLRinDev-with-LRnPPbuffers
- ☐ nPP-LR
- ☐ nPP-Aroad Separation
  - ☑ nPP-NoA-Points
  - ☐ nPP-withAroad
- ☑ npp Buffers
- ☐ nPP-Base-start
- ☐ Devable & NonDevable Zones
- ☑ Base & Core Areas
  - ☐ Current Shales Devt Sites-180318
  - ☐ ResidentialAreasWithinR4-blocks
  - ☑ Residential-osmLU
  - ☐ Source_Protection_Zones_Merged
  - ☐ Combined-NPaonb & Spz1
  - ☐ NatParksAONBs-combined
  - ☐ resNonResidential-LU-UnifiedZone
  - ☑ Combined Shale Units
  - ☑ UK_coast
  - ☑ OSGB-Grid_10km-Clipped
  - ☐ ClipArea
  - ☐ MPAs with ShaleUnit-Combined
  - ☐ LPAs with shale
  - ☐ Mineral-Planning-Authorities
  - ☐ OpenStreetMap

Coordinate 311572,3843 Scale 1:547380 Magnifier 100% Rotation 0.0 ° ☑ Render EPSG:27700

Figure 5.1: Illustration of the Geographic Information Software Qgis Deploying the Model

Commentary: The image illustrates the active panels of the QGIS software used in the case study modelling. The main panel provides a map of Northern England with some vector data layers active. The left panel shows the layer control system with some layers and sublayers open or activated.

5.1 Circumstantial Findings for the Bowland Basin Study Area

The Circumstantial Findings for the case study of SGD in the Bowland basin describes the geographic context for the area in which the dispersed energy modelling is applied. It also provides data on the shale unit coverage, the blocks used in the study, the residential land use, other non-developable areas and roads within the studied blocks. This data sets out the environmental circumstances for the subsequent results from the model analysis. This is useful as it sets the context in which the subsequent model analysis results arise. These are useful for comparing the types and level of effects between blocks with different geographic attributes. This enables the model results to be judged against the prevailing circumstances in each locality. For example, the extent of road coverage influences the level of the traffic effect generated by SGD. This section concludes by examining the relationship between roads coverage and residential land use.

5.1.1 SHALE UNIT COVERAGE

The Andrews study (2013) of the prospectivity of the Bowland basin identifies the extent of the viable shale resource (shown in Figure 3.3). Andrews (2013) identified two shale units, known as the Upper and Lower Hodder-Bowland units. Whilst it is possible to conduct separate analysis for each of the units using the same method and combining outputs, for this thesis these unit have been merged (see Section 4.3). The combined shale unit extends to 13,750 km^2, of which 13,525 km^2 (98%) is on land.

Hydrocarbon extraction licenses have been issued for large area of the Bowland shale unit as well as pre-existing licenses from before the shale unit was recognised. The area covered by extraction licenses within the case study area amounts to 15,847 km^2. Of this 9,879 km^2 lies over the Bowland shale unit. 71.8% of the Bowland shale unit is currently covered by extraction licenses.

5.1.2 STUDY BLOCK SELECTION AND STATISTICS

Whilst commercial shale gas development would seek to develop all of the Bowland shale unit this thesis confines modelling to 96 selected blocks with at least 70% shale coverage, after allowing for administrative exclusions. After sieving, the block with the lowest coverage has 73% shale cover. Table 5.1 gives a statistical summary of the shale unit per block for the case study. Digital Appendix H-Shale provides the results and coverage of shale for each individual study block.

Table 5.1: Study Blocks Shale Unit Coverage - Summary

Combined shale unit with the Bowland Basin – km^2	13,750.8
Total number of $100km^2$ study blocks	96
Number of blocks with 100% shale unit coverage	60
Mean shale coverage – km^2	95.8
Minimum shale coverage – km^2	73.0
Total shale coverage in study slocks – km^2	9,196.5
Percentage of shale coverage within study blocks - %	66.9%

5.1.3 POPULATION AND RESIDENTIAL LAND USE DATA FOR THE STUDY BLOCKS

The study blocks are situated in a region of mixed urban and rural land uses. The human population in the Bowland study area is approximately 15 million and is distributed unevenly throughout the study area. Table 5.2 provides a summary of the residential land-use coverage for the study blocks. Digital Appendix H-ResidentialLandCover provides the residential land use coverage for each study block. Whilst the study blocks have extensive areas of residential land use this amounts to 13.4% of the land area. The maximum residential coverage is 50.5 km^2 or 50.5% of the block. Thirteen of the 96 study blocks (13.5%) account for 33% of the residential land use in study blocks.

Table 5.2: Residential Land Use Coverage within Study Blocks - Summary

Number of study blocks	96
Total area of residential land use within all study blocks – km^2	1,283
Maximum coverage of residential land use within a study block – km^2	50.5
Minimum coverage of residential land use within a study block – km^2	0.2
Mean coverage of residential land use within a study block – km^2	13.4
Median coverage of residential land use within a study block – km^2	11.6
Percentage of residential land use coverage within Study Blocks - %	13.4%

5.1.4 DATA FOR OTHER NON-DEVELOPABLE AREAS WITHIN STUDY BLOCKS

As well as avoiding residential land use, there are prohibitions against SGD in National Parks and Areas of Outstanding Natural Beauty together with potable ground water Source Protection Zones One. Table 5.3 provides a statistical summary for these administrative restricted areas for the study blocks. Digital Appendix H-ResidentialLandCover, cells O1 to R106, provides the individual results for each study block. The study blocks are affected by 1% within National Parks and Areas of Outstanding Natural Beauty with 0.2% affected by Source Protection Zones One.

Table 5.3: Administrative Restricted Area within Study Blocks - Summary

Restriction Type:	NP & AONB	SPZ1
Total area restricted within all 96 study blocks – km^2	96.4	22.4
Total area restricted within all 96 study blocks – %	1.0%	0.2%
Number of blocks with no restricted area within a study block	88	71
Maximum coverage of restricted area within a study block – km^2	25.8	7.5
Mean coverage of restricted area within a study block – km^2	1.0	0.2
Median coverage of restricted area within a study block – km^2	0.0	0.0

Notes: NP & AONB = National Parks and Areas of Outstanding Natural Beauty. SPZ1 = Ground water Source Protection Zones One. The combined studied blocks cover 9,600 km^2 (96 * 100).

5.1.5 ROAD COVERAGE STATISTICS FOR THE STUDY BLOCKS

The study area is well provided for with roads. Table 5.4 provides a statistical summary for road coverage within the study blocks. Digital Appendix H-Roads provides the individual results for each study block. The average study block has 38.6 km of A-roads and 104.9 km of Local roads. Only six blocks have less than 10km of A-roads, which is sufficient to cross the block once, whilst seventy-nine blocks have more than 20km of A-roads. The area within a block beyond 1km of an A-road is an indication the general accessibility within a block to A-roads. Approximately half (on average, 48.4%) of the area within all study blocks is within 1km of an A-road. The block with the poorest A-road access has 71.8% beyond 1 km of an A-road. The study blocks have a high provision of Local roads: typically, 104.9 km per 100km^2 block. Even the block with the lowest Local-road coverage has 42.3 km, sufficient to cross the block in both orientations (north-south and east-west) twice.

Table 5.4: Road Coverage within Study Blocks - Summary

Road Type:	A-Roads	Local-Roads
Total length of roads within all study blocks – km	3,709.3	10,071.5
Mean length of roads within all study blocks – km	38.6	104.9
Minimum length of roads within all study blocks – km	0	42.3
Maximum length of roads within all study blocks – km	144.3	193.2
Median length of roads within all study blocks – km	36.9	104.8
Total area beyond 1km of an A-Roads for all study blocks – km^2	4,644.8	
Total area beyond 1km of an A-Roads all study blocks – %	48.4%	
Maximum area beyond 1km of an A-Roads for a study blocks – km^2	71.8	
Minimum area beyond 1km of an A-Roads for a study blocks – km^2	5.9	

5.1.6 THE RELATIONSHIP BETWEEN ROADS AND RESIDENTIAL LAND USE COVERAGE

Table 5.5 shows the correlation of blocks with high areas of residential land use and road coverage. Although a high correlation, the relationship is not a perfect positive correlation as A-roads are also used to connect major urban centres. The moderate positive correlation for local roads confirms some relationship between local roads and residential land use. Section 4.10.2 sets out that ‘local roads’ for this case study are ‘B’ and ‘C’ class roads with the Highways Hierarchy, whilst lower-level access roads are excluded from assessment (Table 4.6). However, the fact that this positive correlation is moderate suggests that local roads also provide extensive coverage in rural areas, where residential land use is much lower. Digital Appendix H-RoadsResCorrelate provides the statistical analysis for these results.

Table 5.5: Correlation Between Residential Land Use Coverage and Roads

Correlation Coefficient Between Residential Land Use and A-roads	0.829
Correlation Coefficient Between Residential Land Use and Local Roads	0.477
Correlation Coefficient Between Residential Land Use and Both A and Local roads	0.727

Since shale gas development sites are not permitted within residential areas it would be useful to investigate the coverage of roads outside residential areas. Unfortunately, however, the measure of roads outside residential areas is not accurate due to the definition of residential areas used in the source Open Street Map data: in some circumstances roads, particularly major roads and wide dual carriageways, are excluded from residential areas. In other situations, major roads are incorporated into residential land use areas. As a consequence, the data is unreliable and been excluded from these results.

5.2 Operative Outcomes for the Bowland Basin Modelling

This section sets out the Operative Outcomes for the study area. Operative outcomes are part of the calculation used to produce the final model results. These represent an important intermediate stage in the analysis. These outcomes are stated here because they are useful to aid understanding of the final model results. This subsection provides data on four segments of the operative outcomes:

1) Subsection 5.2.1 gives data on the extent of the developable area suitable for SGD once setback buffers, for noise and visual effects, are applied around residential areas, referred to as ‘developable zones’.
2) Subsection 5.2.2 gives data on the aggregate length of laterals and therefore the potential of the shale unit area capable of development.
3) Section 5.2.3 gives summary data on the preferred or notional pad points (nPP) and the resulting areas of ‘development tracts’.
4) Section 5.2.4 provides data on the extent of overlap, between developable zones and development tracts. This provides the ‘landing zone’ where shale gas development sites, or pads, are possible.

5.2.1 OUTCOME ON SURFACE DEVELOPMENT ZONES

Table 5.6 provides a summary of the extent of the developable zones available for shale gas development sites, for the 96 study blocks. Digital Appendix H-ResidentialLandUse, cells G1 to K108, provides the individual results for each study block. The impact of the increase in setback distance is clear. A 200m setback, used for the 30 ppb density, results in 52% more land being available for development over a 500m setback, used for the 1 ppb density ({66.5/43.7}-1*100). The effect of setback is particularly evident in areas of high residential land use. For the block with minimum land availability (due to high residential land use), the

500m setback provides only 7.7% of the land available compared with a 200m setback (1.1/14.1*100). In land area available, this means that while the 200m setback provides 14.1 km^2 in this high residential land use block, the 500m setback provides only 1.1 km^2. Overall, the size of the setback distance has considerable impact of the land available for SGD sites.

Table 5.6: Developable Zones Taking Account of Setback Distances Around Residential Areas and Administrative Restrictions, for Study Blocks - Summary

	200m Setback 30 ppb	275m Setback 10 ppb	350m Setback 4 ppb	425m Setback 2 ppb	500m Setback 1ppb
Total developable zone land available – km^2	6,384	5,767	5,195	4,672	4,199
Mean developable zone land available – km^2	66.5	60.1	54.1	48.7	43.7
Land available in minimum block – km^2	14.1	8.7	4.9	2.5	1.1
Minimum block, % difference over 200m setback	-	61.7%	35.2%	17.6%	7.7%
Land available in maximum block– km^2	95.7	93.2	90.3	87.7	85.0
Median land available – km^2	68.3	62.4	57.9	50.7	44.8

5.2.2 OUTCOME ON SHALE UNIT COVERAGE

Table 5.7 shows the extent to which the shale unit is accessible within the study blocks, taking account of:

- The extent of shale coverage within each study block.
- The consequence of aligning the laterals to 60-240 degrees, to take account of the maximum horizontal in-situ stress (S_{Hmax}) (Section 4.8.3).
- The reduction of laterals at the block boundaries to avoid the fracture zone overlapping the block boundary (Section 4.8.3).

Digital Appendix H-Laterals provides the individual results for each study block. Taking account of subsurface requirements, 91.6% of the study blocks is capable of extraction. Sixty-two of the 96 study blocks have the maximum lateral length and shale unit.

Table 5.7: Lateral Length and Shale Unit Area Covered across the basin, within Study Blocks - Summary

	Total Length of Laterals (km)	Area of Shale (km^2)
Total within all study blocks	26,421	8,798
Mean within all study blocks	275.2	91.6
Minimum within all study blocks	209.9	70.0
Maximum within all study blocks	268.8	95.5
Median within all study blocks	286.8	95.5

5.2.3 OUTCOME ON NOTIONAL PAD POINTS AND PAD DEVELOPMENT TRACTS

Whilst the theoretical number of pads required nominally equates to the pad density, when the shale unit coverage is applied the number of pads required for the study blocks reduces. These are referred to as Notional Pad Points or nPP. The overall number of Notional Pad Points required to cover the extent of the Bowland shale unit is shown in Table 5.8. Digital Appendix H-PadTracts, cells I1 to M109, provides the individual results for each study block. This shows how the shale unit and required laterals, from Table 5.7, common to all pad densities, are transposed for each pad density. There is no reduction in the number of pads required for lower pad densities, 1 and 2 ppb, since this number of pads are still required to access the shale within the block. A few of these pads have shorter aggregate lateral length. For higher pad densities the number of pads required to cover the shale unit falls, approximately in proportion to the shale unit coverage available in each block. In the case of the 30ppb density 2,778 pads are required, which is 96.5% of the theoretical maximum (96*30=2880; 2778/2880*100=96.5%). The block with the smallest number of required pads for 30ppb has 22 pads, which is 73% of the 30ppb maximum.

Table 5.8: Notional Pad Points for each Pad Density for Study Blocks - Summary

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Theoretical total number of pads required - all bocks	96	192	384	960	2,880
Total number pads required (nPP) – all blocks	96	192	381	933	2,778
Total number of pads required taking account of shale unit coverage as a percentage of the theoretical total.	100%	100%	99.2%	97.2%	96.5%
Mean number of pads required for all blocks	1	2	4	9.7	28.9
Minimum number of pads required for all blocks	1	2	3	8	22
Maximum number of pads required for all blocks	1	2	4	10	30

Having identified the number and location of the notional pad points required to cover the shale unit in each block, it is then possible to ascertain what area around for each nPP might be available for development. These are referred to as development tracts (Section 4.8.2). The method of determining the radial size of development tracts was set out in Section 4.8.2. These radial development tracts are set at 4.441, 2.45, 1.991, 1.01 and 0.51 kilometres, for 1, 2, 4, 10 and 30 pads per block densities respectively. Table 5.9 shows summary data for the extent of the development tracts for all study blocks. Digital Appendix H-PadTracts, cell O1 to S109, provides the individual results for each study block. For each pad density, the table shows the scale of aggregate development tracts area for all blocks. This varies between 61% for 1ppb to 23.2% for 30ppb, for the whole of the 96 study blocks. (The ninety-six 100km^2 study blocks cover 9,600 km^2).

Table 5.9: Development Tracts for each Pad Density for Study Blocks - Summary

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Total number pads required for all blocks (Table 5.8)	96	192	381	933	2,778
Radial extent of development tracts – km	4.441	2.450	1.991	1.010	0.510
Total area of all development tracts for all blocks - km^2	5,854	3,564	4,671	2,944	2,222
Percentage coverage of all blocks	61.0%	37.1%	48.7%	30.7%	23.2%

Whilst the area extent of the development tracts is set as a radius around the notional pad point this does not precisely match a perfect circle. This is because the GIS system uses 20 equiangular points on the circumferences, rather than a perfect circle, to plot the tracts. This

GIS zone is applied in the modelling. For all pad densities this covers approximate to 98% of a perfect circle, with all losses being near the perimeter of the tract.

5.2.4 CONCOMITANCE OF PAD DEVELOPMENT TRACTS AND SURFACE DEVELOPABLE ZONES

The operative outcomes so far show the aggregate area of developable zones (the areas outside residential areas, administrative restrictions and their setback) and the development tracts around notional pad points. These reflect the constraints on SGD site development for the surface and subsurface, respectively. These areas do not necessarily correspond. Potential SGD sites need to be within both developable zones and the development tracts. This concluding subsection on the operative outcomes bring these two together, to show the extent where developable zones and development tracts coincide.

Table 5.10 gives the summary data on this landing zone, where the development tracts and the developable zones coincide (see Figure 4.14). Each column of data in the table relates to a pad density, the related development tract radius and the appropriate residential areas setback distance. These areas can be classed as 'area suitable for development'. The mean, minimum, maximum and median are also shown. Digital Appendix H-DevTractIntectDevZone provides the individual results for each study block.

Table 5.10: Concomitance of Developable Zones and Development Tracts for each Pad Density for Study Blocks - Summary

	1 ppb / 4.441 / 500m	2 ppb / 2.450 / 425m	4 ppb / 1.991 / 350m	10 ppb / 1.01 / 275m	30 ppb / 0.51 / 200m
Total area of overlapping development tracts and developable zones - for all blocks – km^2	2,317	1,735	2,525	1,768	1,487
Mean area of overlapping development tracts and developable zones - for all blocks – km^2	24.1	18.1	26.3	18.4	15.5
Minimum area of overlapping development tracts and developable zones - for all blocks – km^2	0.0	0.7	2.3	2.1	3.4
Maximum area of overlapping development tracts and developable zones - for all blocks – km^2	54.0	34.6	46.0	30.4	23.0
Median area of overlapping development tracts and developable zones - for all blocks – km^2	22.7	19.4	28.2	19.0	16.0

Having now shown the data on developable zones and development tracts the 'area suitable for development' has been identified. These areas suitable for development, or landing zones, have taken account of the local environmental effects of noise and visual amenity. These effects have been mitigated to the point where they are not environmentally significant. It is now possible to use the model to conduct analysis to reduce traffic effects to the minimum necessary to facilitate SGD. The following results show what traffic effect arises on local roads as a consequence of a positive planning process for SGD.

5.3 **Analytical Results Produced from Modelling the Bowland Basin Shale gas Development**

This subsection presents the overall results of the modelling of the traffic effects of SGD across the Bowland basin. Box 5.1 provides an overview of the seven sets of results from the modelling process, explained in detail in each subsection. The overview provides a useful synopsis of how the model logic evolves and the computational progression towards the concluding results. This conclusion predicts the environmental effect of traffic on local roads from shale gas development across the Bowland basin. The comparison of traffic effects per unit of developable shale area at the alternate pad densities, which are the alternate planning scenarios, is striking. This conclusion is an indicator to any planning authority which scenario of shale gas development is preferrable.

Box 5.1: Overview of the Modelling Analytical Results

Section	Results	Comments
5.3.1	Generic Transport Loading Capability	These convert generic lengths of boreholes and pads size data into the required number of vehicles loads. These set the basic load parameters of bore length and pad size which are later applied to the specific circumstances of each pad. For example, these results might give the number of vehicle loads required per kilometre length of borehole for the production casing. Results cover every modelled aspect of the materials and plant required to develop an SGD site.
5.3.2	Final Pad Locations	These final pad points (fPP) are located somewhere within the 'areas suitable for development'. The modelling identifies the pad sites which minimise travel on local roads, either by siting pads next to A-roads or on local roads where the distance to A-roads is minimised.
5.3.3	Required Borehole Lengths	Having found the final pad locations, the required borehole lengths to access each lateral sections from the pad location can be calculated. This takes account of the lateral section lengths as well as the vertical or near vertical bore. The calculation includes the length of conductor, surface, intermediate and production casing as well as the drill string. All of the modelled associated materials, such as cement and drilling mud, are included. The material for the pad construction is included together with all the drilling, hydraulic fracturing and

Box 5.1: Overview of the Modelling Analytical Results

Section	Results	Comments
		construction plant. Applying the generic transport loading capability, this data is then used to derive the number of loads required for each individual pad.
5.3.4	Pad Road Access Categories	This section gives the results of categorisation of pads into road access groups. These give results on how each pad is accessed from the road network, gives the number of pads which fall within the following categories: a) Notional pad points that have no access to any road within their development tract. These nPPs therefore have no opportunity of being developed. These non-developable nPPs occur where all or almost all of the development tract is occupied by residential areas and setbacks. There are no roads (A-road or local) where the pad could be located in the developable zones. The associated shale unit is therefore not developable. b) Final pad points can be located adjacent to an A-road. These pads can therefore be developed without any requirement for SGD transport to travel on local roads. Since this is preferable these final pad points are prioritised. c) Pads which are developable and not directly accessible from an A-road, but the pad points are located on a local road. These pads can therefore be developed but require SGD transport to travel on local roads. The model seeks to find the location which provides the shortest distance for travel on local roads to access the A-roads network. d) Final pad points that can only gain access to roads by using an access track. A limit is set that access tracks can be no more than one kilometre long. These pads can be developed but result in travel on either A-roads or local roads. The load requirement needs to be adjusted to take account of the additional materials required to construct the access track. Again A-road access is preferred and when located on a local road the point of access with the shortest distance for travel on local roads is used.
5.3.5	Shortest Path Distances	For pads in categories (c) and (d) above, using local roads, the results are then given of the shortest distances, on local roads, between the final pad point and the nearest major road junction. This data provides the distance that is required to be travelled on local roads.
5.3.6	Distance Travelled on Local Roads	The local road distance and the number of vehicles that are required for the SGD pad are multiplied together to give the 'distance travelled on local roads' (or DToLR) for each pad
5.3.7	Distance Travelled per Shale Unit Area	The pads, from categories (b), (c) and (d) above, using A-roads, local and access tracks, are compared against the whole area of the shale unit which is developable. This gives the accumulated traffic effects of the 'distance travelled on local roads' per unit area of shale. Overall, this provide the most significant measure of the relative effectiveness of the different pad densities.
5.3.8	Comparison with earlier Findings	The 'distance travelled on local roads' results are compared with the residential area coverage and road coverage from the Circumstantial Findings

5.3.1 RESULTS OF THE GENERIC TRANSPORT LOADING CAPABILITY

This subsection provides the results on transport loading capability. The results give the number of vehicle loads required per unit of drilling and fracturing activity. The units used are: per kilometre of bore, per bore, per hectare of pad size and per pad. These results are shown in table 5.11. The total no of vehicles required for each pad's development is derived by applying the vehicle load factors to the appropriate specification of each pad. The requirement for drill string needs to match the length of the longest bore on a pad as well as to provide for wear on the components when applied to the aggregate length of all other bores on the pad. The wear replacement rates is assumed to be 25% of the aggregate borehole length at the pad. From all of these factors the total number of vehicles required to service a pad can be calculated once the pad parameters are known.

Table 5.11: Generic Transport Loading Capability

Activity	unit	Loads	ref
Site construction:			
Site Construction Plant	Per pad	10	1
Geotextile	Per ha	5	2
Aggregate for base	Per ha	320	3
Security fencing	Per ha	5	4
Offices & storage	Per ha	10	5
Borehole: drilling			
Drilling rig & associated equipment	Per pad	40	6
Conductor casing	Per bore	0.9	7
Surface casing	Per bore	1.4	8
Intermediate casing	Per km vertical bore	3.3	9
Production casing	Per km of all bores	2.4	10
Drill string	Bespoke	See note below	11
Drilling muds, cements and materials	Per km bore	1	12
Hydraulic fracturing:			
Hydraulic pumps & associated equipment	Per pad	40	13
Fracturing materials (other than water)	Per km lateral section	2	14
Site remediation			
Site remediation plant	Per pad	10	15
Removal of base aggregate	Per ha	320	16
Removal of other materials	Per ha	12	17
Offices & storage	Per ha	10	18

Appendix G provides the full calculation of each activity load figure, for each item detailed under the reference (see reference list in Appendix G). **Notes:** Drill String: For the drill string the number of loads is calculated as the length of the longest bore on the pad, plus 25% of the aggregate length for all other bores at the pad, divided by 9.5m to give the number of drill string sections required on the pad, divided by 61 sections per load, multiplied by two to provide for the removal of all section from the pad after drilling. No provision is made for replacing sections being removed by using empty returning loads.
DataSource: truckLoadsTable 2020Aug

5.3.2 RESULTS ON THE FINAL PAD POINTS

The process of finalising pad positions seeks to optimise the coverage of the shale unit whilst minimising any environmental effects at the surface. From the potential number of pads per block, for each density, pads are removed either because there is no shale unit to access, or because surface restrictions mean that it is not possible to develop pads in that location. Table

5.12 provides the results on the final pad points (fPP) to maximise development of the shale unit for each pad density, showing how many are removed due to shale coverage and the number that are not developable due surface restrictions. The final number of developable pads is given. These pads fall both within the surface developable zones and subsurface derived development tracts.

Table 5.12: Final Pad Point Summary for Study Blocks

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Theoretical maximum number of pads for 96 study blocks (pad density x 96)	96	192	384	960	2,880
Number of pads required to cover the shale unit – nPP (from Table 5.8)	96	192	381	933	2,778
nPP as percentage of theoretical maximum	100%	100%	99.2%	97.2%	96.5%
Number of nPPs that are not developable due to surface restrictions	0	8	12	32	753
Percentage number of nPPs that are not developable due to surface restrictions	0%	4.2%	3.1%	3.4%	27.1%
Number of Developable Pads	96	184	369	807	2,025

DataSource: fPadPoints-Basin-Master

As the table shows, there is clearly a trend of lower pad densities having better access. This trend reflects the spatial extent of the development tracts for each pad density (Table 5.9). As stated in section 4.8, development tracts are a product of the horizontal distance between pads points and heels. Lower densities therefore have larger tracts. The tracts have a radius of 4.41, 2.45, 1.99, 1.00 and 0.51 km for 1, 2, 4, 10 and 30 ppb respectively. This mean that allowing for both the tract size and number of tracts in a block, for each density, the tracts coverage is 62%, 38%, 50%, 31% and 25% of the block for 1, 2, 4, 10 and 30 ppb respectively. This greater coverage, for lower pad densities, affords more opportunity to access roads and thereby reduced impact of surface development restrictions.

5.3.3 RESULTS OF THE REQUIRED BOREHOLE LENGTH

Having finalised the location of pads (fPP) the final data for borehole lengths can be calculated. For the pads that can be developed, this provides the length of near vertical bores, the length of lateral sections served, the number of bores and average lengths. Using this data, it is possible to calculate the area of shale covered, at each density. Table 5.13 gives summary data for the length of boreholes required for all developable pads within the study blocks. Digital Appendix I provides the individual results for each study block, for each pad density. The results are consistent with expectation. The number of bores per pad and the average lateral section length are in line with the theoretical lengths. The vertical bores are all above 3km, with the shortest pad to heel bores for 30ppb. As expected, the vertical bore lengths increase with lower pad density. With the assumed standard fracture zone width of 333.3m the area of shale covered by each pad density can be derived, as a multiple of the lateral section lengths. The consequent area of shale accessible for each pad density is provided. It is notable that the shale coverage declines as pad density increases. This is caused by the higher pad density pads having to be excluded due to surface restrictions.

Table 5.13: Required Boreholes Lengths for All Developable Pads in Study Blocks – Summary

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Number of Pads Developed (from Table 5.12)	96	184	369	807	2,025
Number of Boreholes	5,982	5,711	10,257	9,161	11,232
Total Length of lateral sections – km	26,351	25,162	25,480	23,197	20,723
Total length of vertical bores – km	26,296	20,736	35,688	29,494	36,829
Total length of bores – km	52,647	45,898	61,168	52,691	57,552
Average number of bores per pad	62.3	31.0	27.8	11.4	5.5
Average lateral section length per bore – km	4.40	4.41	2.48	2.53	1.84
Average vertical bore length – km	4.41	3.63	3.49	3.31	3.27
Area of shale unit accessed – km^2	8,783	8,387	8,492	7,731	6,907
Shale unit area in study blocks - km2^2 (Table 5.1)	9,196	9,196	9,196	9,196	9,196
Percentage of study block shale area developed	95.5%	91.2%	92.3%	84.0%	75.1%

5.3.4 CATEGORISATION OF PADS INTO ROAD ACCESS GROUPS

The modelling presumes that where possible, to avoid travel on local roads, pads would use access to A-roads. Where this is not possible local roads are used. Where there are no A-roads or local roads accessible within the development tract, an access track is required. These can be up to one kilometre long and must connect straight to a road without passing through a residential area. Table 5.14 shows the modelling results on the categorisation of how pads are accessed from the roads network. The number of pads that are accessed from A-roads, local roads or require access tracks are given. Also, whether access tracks have access points onto an A-road or local roads. (Summary data on the road coverage in the study blocks is given in Section 5.1.5).

Table 5.14: Categorisation of Pads into Road Access Groups

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Number of Developable Pads (from Table 5.12)	96	184	369	807	2,025
Number of pads accessible via an A-road	87	126	236	327	495
Percentage of pads accessible via an A-road	90.6%	68.5%	64.0%	40.5%	24.4%
Number of pads accessible via a Local road	9	58	133	480	1,530
Percentage of pads accessible via a Local road	9.4%	31.5%	36.0%	59.5%	75.6%
Number of pads accessible via an access track	0	0	0	52	614
Percentage of pads accessible via an access track	0.0%	0.0%	0.0%	6.4%	30.3%
Number of pads accessible via an access track from A-road	0	0	0	13	139
Number of pads accessible via an access track from local road	0	0	0	39	475

5.3.5 RESULTS OF THE DISTANCES ON LOCAL ROADS, FROM PAD POINTS TO MAJOR ROADS

The finalised location results for pads mean that the distance on local roads of pads from A-roads to access points can also be determined. This is the ‘shortest path’ distance to connect pads to the major roads network (where traffic effect become environmentally insignificant). The modelling finds the optimum location to minimise the distance travelled on local roads. The number of pads requiring to use local roads to gain access to pads was given in Table 5.14. Table 5.15 provides the distance of these shortest routes on local roads required to connect final pad points to the A-roads network, aggregated across all pads across all study blocks. The table provides the average and the maximum distance, for all pads using local roads across the basin. Digital Appendix J provides the individual results for each study block. Digital Appendix J is organised by pad density. It covers all of the individual block results given in this Section 5.3. A summary tab, combining the different pad density data, is provided for aggregated cross-density comparison.

Table 5.15: Aggregate Shortest Path Distance on Local Roads, from Final Pad Points to Major Roads, for Study Blocks – Summary

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Number of pads accessible via a local road – (from Table 5.14)	9	58	133	480	1,530
Average shortest path distance on local roads to the nearest A-road– km	1,238	1,483	1,822	2,239	2,442
Basin wide greatest shortest path distance – km	2,687	7,182	7,840	13,518	14,265
Total length of affected local roads (including overlapping routes) -km	11,142	86,014	242,326	1,074,720	3,736,260

5.3.6 RESULTS ON THE AGGREGATE DISTANCE TRAVELLED ON LOCAL ROADS

The results have provided: the finalised pad positions; the identity of pads which need to use local roads; the number of loads required for these pads; and the distance on local roads to connect pads to the A-road network. With this information assembled it is now possible to use the model to predict the total accumulated distance travelled on local roads by SGD traffic across the basin. Table 5.16 provides the distance travelled on local roads, for all pads using local road access, aggregated for all study blocks, for each pad density. The distances travelled on local roads results have been calculated individually for every pad. This takes account of the material required for each pad and the consequent number of loads needed to develop the pad. It provides for two-ways journeys for each load. The ‘distance travelled on local roads’ by the resultant SGD traffic are aggregated by block and then aggregated for all blocks to give the basin-wide results shown. The average distance travelled per pad, for those pads which require travel on local roads, is also shown.

Table 5.16 shows there is considerable variation in 'distance travelled on local roads' between pad densities. The traffic effect increases commensurate with pad density. Whilst the average distance travelled is lowest for high pad density, by a considerable margin, the number of pads requiring travel on local roads means that the overall distance travelled on local roads is far greater for high pad densities. Digital Appendix J provides the individual results for each study block.

These results clearly show that lowest travel on local roads from SGD arises from the lowest pad density. Consistently over all densities, the lower the pad density the lower the level of traffic that arises from SGD. The modelling chose pads locations which avoid noise and minimise visual presence effects on the residential population. The remaining potentially significant local environmental effects of SGD is traffic on local roads. Organisation of pads which minimises traffic on local roads minimises the overall environmental effects of the dispersed energy development across the region. This is best achieved by concentrating SGD into larger pads which reduce the traffic impact.

Table 5.16: Distance Travelled on Local Roads Aggregated for Study Blocks - Summary

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Number of pads accessible via a Local road – (from Table 5.14)	9	58	133	480	1,530
Total length of bores – km (from Table 5.13)	52,647	45,898	61,168	51,758	53,548
Average Shortest Path Distance – km (from Table 5.15)	1,238	1,483	1,822	2,239	2,442
Total distance travelled on local roads by SGD traffic – million km	172.0	794.9	1,641.6	4,149.3	7,389.6
Average distance travelled on local roads, per pad using local roads – million km	19.1	13.7	12.3	8.6	4.8

5.3.7 RESULTS OF THE DISTANCE TRAVELLED ON ROADS AGAINST THE AREA DEVELOPED SHALE UNIT

This section of these analytical results compares the distance travelled effect of SGD traffic with all of the developable area of the shale unit, for each pad density. To consider the full value of shale area developed for each pad density recognition is also needed of those pads which are accessed from A-roads as well as any pads generating traffic on local roads. To take full account of this, the traffic on local roads effect need to be considered against the whole area of developable shale. This includes shale development sites accessed from A-roads as well as those accessed from local roads. Table 5.17 shows the area of shale unit which is accessible from all developable pads together with the traffic effect arising on local roads. The area of shale developed includes all developable pads, whether SGD transport uses an A-road, local road or an access track. The reduced environmental effects of lower pad density are further enhanced (over the Table 5.16 results) when the pads using A-roads are added to the assessment. This is because lower pad densities have a higher proportion of pads connected to A-roads (see Table 5.14). When looked at the accumulated local environmental effects of SGD from this perspective the difference between the pad densities is substantial: orders of magnitude of difference. The distance travelled per km^2 of shale unit at 1ppb results in less than 2% of the traffic effect for 30ppb density. Even at 10ppb the distance travelled per km^2 of shale area developed is less than half of that at 30ppb.

Table 5.17: Distance Travelled on Roads Against the Area of developable Shale Unit for Study Blocks - Summary

	1 ppb	2 ppb	4 ppb	10 ppb	30 ppb
Total distance travelled on local roads by SGD traffic – million km (table 5.16)	172.0	794.9	1,641.6	4,149.3	7,389.6
Total Length of lateral sections – km (table 5.13)	26,351	25,162	25,480	22,783	19,279
Area of shale unit accessed – km^2 (table 5.13)	8,783	8,387	8,492	7,594	6,426
Distance travelled on local roads per km^2 of shale unit- (1,000 km travelled per km^2 of shale unit)	19,583	94,778	193,311	546,392	1,149,953
Percentage of the highest distance per km^2 shale unit (30ppb)	1.7%	8.2%	16.8%	47.5%	100.0%

5.3.8 RELATIONSHIP BETWEEN THE TRAFFIC EFFECT OF SGD AND THE CIRCUMSTANTIAL FINDINGS

The final section in these Analytical Results compares the traffic effect of SGD with the Circumstantial Findings (Section 5.1). The positive planning modelling for SGD has provided for full mitigation of the noise and visual amenity effects, leaving traffic as the only environmental effects of SGD. This subsection compares the modelled traffic effects of SGD against the extent of residential areas and the road coverage. For each pad density, Table

5.18 shows the results of correlation analysis between the accumulated distance travelled on local roads and the DToLR per unit of shale developed against the residential land use, road coverage and area beyond 1 km from an A-Road, within each block. As expected, there is a negative correlation between the traffic effect and the residential land use and road coverage. This correlation is relatively low for all pad densities. There is a positive correlation between the traffic effect and the area beyond 1 km of an A-road. It is also notable that the correlation strengthens as pad density increases. Whereas the correlation between traffic effect and the area beyond 1 km of an A-road is only 0.42 for 1-ppb, it is 0.88 for 30-ppb. This suggests that higher pad densities are more susceptible to the availability of access to A-roads. This variation is a reflection of the relative sizes of the respective development tracts (Section 4.9.2: 0.51km for 30-ppb compared to 4.441km for 1-ppb). Given a comparison between the correlation of area beyond 1km from an A-road (average = 0.718) against the correlation of traffic effect to residential land use (average = -0.4), the area beyond 1km from an A-road is more influential factor on the traffic effect. These statistics confirm the important influence of the area beyond 1 km from an A-road on the traffic effect of SGD, particularly as pad density increases.

Table 5.18: Correlation Between SGD Traffic Effect and Circumstantial Findings

Correlated factors	Pad Density	Residential Land use	A-Roads	Local Roads	Area Beyond 1km of an A-Road
Distance Travelled on Local Roads	1-ppb	-0.17	-0.28	-0.09	0.42
	2-ppb	-0.37	-0.51	-0.27	0.68
	4-ppb	-0.38	-0.57	-0.25	0.77
	10-ppb	-0.51	-0.66	-0.32	0.84
	30-ppb	-0.57	-0.72	-0.33	0.88
	Average	-0.4			0.718
DToLR per Shale Unit Area	1-ppb	-0.17	-0.28	-0.09	0.42
	2-ppb	-0.36	-0.51	-0.27	0.67
	4-ppb	-0.38	-0.57	-0.26	0.77
	10-ppb	-0.49	-0.67	-0.32	0.85
	30-ppb	-0.55	-0.73	-0.34	0.89

5.4 Results for Alternative Cumulative Assessment Criteria

This section presents the results on cumulative effects assessment of the dispersed energy. The modelling presented in the Methodology could be used to predict the potential cumulative effects of shale gas development. Table 5.17 shows the aggregate or accumulated effect of SGD traffic across the whole basin. However, within the UK planning system cumulative effects are only assessed to see whether effects arise out of adverse interactions of effects from multiple developments. This follows the Planning Inspectorate cumulative effects assessment guidance (PINS 2019). Cumulative effect assessment first considers whether an environmental effect is cumulatively significant. If found to be significant, consideration then turns to whether or not the effect can be mitigated. For each individual development the significant effects can be identified and weighed within the overall planning merits of the proposal. However, cumulative effects can potentially arise outside this system, where the effects of one development adversely interact with the effects of a second development. In the case of basin-wide shale gas development this might arise where the environmental effects from developing one pad adversely interact with the effects of a second pad.

The modelling is based on an adequate spatial separation of SGD sites from residential land use. There is a theoretical potential for noise from two nearby pads to overlap to create an adverse cumulative effect. However, the separation distance between pads, required to obtain access to the subsurface shale, means that such overlap and cumulative effect of noise is highly improbable. The potential noise and significant visual amenity cumulative effects of SGD are thus dealt with inherently within the positive plan model and by separation from residential property. Cumulative effects could arise from SGD traffic. The effect of SGD traffic was identified as a linear and unidirectional effect (see section 4.9.1). Since some SGD transport is using local roads to gain access to the A-road network it is possible that traffic from another pad in the vicinity could use the same road. The UK system of cumulative effects assessment requires a two-stage process to consider cumulative effects. Firstly, spatial overlap is considered and then whether a temporal interaction is possible (PINS 2019). This section considers the potential for cumulative effects of SGD traffic by firstly reporting the results as to whether any spatial cumulative effects arise and then considers the potential for temporal cumulative interaction.

5.4.1 SPATIAL IMPACT OF CUMULATIVE EFFECTS ASSESSMENT

Adverse cumulative effects could potentially arise where traffic from two or more pads needs to use the same road. This spatial overlap from traffic from two or more pads could potentially lead to the road's capacity being exceeded, even where individual pad traffic is managed to be with the road's capacity. This would constitute an adverse spatial cumulative effects of SGD traffic.

The case study spatial model has been used to identify locations where adverse cumulative effects of SGD traffic could arise. The results for spatially overlapping routes are given in Table 5.19, for each pad density. The separation between pads at 1 ppb, with one pad in each block, means that no cumulative effects can arise for SGD traffic for this density, given the road coverage. Potential cumulative effects arise at 2, 4, 10 and 30 ppb densities. These densities have higher numbers of pads within each 100 km^2 block and therefore a greater propensity for route overlap. This is likely to be greater in areas where there are fewer roads (e.g., in rural areas). To identify route overlap pads using a common road junctions on A-roads are first identified. Then the routes on the local roads network are checked for overlap. This shows the number of pads affected by overlapping routes and the distance of overlaps. The level of spatially overlapping routes for 2, 4 and 10ppb are relatively low. The proportion of overlapping routes for each of these densities are all below 8% and the aggregated distance below 50km. Given the aggregate length of local roads within the study blocks of 10,071.5km (Table 5.4) the cumulative effects of roads affected by SGD traffic for these densities is very low. For the 30ppb density, however, nearly two-thirds of all pad access routes use shared local roads. Since there are up to thirty pads in a block the need for access on local roads is spread throughout the block. In rural areas, with few or no A-roads (which produces longer transportation routes), this results in a concentration of SGD traffic onto the local roads. Thus, at this density considerable spatial overlap and adverse cumulative effects of SGD traffic are created.

Table 5.19: Spatial Cumulative Effects Assessment - Summary

	1ppb	2ppb	4ppb	10ppb	30ppb
Number of pads accessible via a Local road – (Table 5.12)	9	58	133	480	1,530
Number of pads affected by overlapping routes.	0	4	10	27	955
Percentage of pads using local roads affected by shared routes	0%	6.9%	7.5%	5.6%	62.4%
Aggregate distance of overlapping routes for all overlaps – km	0	8.1	33.0	46.4	4,560.7
Average length of shared routes - km	0	2.02	3.30	1.72	4.77
Maximum number of routes affecting any single road section	0	2	2	6	16
Number of overlapping routes from pads in different blocks.	0	0	0	0	33

5.4.2 TEMPORAL IMPACT OF CUMULATIVE EFFECTS ASSESSMENT

Having identified the potential for spatial cumulative effects the assessment process then requires consideration of temporal separation. The question is, where spatial overlap arises is temporal separation likely to occur or possible. If not, adverse cumulative effects do not arise. If spatial and temporal separation could not be achieved appropriate mitigation would be required, or the cumulative effect is unavoidable.

Table 5.19 showed that some spatial overlap arises particularly at the 30-ppb density. No spatial overlap arises for the 1-ppb density with very low overlap for the intermediate pad densities. The modelling has been developed on the basis that there is only one set of primary plant, drilling rig and hydraulic fracturing pump set, per block (see section F.1.2). Given that pad construction, drilling, hydraulic fracturing and remediation takes place in series at each pad across each bock, some degree of temporal separation is inherent within the system of modelling. Even where pads within a block share common parts of road routes the traffic will not necessarily arise at the same time. Consequently, within each block there is an inherent temporal separation of traffic. It is possible that traffic from different stages of development on pads within reasonable proximity could overlap temporally. This appear to be only possible with the 30-ppb density. Whether this applies in real world life depends on the developer and the planning authority. There is a choice to be made about the sequencing of pad development within each block. Assuming the developer and the planning authority are cognisant of the potential for cumulative traffic effects it should be possible to temporally separate traffic within a block. Thus, any cumulative effect of traffic within a block should be avoided.

The modelling here and the licensing are based on one developer being responsible for all pads with a block. This developer should be cognisant of the need to avoid overlapping traffic from different pads. However, adjoining blocks could have different developers. It is possible for overlapping routes, from pads in different blocks, to be used at the same time. Table 5.19 shows this situation arises on thirty-three occasions at the 30ppb density, for the whole basin. However, the process for identifying potential cumulative effects, as set out in the planning system, should be capable of distinguishing where cumulative effects might arise. The developer, in practice the second develop, and the planning authority would then need to take steps to avoid the cumulative effect by sequencing development to provide temporal separation. Where there are thirty-three pads using the same route, this may prove problematic. However, planning control could be applied to ensure that adequate temporal separation takes place to avoid overloading the capacity of the affected road.

Overall, the potential cumulative effect of SGD traffic, where development is taking place in the same vicinity, should be avoidable. The level of spatial separation is generally sufficient to avoid cumulative effects, particularly at mid and low pad densities. Significant spatial overlap only arises at the highest pad density, of 30ppb. However, appropriate measures can be taken by sequencing development to provide sufficient temporal separation to avoid any cumulative effects.

The modelling of a strategic planning process has shown that there is a slight possibility of cumulative effects arising in one of the alternate pad density scenarios studied. This demonstrates that the strategic planning process, of considering alternate scenarios of development, has shown that certain pad densities would be preferrable over others. Were the 30-ppb density to be adopted in a strategic plan, the plan would need to make provision to handle the possibility of the traffic cumulative effects. The potential issue is made explicit by the planning process and can be managed through the plan preparation process. A benefit of development planning process is that the potential for cumulative is clearer and can be provided for in the subsequent planning policies. Overall, the strategic planning process has shown that noise and visual amenity cumulative effects do not arise due to the separation between pads provided for in the planning process. The positive planning process, applied through the model, demonstrates that the dispersed energy plan can inherently handle any cumulative environmental effects.

5.5 Shale Gas Development, Pads, Environmental Effects and Planning Authorities

This section considers how the potential development of Bowland shale is spread amongst local planning authorities. Part of the raison d'etre of the thesis is to consider whether the decision system, which determine whether dispersed energy development takes place, influences the provision of dispersed energy and the consequent local environmental effects that might arise. Where energy development takes place across a large area or region issues could arise over the coordination of development decisions between authorities. Given the modelling of SGD across the Bowland basin, it is interesting to consider how many planning authorities would be involved in development decision making.

Table 5.20 gives the distribution of the shale unit, identified in the modelling, across the planning authorities which at present cover the Bowland basin. This is then compared with the number of planning authorities which are affected by pad final position, for each pad density. The planning authorities are ranked by the size of the area of the shale unit within their boundary. There is a high positive correlation between the modelling projection for the number of pads within a planning authorities' area and the extent of the shale unit. The increased granularity of pads at higher pad density increases the correlation.

The current system of decision making on shale gas development places responsibility for determining suitability of sites on the planning authority where pads are located. If development proceeded in accordance with the model findings, between 30 and 41 (dependent upon pad density), of the 44 planning authorities with shale below them, would be involved in decision making on shale gas developments. Between 4 and 15 planning authorities would have no formal role. These are likely to be smaller authorities or those that are predominantly urban. SGD developments may involve shale unit below the surface in their area but not require pads within their territory. Government guidance is intended to provide consistent application of national planning policies. With a large number of planning authorities involved in decision making on shale gas developments there is considerable scope for inconsistent or uncoordinated application of policy. The consequence of this are discussed further in chapter 6 discussion.

Table 5.20: Distribution of Pads across Planning Authorities

Planning Authority	Shale Area-km^2	% of Shale Area	1ppb	2ppb	4ppb	10ppb	30ppb
North Yorkshire County	2853.2	21.1%	11.5%	14.3%	14.4%	13.7%	14.0%
Lancashire County	1781.6	13.2%	14.6%	13.8%	14.7%	14.4%	14.7%
Nottinghamshire County	960.7	7.1%	8.3%	7.9%	7.9%	8.6%	8.4%
Cheshire East (B)	942.8	7.0%	7.3%	8.5%	8.4%	8.6%	8.1%
Cheshire West and Chester (B)	743.7	5.5%	6.3%	6.3%	5.8%	5.8%	5.8%
East Riding of Yorkshire	664	4.9%	6.3%	4.8%	5.0%	5.1%	4.7%
Derbyshire County	489.1	3.6%	2.1%	2.6%	2.9%	2.7%	2.5%
Doncaster District (B)	426.8	3.2%	4.2%	3.7%	4.2%	4.0%	4.1%
Sheffield District (B)	316.3	2.3%	1.0%	1.1%	0.8%	0.8%	0.9%
Barnsley District (B)	299.5	2.2%	3.1%	3.2%	3.1%	2.8%	3.0%
Rotherham District (B)	286.7	2.1%	3.1%	3.2%	3.1%	3.2%	3.1%
Wakefield District (B)	281.2	2.1%	3.1%	2.1%	2.6%	3.0%	2.7%
York (B)	272.2	2.0%	3.1%	2.6%	2.4%	3.0%	3.0%
Lincolnshire County	252.8	1.9%	2.1%	2.1%	1.8%	1.7%	1.7%
Wirral District (B)	226.2	1.7%	0.0%	0.0%	0.0%	0.1%	0.1%
Sefton District (B)	194.5	1.4%	1.0%	1.1%	0.8%	1.2%	1.0%
Wigan District (B)	188.3	1.4%	1.0%	2.1%	2.1%	2.0%	2.1%
Warrington (B)	182.5	1.3%	3.1%	2.1%	2.1%	2.0%	1.8%
Leeds District (B)	171.5	1.3%	2.1%	2.1%	1.6%	1.4%	1.6%
Bolton District (B)	139.9	1.0%	2.1%	1.6%	1.0%	1.3%	1.6%
Bradford District (B)	138.1	1.0%	2.1%	1.6%	1.6%	1.6%	1.6%
Blackburn with Darwen (B)	137.1	1.0%	2.1%	1.6%	1.3%	1.2%	1.4%
St. Helens District (B)	123.5	0.9%	1.0%	0.5%	1.0%	1.1%	1.3%
Kirklees District (B)	122.4	0.9%	1.0%	1.1%	0.5%	0.6%	0.7%
Manchester District (B)	115.7	0.9%	2.1%	1.6%	1.0%	1.2%	1.3%
Rochdale District (B)	107.3	0.8%	1.0%	1.6%	1.0%	1.0%	0.9%
Trafford District (B)	106.1	0.8%	1.0%	1.1%	1.3%	1.1%	1.0%
Sir y Fflint - Flintshire	105.1	0.8%	1.0%	0.5%	0.8%	0.8%	0.8%
Bury District (B)	99.5	0.7%	0.0%	0.5%	1.3%	1.0%	0.9%
Salford District (B)	97.3	0.7%	0.0%	1.1%	1.0%	1.3%	1.2%
Halton (B)	90.4	0.7%	0.0%	1.1%	1.0%	1.2%	0.9%
Tameside District (B)	83.5	0.6%	1.0%	0.5%	0.8%	0.8%	0.6%
Stockport District (B)	77.8	0.6%	1.0%	1.1%	0.8%	0.6%	0.8%
Wrecsam - Wrexham	76.6	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
Liverpool District (B)	63.7	0.5%	0.0%	0.0%	0.5%	0.3%	0.4%
Oldham District (B)	59.9	0.4%	0.0%	0.0%	0.0%	0.0%	0.1%
North Lincolnshire (B)	57.6	0.4%	0.0%	0.5%	0.3%	0.2%	0.4%
Knowsley District (B)	45.2	0.3%	1.0%	0.5%	0.3%	0.2%	0.2%
Blackpool (B)	43.2	0.3%	0.0%	0.0%	0.5%	0.4%	0.4%
Calderdale District (B)	23.7	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Leicestershire County	22.9	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%
City of Derby (B)	22	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Shropshire County	18	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%
City of Nottingham (B)	9.7	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Staffordshire County	5.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Number of PAs with Pads			30	34	36	37	41
Number of PAs with No Pads			15	11	9	8	4
Correlation of pads distribution to PA area.			0.897	0.951	0.951	0.94	0.945

Key: PA= planning authority. (B) = Borough.

Notes: Planning Authorities responsible for minerals, ranked by area of shale unit.

5.6 Summary of Findings and Results

The results from the case study modelling show there is a considerable difference in the accumulated local environmental effects arising at different pad densities. Under all pad densities adverse local environmental effects of noise and visual amenity are minimised or entirely avoided by imposing an appropriate separation distance between development and residential areas. However, were SGD to proceed at a density of 30 pads per 100km^2 block there is likely to be considerable accumulated local environmental effects from traffic. Whilst significant cumulative environmental effects of traffic can be avoided by temporal separation, substantial aggregate levels of traffic would arise on local roads. To some extent this traffic is dispersed throughout the basin, from the pads spread across the 96 blocks. However, Table 5.16 and 5.17 show there is a significant effect on local roads, with 7,389.6 million kilometres travelled by SGD traffic on local roads for a 30-ppb format of development. The local environmental effect of traffic from SGD is substantially lower at low pad densities. Having assessed the alternative forms of development represented by the different pad density scenarios, a strategic planning body would select the form of development which minimised or avoided the local environmental effects. Low pad densities offer technical and operational advantages. By concentrating development into a fewer but larger pads the number of local roads affected by SGD traffic is substantially reduced. In addition, lower pad densities, with their far larger development tracts, clearly offer greater opportunity for placement of pads next to A-roads, to reduce traffic intensity.

The modelling has shown that a strategic planning approach reduces, if not altogether avoids, adverse local environmental effects. Assuming this is replicated in other types of energy this has wide implications for the development of dispersed energy. As has been explained in the Context Chapter (3) and the Literature Review Chapter (2), there is a gap in practice and in academic scholarship between energy policy and planning. This is emphasised by the historic practice in planning of limited engagement with energy developments. In current practice local planning processes do not include planning for new energy developments in any meaningful way. The statutory planning authorities do not plan for dispersed energy at all, whilst the soft space entities provide regional energy strategies which tend towards vague statements of intention without provision at site specific or area level (Section 3.1.3). The results presented in this chapter demonstrate that it is possible to plan at least one type of dispersed energy – shale gas. Strategic or positive planning for dispersed energy at a supra-local or regional level can reduce the local environmental effects arising from dispersed energy development. Potentially the energy resources could be developed in an environmentally efficient or more effective way. The modelling here demonstrated that it is possible to assess the trade-off between efficient dispersed energy development and the consequent accumulated local environmental effects. Armed with this information and the options provided by different forms of dispersed energy it would be possible to strike an optimal balance between these. Essential to finding this optimal balance it is crucial that the technical and engineering aspect of the dispersed energy development are incorporated into the planning process. The thesis now turns to consider the research implications of these findings and results.

6. Discussion: How Best to Plan for Dispersed Energy?

The question posed at the start of the thesis asked whether we can plan for dispersed energy and, if so, how best. The context for this research is that the arrangements which have been in place for energy production in the UK are inappropriate for the transition to net-zero emissions. Instead, the energy transition requires an enduring shift to dispersed energy. These newer forms of energy production are either locationally tied to a resource or require a very extensive geographic coverage or both. Due the extensive geographical spread of dispersed energy, it seems likely this may adversely affect local environments. These effects are such that, in England and Wales at least, major forms of dispersed energy, such as onshore wind and onshore unconventional gas, have incurred problems of social acceptance (Section 2.2.3). Whilst dispersed energy has been developed in Scotland (where the population density is much lower) it is unclear whether this represents an optimal balance or trade-off between energy provision and local environmental effects. Despite the low population density social acceptance issues still arise (Save Our Hills 2021, Scotland Against Spin 2020).

The Literature Review and the Context Chapters showed that there is gap between energy policy and provision for dispersed energy by the planning system. Whilst the thesis has considered the UK context similar dispersed energy provisioning problems arise in other jurisdictions. UK energy policy sets laudable goals for the energy transition to net zero and indicates what type of dispersed energy should be financially subsidised. However, it does not identify where this development could geographically take place. Policy is aspatial. It also leaves issues related to the potential local environmental effects of the dispersed energy programme to the local planning system to deal with. However, the planning system appears to lack capacity to meet this requirement of providing for the cumulative effects of dispersed energy, at least in a conscious or considered or strategic way. Some of this role has been carried out by ‘soft space’ entities, through local energy strategies, but this planning for dispersed energy is largely spatially ambiguous and not site specific (Sections 2.1.1 and 3.1.3). There is no proactive identification of areas suitable for dispersed energy development.

As of 2021 in the UK, decisions over dispersed energy development proposals are largely being made on an ad hoc reactive piecemeal basis. While each proposal is weighed on its own merits there is no sign of a holistic planned approach, and little or no sign of a strategy which might provide comprehensive decision making. There is apparently no joined up thinking. This is surprising for a planning system that claims to be plan-led, that prides itself on applying positive planning approaches to meet societal requirements for land use and which is charged with undertaking sustainable development. The absence of positive planning for dispersed energy perhaps arises from a legacy of dependency on centralised control over energy allied with, in recent decades, a political culture against a positive local planning process. Nevertheless, there appears to a crucial void between energy policy and planning provision for dispersed energy. It is not clear we are making decisions on developing dispersed energy which minimises accumulative adverse local environmental effects or in any way strikes a balanced trade-off between dispersed development and local environmental effects.

This thesis examined this void by seeking a definitive answer to the question of whether or not it is possible to plan for dispersed energy, in a meaningful way. The research aim was set to develop and demonstrate the value of an analytical technique for guiding the spatial planning of dispersed energy facilities. This required the identification of the factors than need to be considered (RO1), the setting out of the principles of a spatial planning methodology (RO2), all based on the use of actual data (RO3). Rather than developing a plan for all dispersed energy, this has been investigated by attempting to prepare a plan for one particular type of dispersed energy. This planning process is undertaken by modelling a possible plan for the dispersed energy using the approach set out in the Chapter 4. This is in effect simulating the development decision process and seeking to define criteria that would be applied through a development plan. The quantitative findings for this modelling and plan preparation process are set out in Chapter 5. This demonstrates that a plan for dispersed energy can be prepared. It successfully demonstrated an analytical technique for guiding spatial planning for dispersed energy. There are no evident structural or systematic obstructions which prevent a plan being prepared for a type of dispersed energy. The constraint on its implementation appears to institutional willingness to adopt the positive planning approach.

This Discussion Chapter seeks to draw out the lessons from this plan preparations process and considers wider conclusions. It initially focuses on the lessons from the case study, then on the wider issues of preparing a positive plan for dispersed energy.

6.1 Lessons from the Case Study on Preparing a Plan for a Dispersed Energy

The case study sought to consider whether it is possible to plan for dispersed energy by modelling an exemplar for one type of energy in one region. This approach took account of the local environmental effects at two levels. Firstly, in ways similar to EIA scoping and identifying the key issues in planning, it identified which are the significant local environmental effects which would be likely determine decision making on the dispersed energy (Section 3.5). Three key effects were identified through analysis of recent planning experience: noise, visual amenity and traffic. For these three local environmental effects criteria were established for mitigating each effect. This forms the basis for preparing a strategic or positive plan for the dispersed energy concerned. The case study was applied to a regional scale development of shale gas energy in northern England, but this two-stage approach should be applicable to other dispersed energy types.

6.1.1 BROAD OBSERVATIONS FROM THE CASE STUDY ON PLANNING FOR DISPERSED ENERGY

The case study demonstrated that it is possible to develop a planning process that takes account of local environmental effects for one type of dispersed energy. This was applied at a supra-local level to develop a strategic or positive planning approach which seeks to avoid or minimise local environmental effects. This represents an important cardinal gain in the provisioning of dispersed energy. Since it is conceivable to plan positively for dispersed energy it is possible that the gap between energy policy and planning practice can be filled. Whilst apparently a simple observation, this finding has important implications for the wide body of research discussed in Section 2.2.2.

The case study has demonstrated that GIS modelling can be applied to directly take account of local environmental effects. Particularly relevant to RO3, this circumvented the problems of using effects generalisation and proxies (Harper 2019), although care needs to be taken when selecting the local environmental effects to be assessed. Whilst accounting for greenhouse gas emissions in regional energy planning is useful (Cormio 2003), the case study shows this analysis can be extended to consider local environmental effects. This planning would need to take account of the spatial and temporal needs comprehensively. Whilst not included in the case study it is reasonable to assume that a strategic planning approach could take account of energy transportation needs and thereby avoid wasteful curtailment of poorly connected regions (Joos & Staffel 2018). The positive planning process could also take account of the local environmental effects of developing transmission infrastructure and provide a balanced choice to the development of a dispersed energy resource. Overall, the approach applied in the case study confirmed Steingrimsson et al (2008) and Hreinsson (2008), that a strategic approach identifies areas suitable for development and finds locations for development which best suit technical and environmental circumstances.

The literature review identified a research gap between the two stools of energy policy and planning. Wolsink (2007) had similarly identified the important separation of the ‘two domains’ of spatial planning and energy policy (Section 2.2.2). He observes that without an effective means of finding sites for dispersed energy “the success rate of national efforts in establishing renewable energy capacity” will be seriously reduced (Wolsink 2007, p2692). In other words, the non-alignment of spatial planning and energy policy domains has grave consequences for delivery of dispersed energy and the energy transition. The UK government policies on energy, which can be characterised as ‘top down’, do not assure local development consents.

Wolsink’s answer, to filling this void between the two domains, is collaborative planning (Healey 2003). He states “the best way to facilitate the development of appropriate wind farms is to build institutional capital … with collaborative approaches“ (Wolsink 2007, p2702). He is implicitly indicating that the challenge of social acceptance, known as the social gap, arises from poor institutional arrangements. To Wolsink these arrangements fail to take account of public views. However, with respect to Wolsink’s eminent work, I suggest he gives insufficient weight to what ‘appropriate’ dispersed energy (wind farms for Wolsink) might mean. Wolsink does not identify ways to provide suitable mitigation which address local residents' concerns, other than allowing them a voice. He suggests institutional arrangement which might bring social concerns to the fore, presumably so that these social concerns could be avoided. The case study research here gives the plan preparation process much greater focus. It shows positive local planning for dispersed energy should be capable of mitigating or avoiding local environmental effects upon local receptors. Rather than seeking public views on poorly sited proposals it would be wiser to plan positively to avoid receptor impact. Instead of siting development, metaphorically in someone's back yard, it would be more appropriate to locate dispersed energy beyond receptors' effects buffer.

The conclusion here raises the imperative that the first stage should be to plan to avoid adverse receptor effects. This is a top-down approach which extends to takes account of local environmental effects. Importantly, it bridges top-down goals at the policy level with a strategic planning examination and resolution of environmental effects at the local level. This is a significant contrast to ad hoc piecemeal siting of proposals and then seeking receptors views, collaboratively or otherwise, on whether or not the proposals are socially acceptable. The failing of institutional arrangements may not, as Hettinga (2018) and Wolsink (2007) suggest, only be in public collaboration. Social acceptance and institutional failures may arise because planning has been purely reactive to developer-identified sites. In the UK, at least, it is clear that inappropriately sited proposals are being put forward and subsequently debated (Harper et al 2019, p955, Scotland Against Spin 2020)

As the Context chapter showed, there has been little positive planning for dispersed energy in the UK (Sections 3.1.2 and 3.2). It has really only been applied offshore (Section 3.3) where, of course, the need for social acceptance is largely avoided. The case study findings show that the crucial institutional weakness can be addressed by positive strategic local planning.

6.1.2 THE CASE STUDY'S IMPLICATIONS FOR SHALE GAS DEVELOPMENT LITERATURE

This subsection discusses the implication of the case study findings and methodology for the UK based literature on shale gas development (covered in Section 2.3.3) and then considers the implication for international literature (covered in Section 2.3.2). By early 2021, only five published papers have considered the local environmental effects of shale gas development for the UK in depth. Clancy et al (2018) and Worral et al (2017) considered surface environmental footprint, focusing on setback and the adequacy of environmental buffers.

Goodman et al (2016) considered traffic. Cooper et al (2014, 2016) considered social sustainability through environmental and economic factors. Burbridge and Adams (2020) assessed social and environmental impact from an energy justice perspective. The Clancy and Worral teams found potential gas volumes would be reduced due to setback requirements; Goodman predicted notional aggregate traffic effects; and Cooper et al suggest that environmental issues with SGD "can be mitigated" (2016, p16), particularly in long term strategy; while Burbridge & Adam's (2020) findings were largely inclusive.

Two central criticisms of these UK based studies were set out in the Literature Review. All four research groups have based their assessment of the likely level of activity required to develop a UK shale basin on assumptions or externally derived estimates. None of these studies examined the engineering / technical element of SGD; a crucial omission given the importance of rapidly innovating petroleum engineering in mitigating the effects of the development process. The constraining assumptions, particularly on the activity levels (aka. pad density) limit the value of the published research. This thesis has shown that it is possible to incorporate the technical engineering elements of SGD to gain better estimates of the amount of surface development needed to access the estimated in situ gas. Importantly, adding this element to the research here, facilitated an understanding of alternate possible scenarios for shale gas development, defining different levels of surface activity which could be achieved through feasible engineering technology. The case study here applied five densities of pad coverage and separation, reflecting a range of petroleum engineering development approaches. The findings (Section 5.3) demonstrate that these alternative densities have a substantial impact on the scale of environmental effects arising from shale gas development: in particular that when pad density is lower, facilitated by extended reach drilling that is technically possible, environmental effects are reduced significantly.

The estimated activity level applied by the other early research groups was equivalent to pad densities of 33ppb [4] (Cooper et al 2018), 44ppb (Goodman et al 2016), and 100ppb (Clancy et al 2018). It is obvious by comparison to the findings here that such a large pad density need not be deployed (the highest pad density considered was 30ppb), so there must be doubt

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[4] Caution should be applied to this figure. Whilst Cooper et al refer to 4,000 wells for the Bowland shale, this is observation based on Ernst & Young (2014) and Taylor (2013). The implied pad density is unclear. They refer to laterals of 1.5km in length, without stating the width of the fracture zone or area covered, and to an average 6 wells per pad. If the fracture zone width applied in the thesis is applied (333m) then the area per well is 0.5km2 implying 200 wells pe 100km2 block. At 6 wells per pad this implies 33.3 pads per block.

over the scale of the impacts predicted by the early published research. The later study by Burbridge and Adams (2020) using 10ppb is more in line with the level of activity assessed in this thesis. Their study found that “proximity to wells” is a factor for environmental risk (Burbridge and Adams 2020, p508).

While it is technically feasible to employ extended reach drilling (at 1 ppb density), this may incur costs for the operator. Economics are relevant to how an area is developed and a trade-off will likely be taken by operators in balancing construction costs verses environmental costs and the costs of gaining a ‘social licence’. The planning authority will also give consideration to this when it assesses the planning balance in a positive planning approach to SGD as well as in the adjudication of the merits of individual development proposals. Nevertheless, the case study scenarios of 2ppb, 4ppb and even 10 ppb demonstrate that, even without extensive extended reach drilling, there are viable development approaches which substantially reduce the local environmental effects from SGD.

The research method adopted in this thesis offers other merits which go beyond previous research. Cooper et al, in their studies, prepared a life cycle economic viability assessment. Whilst adjudged on ‘social sustainability’ this does not consider environmental effects meaningfully. The Context exposed the decisive influence of traffic effect in recent planning judgements (Section 3.5) while the Literature Review highlighted the importance of research on traffic on the UK road network. Goodman (2016) considered this for the UK, basing their method on Banerjee (2012). Similar to Banerjee, this thesis computed ‘vehicle mile travelled’. This measure enables comparison of the effect under different development scenarios and comparison of the incidence of the effect between different types of locations (rural/ urban/ semi-urban) and different road densities. Goodman’s study estimated the road pavement damage arising from SGD on a notional road network. Here the traffic effect was reviewed from the perspective of environmental disturbance to residents and other road users together with roads’ design capacity. The methodology deployed in the case study here applied a real-world road network, for the shale basin, rather than Goodman’s theoretical network. Findings in regard to the actual road network are considerably more meaningful, than a notional network, to any planning authority which deals with real places. Whilst the roads shown to be affected in the modelling here may not be the roads affected in real world SGD (because pad locations may differ), the modelling can be used to indicate the types of locations most vulnerable to the effect and the potential level of effect. This is far more meaningful than Goodman’s findings. With enhanced data on residential property, pedestrian, cycling and other traffic activity the modelling here could be refined to highlight areas of greatest conflict with SGD traffic. This is a far more useful decision tool that Goodman’s notional network.

The prime conclusion of Clancy et al (2018) and Clancy & Worral (2017) was that, in their view, the resource estimates have not taken due account of surface restrictions. They argue environmental footprints are limited due to proximity to receptors and set back requirements. The case study here concurs with their observation that there will be restrictions due to setbacks or buffer zones around sensitive locations. However, the study here has shown that by positive planning, these restrictions can be contended with and minimised. The flexing of development siting, in line with Milt and Armsworth (2016), enables the impact of restrictions to be substantially reduced. In the case of lower density using extended reach drilling, surface restrictions barely inhibit SGD: in fact, almost all of the basin can be accessed without restriction. However, the preeminent value of the current research over the Clancy / Worrall assessment is the recognition that a planning process could be used to influence the development format. Rather than viewing assessment as a static process of measuring effects, by including the opportunity of strategic plan-making the expected effects can be mitigated. The study here demonstrates that environmental effects can be minimised or even avoided (e.g., no traffic ending up on local roads or no residential receptor noise effect) whilst footprint restrictions are largely circumvented, by a strategic planning process that takes into account advanced subsurface technology.

The international literature has a broader perspective with several themes. The review of international literature opened with Adgate et al (2014), who identifies rings of potential effects of SGD. The findings here concur with Adgate et al’s assessment that effects can be grouped into radial zones around pads. The study here adds refinement to those observations with greater detail on the most significant environmental effects in the UK context. This study also highlighted that traffic has a linear and unidirectional effects rather than being amorphously spread throughout the full extent of the ‘local area’. In part this arises in the UK due to planning regulation and this restraint may not apply globally. The study here contributes to Adgate’s call for further research, particularly addressing the “process uncertainty” of location and extent of SGD (ibid, 8315). Several US studies have sought to model SGD effects particularly on impacts on water resources, forestry and wild areas. The emphasis of many of these studies can be categorised as cumulative effects or effects which are not, at present, adequately considered. The findings of this study, in relation to cumulative effects, are discussed below (Section 6.1.5).

Several international studies have used GIS-based analysis to model environmental effects (e.g., Davies & Robinson 2012, Meng 2015, Slonecker and Milheim 2015, Evans & Kiesecker 2014). Other groups considered the economic efficiency and optimisation of shale gas development across an area (e.g. Gupta 2012, Mauter et al 2013, Cafaro & Grossmann 2014, Bartholemew & Mauter 2016, Gao & You 2017, Gonzales et al 2018, Ondeck et al 2019). This case study has built upon these international studies in important ways. As well as applying GIS analysis, the research here has used direct effects rather than surrogates or proxies. Rather than applying imprecisely located generic population data the study here mapped buffer zones around identified residential areas. Rather than using formulaic interpretation of environmental effects, such as spatial rings and spatial footprints, quantification of direct effects have been investigated. The case study built on Cafaro & Grossmann's (2014) multi-well concept and enhanced this to create alternative pad density scenarios. It provided the regional environmental impact analysis and cumulative effects mitigation envisaged by Mauter et al (2013). The case study not only assessed the collective impact of multiple projects, it demonstrated that the strategic management of these effects, called for by Rahm & Riha (2012), is beneficial. The research method developed and applied in the case study here could be applied to the US requirement to manage various cumulative effects of SGD, such as on forestry and water resources. The case study here successfully applied Arredondo-Ramirez et al's (2016) strategic planning approach to the minimising of environmental effects of SGD.

Special emphasis was given in the Literature Review to the merits of the technique applied by Milt and Armsworth (2016) in seeking spatial optimisation of pad siting across a region. Like this thesis, their aim was to minimise local environmental effects. Milt and Armsworth's and this study differed in the effects considered, reflecting the different environmental priorities of the studied locations. The thesis here appears to be unique amongst nearly all published research by incorporating petroleum engineering technology into the analysis. A notable difference between Milt and Armsworth's and this study is inclusion of a decision system for SGD. Milt and Armsworth produced an effects assessment process methodology for quantifying site level environmental costs applicable across a shale basin. They finalised pad locations based on a shuffling algorithm which balanced resource access and environmental costs. Here I adopted a planning approach by identifying sites which meet appropriate local environmental criteria. This involved a technique of directly calculating optimal pad positions which recognised surface constraints, subsurface disposition and the technical engineering capacity to bridge the two. The opportunity for this approach, not available to Milt and Armsworth in the US, arises because of the UK's distinct discretionary planning system. Milt and Armsworth's assessment can only be deployed through advocacy for what is possible. In the UK, however, the planning system (if it is deployed effectively for dispersed energy) enables pad location optimisation, maximising resource development whilst minimising environmental cost, to be implemented through a prescriptive local plan. The development plan could identify areas suitable for SGD, or other forms of dispersed energy, and can lay down the criteria that need to be met before development approval.

6.1.3 STRENGTHS AND WEAKNESS OF THE CASE STUDY PLANNING PROCESS

This subsection considers the strengths and weakness of the planning process applied to shale gas in the case study. Initially the weaknesses and limitations of the case study are discussed. The first and most significant weakness of the case study planning process is the limitation provided by the lack of subsurface data. The model assumed the shale is homogeneous with no account being made for the variability of the shale thickness, depth, angle, faulting, porosity and variation in total organic carbon (TOC). At the current time details on the spatial distribution of the shale unit and its physical properties are very bounded. Andrews (2013) has identified the likely extent, depth, porosity and potential TOC. This data was simplified in the study to reduce research complexity. In practice full details on the potential distribution, technical challenges, such as faults, and value of gas within the shale will only arise when exploratory drilling takes place across the shale unit. A real-world planning process would seek additional detailed data of the resource to improve on the sophistication of the plan. In addition, the economics of shale maybe marginal, if the gas price drops too low the scope for development may reduce.

In terms of the research value of the case study exercise, it is likely that whilst some forms of dispersed energy will have reliable comprehensive data on the resource others will not. The onshore wind and solar resources are largely well understood or understandable with a relatively small investment in site characterisation, for example to record wind speed. Conversely geological resources will always require high capital cost exploratory drilling to establish the volume and optimal production strategies. In the case of newer geological resources such as subsurface energy storage or low enthalpy geothermal, these require much further research to understand how to optimise resource recovery. Any generic planning process for dispersed energy will be required to adapt and take account of this varying level of uncertainty. They could do this by estimating probability of the resource in-place (e.g., high-medium-low estimates).

The case study analysis has also been limited to the few surface factors which have been modelled. This was restricted to existing residential areas, the roads network and administratively restricted areas. This does not take account of other surface features such as watercourses, railways, motorways and local access roads, industrial commercial & other land use, planned future development and other local restrictions. With sufficient time and data these could be added to the planning process reasonably easily. These exclusions might mean, for example, that access tracks do not cross reasonably sized watercourses or pass-through protected woodland. The siting of pads might be excluded from certain types of land use, such as green belt, or zoned future development areas. Seismicity could be incorporated into the planning criteria once the extent of the effects is understood. The case study also did not take into account all possible engineering elements, such as export gas pipelines, fresh water supply and wastewater transportation. These are not short comings in the potential planning process for dispersed energy, merely simplifications for research purposes.

Overall, the case study planning process is seen to have demonstrated significant research value. It has fulfilled the research aim of developing and demonstrating the value of an analytical technique for guiding spatial planning of dispersed energy facilities. It has established the principles of spatial planning methodology for the coherent development of dispersed energy (RO2). The case study modelling has been applied to actual data on receptors, effects and local characteristics such as the real-world road network, reinforcing the potential of RO3. While it would need to be extended for other energy vectors, the case study has identified the factors that need to be considered in dispersed energy spatial planning, in partial fulfilment of RO1. In particular it has shown that there is considerable merit in combining the technical resource exploitation process (in the case study petroleum engineering) with consideration of local environmental effects. Importantly, this integrated combination provides a pathway to reducing accumulated local environmental effects.

The modelling has shown that it is possible to take account of local environmental effects and to largely mitigate or avoid these through a positive planning process. The modelling showed that the identified effects of noise and visual amenity can be reduced to the point where the environmental effect becomes insignificant to receptors. While the effect of traffic cannot be entirely avoided, it can be substantially reduced in significance by a positive strategic planning approach. The key to reducing traffic effects is in sensitive siting of pads following the planning criteria evolved in the modelling.

Particular standards of noise thresholds were developed and applied in the modelling leading to finite setback distances. In a more sophisticated planning exercise these setback distances could be adjusted to be more refined: for example, to take account of the expected duration of noise, tree cover and topography to reduce noise and/or visual impact. Nevertheless, the methodological principle of these setback standards demonstrates there is a viable approach to planning for shale gas development. Taking account of these and the other factors which determine pad location, such as the resource distribution and the technical requirement for exploitation, leads to the resource being developed in ways which minimise local environmental effects. Applying this approach across the basin provides greater consistency in minimising effects throughout the region whilst optimising the energy value. There is therefore value in positive planning process using a wide spatial coverage and a strategic approach to decide the location of the shale gas development activity. As well as reducing overall accumulated local environmental effects, it provides a level of consistency which cannot be assured by piecemeal, project by project, decision making.

An important benefit of a positive planning approach for SGD arises from the consideration of alternative forms or scale of development. The modelling considered five different densities of pad coverage. These represent different approaches to planning for SGD development. Or different strategies. Consideration of these alternatives demonstrate that different local environmental effects arise with different scenarios. Having identified these alternatives the subsequent planning-making decisions can select which of the alternate strategies is more desirable, which is more likely to result in lower environmental effects. This may involve blending alternatives. At the lowest pad density, at one pad per one hundred square kilometres, the petroleum engineering is particularly challenging with bores stretching out up to 14.5 km. The environmental planning decision making needs to take into account the technological capability as well as the economics of the resource exploitation. However, if the benefit of low pad density is a social license that may encourage developer to bear the increased cost. Concentrated operations may improve economic viability by improving returns on permanent infrastructure (e.g., pipelines) and measures to ameliorate environmental effects (e.g., tree planting for screening or permanent sound baffles for noise).

The modelling of the different pad densities could be further refined. The modelling assumed that noise becomes insignificant at a fixed distance from the pad. In reality the position of insignificance steadily declines over distance rather than one fixed radius. Residents situated just beyond the setback distance may find that over time the persistence of noise becomes a burden. The modelling could be refined to take account of this. Beyond the radial distance of noise insignificance, further zones might be calculated taking account of both the noise level and the noise duration, as well as the potential barrier such as tree planting to mitigate noise effects. The pads which operate for a few months, for higher pad densities, may be found less detrimental than pads which require to operate for several years. Whilst these overall refinements have not been applied in the current case study the research has shown that the sophistication of the modelling can be refined and improved to suit the circumstances of each type of dispersed energy.

6.1.4 WHO PREPARES THE PLAN AND THE CONSEQUENCE OF CURRENT LOCAL PLANNING AUTHORITIES COVER

An important part of the research question is how can we plan for dispersed energy. This was based on the presumption that outcome of the first part of the research question was positive: that we can plan for dispersed energy. The confirmation that it is possible to plan for dispersed energy leads on to the question of what institutional arrangements are required to be able to plan for dispersed energy? At this point it useful to consider the specific lessons from the case study. What are the institutional arrangements which apply in the case study area in the Bowland basin?

The research found that some forty-four local planning authorities hold parts of the Bowland shale unit within their territorial boundaries. Twenty authorities that have shale underlying them, nearly half, collectively hold less than 10% of the overall shale unit. By contrast, twelve planning authorities account for 75% of the shale unit. For twenty-two authorities more than two thirds of their area is occupied by shale. This analysis of the shale unit coincidence with local planning authority areas shows considerable variation in cover. From the authority perspective the area of shale unit varies from covering 100% of the authority area to just 0.2%. From the resource perspective the authority with the smallest shale area has 0.2% of the resource whilst the authority with the greatest shale area has 21% of the resource. This highlights that the planning authorities' interest in developing the resource is likely to vary substantially.

Given this statistical spread of shale coverage (Table 5.20) it seems likely that the focus of planning authorities on shale is likely to vary in importance. Under some scenarios, particularly at lower densities, many planning authorities might not need to accommodate any SGD pads within their boundaries. The shale unit below some authorities could be accessed from adjoining authority's areas. Under a development control-based, purely project by project, system of decision making, these local planning authorities would not be directly involved in any decision making on proposals.

The number of planning authorities involved in making decisions on the development of the resource suggest that there is a high potentiality for inconsistency in decision making. This would be likely to increase with a project-by-project approach to decision making. Whilst planning authorities have a 'duty to cooperate' (PAS 2020) organising this collaboration appears challenging, even where it is being undertaken by professional officers with a common professional background. The real-world practice, set out in section 3.5, also confirms there is considerable potential for inconsistency, as authorities made different choices despite the common planning merits. The case study findings thus highlight one of the key challenges of deciding how dispersed energy can be planned. An agreed common strategy would seek to apply common criteria to decision making throughout the basin. It could involve all authorities even including authorities where pads siting is not required, especially if traffic requires to be routed through their local area.

6.1.5 DOES A STRATEGIC PLANNING APPROACH REMOVE THE NEED FOR CUMULATIVE EFFECTS ASSESSMENT

The Literature Review (Chapter 2) has shown that cumulative effects assessment (CEA) is an important issue in academic research (Section 2.1.2). The Review highlighted the difference between North America and the EU/UK approaches to CEA. In North America, where there are extensive natural valued ecosystems and no discretionary planning system, Cumulative Environmental Assessment and Management (CEAM) and Adaptive Management (AM) have been evolved by scholars. Whereas in Europe and particularly the UK, where the emphasis arises due to effects interaction with the local population, the planning system appears to meet the needs dealt with by CEAM and Adaptive Management (Section 2.1.2).

The research case study here has confirmed this. It has shown the cumulative effects are reduced or even eliminated when a strategic planning approach to shale gas development is applied. Assuming, of course, that these effects have been considered within the planning process. The potential noise and visual amenity effects of shale gas development were mitigated by applying a consistent planning parameter: deploying an adequate buffer area around receptors. This type of broad strategic application is intrinsic within the development planning process. For traffic, cumulative effects only arose in a few locations when development was undertaken at high densities. Even then, the cumulative aggregate effects of overlapping traffic on a few local roads could be avoided by temporal separation. This limited spatial overlap could be avoided entirely by applying a lower density alternative for development.

It needs to be stressed, however, that this intrinsic handling of cumulative effects is only valid where the planning approach applied is holistic positive ‘development planning’. There is no assurance that cumulative effects are handled appropriately, or effects avoided, where decision making is on a piecemeal ‘development control’ basis. This confirms the issue of cumulative effects arising in a project-by-project decision system (Cocklin et al 1992, Spaling & Smit 1993, Canter et al 2010, Spaling et al 2000). The history of decision making on shale gas development, from 2014 to 2019 (Section 3.5), has been carried out in a shale gas development planning vacuum. Without an appropriate prior development planning process being applied cumulative effects may arise. Importantly, the research has therefore confirmed the value of a positive planning approach as it successfully handles cumulative environmental effects to inherently mitigate potential cumulative effects of project-based decision making. This research observation reaffirms Spalling and Smits findings that cumulative effects are more appropriately considered utilising “planning principles and procedures” (Spaling & Smit 1993, p593).

The Literature Review also identified that in the UK and European context environmental assessment was an ‘information provider’ and ‘decision support tool’ (Spaling & Smit 1993, Bragagnolo & Geneletti 2012). Cooper and Sheate (2004) proposed that Strategic Environmental Assessment (SEA) was an appropriate venue for consideration of cumulative effects. They claim cumulative effects arise at different scales and that these effects arise beyond the project level. The Literature Review cast some doubt over this, due to SEA not really encompassing a complete or thorough planning process. The research here confirms that cumulative effects are better considered within a comprehensive strategic planning process, rather than on SEA’s partial policy evaluation basis, because of differences in the scope and treatment of environmental information. SEA has limited scope. When environmental assessment provides ‘information’ or is a ‘decision support tool’ it is not necessarily incorporated into policy decisions. And even if it is, this assumes a simple binary information-decision model: that information in assessment is comprehensive and complete. It also assumes that decisions fully rest on the information provided. Neither of these assumptions are reliable. The research findings here suggest environmental assessment should not merely be a ‘support tool’. It should be an integral component within the planning process.

As Piper (2016) observed, CEA is far more effective where it is part of a strategic planning process. This partly arises because strategic planning offers greater flexibility in determining suitable development locations (Ref. Piper 2016). The case study here has shown strong evidence that a strategic planning process obviates the need for a separate cumulative effect assessment. This is essentially because strategic planning inherently takes account of cumulative effects, or rather accumulated effects. Due to the supra-local or regional scale, which operates well above the level of individual project-based decision making, these potential accumulated and aggregate effects are fully accounted for. The accumulated effects are evaluated within, rather than outside, the realm of the planning process. Within the UK planning system any failure to adequately address cumulative effects is likely to arise, not because of problems with the limitation of environmental assessment, but because strategic planning is not taking place. This research confirms a need to prepare strategic plans for dispersed energy, rather than attempting to compensate for the shortcomings of project-based decision making with cumulative effects assessment.

6.2 Planning for Dispersed Energy

This section of the Discussion Chapter now moves beyond the case study findings to consider the wider perspective on planning for dispersed energy. As set out earlier, in Sections 5.7 and 6.1, the case study has demonstrated that it is possible to plan for dispersed energy. Adopting a positive or strategic planning approach enables local environmental effects to be judiciously addressed. This approach deals with cumulative environmental effects (Section 6.1.5) much more effectively than project-based decision-making. The discussion on the case study lessons also suggested that before collaborative planning is applied due care should be taken to plan positively so that dispersed energy could be sited away from receptors (Section 6.1.1). It is notable that the one dispersed energy type which has seen successful deployment of a strategic planning approach, offshore wind energy, has been delivered by a single central controlling agency (Crown Estates)(Section 3.3).

6.2.1 REVIEWING THE CURRENT SYSTEM OF STRATEGIC PLANNING

The Literature Review and Context Chapters both included notable insights regarding the institutional arrangement for planning for dispersed energy onshore in the UK. Before moving into detail discussion on the potential for planning for dispersed energy it is worth drawing out the salient points pertinent to a discussion on the institutional arrangements for dispersed energy.

The Context Chapter highlighted the two complimentary sides of the UK's planning system of 'development planning' and 'development control' (Section 3.2.1). Development planning sets out how or where development should take place. Development control decides on whether permission should be given for individual development proposals, or projects, based on the development plan for the area. Whilst these two components of the planning system have remained in place since the post-war introduction of the modern planning system, the development planning side has undergone most change. The Literature Review detailed how the development planning side had been changed following successive changes in government in the last few decades (Section 2.1.1). Regional spatial strategies have been done away with and regional governmental institutions largely dissolved. The aim was to sustain a development planning activity which was more closely integrated with other government programmes and policy delivery (Baker et al 2010). This would appear to suggest that development planning should be aligned with national policy goals. For example, on the delivery of dispersed energy.

The reforms of the planning system in the last decade, however, have attenuated the development planning system. This has taken place by general and specific reform. Positive spatial planning has been reduced to Local and Neighbourhood planning, in part to provide for Localism. Higher level Structure Plans and formal strategic planning, including regional planning, have been removed. In England and Wales, specific reforms have required onshore wind energy development to demonstrate local social acceptance. In place of the upper-level development planning two key instruments have arrived. Firstly, to fill the void of supra-local planning a statutory ‘duty to cooperate’ has been laid down. Local planning authorities are required to participate, or ‘cooperate’, with other authorities in their area to address shared common problems. Bridging both spatial planning and other policy fields ‘soft spaces’ have developed where authorities and agencies come together informally to address common challenges. Allmendinger et al suggests these ad hoc clusters, to a degree, fill the void between policy goal orientated central government and statutory local planning activity (2013, 2016).

The question that needs to be discussed is whether these soft space clusters and the duty to cooperate can fill the vacuum between the two stools of energy policy and planning, for dispersed energy (see Sections 1.3, 1.4, 2.2 and 3.1). The long-term background is that planning for energy development has not been a priority for local authorities. In part this is because of the historic centralised provision of energy production concentrated is a few locations. This has not required significant change for four decades. In part the separation arises because energy policy has been consciously conducted beyond the local planning system. The issues of social acceptance arise where institutional arrangements mean there is little to no meaningful planning of dispersed energy: no governmental identification of areas suitable for, for example, wind energy. In this vacuum, developers are left to find and appraise sites, and then assessing impacts on a project-by-project basis.

6.2.2 GENERAL REQUIREMENT FOR PLANNING FOR DISPERSED ENERGY

The case study has applied a planning process to contend with local environmental effects for shale gas development of a large area of Northern England. The case study therefore demonstrates the viability of a regional planning approach for dispersed energy. As well as considering surface constraints and local environmental effects the planning process also took account of the distribution of the resource and the technical engineering required to exploit the resource. Whilst the transportation of the energy was not explicitly examined in the case study it should be expected that, due to the extensive gas network in the UK, this would not be an obstacle to development. In other parts of the world, where the gas distribution network might not be so well developed, or for new technologies where there no distribution network yet exists, for example district heat networks for geothermal energy, this would have to be explicitly factored into the modelling. The strengths and weakness of this planning process are outlined above in section 6.1.3. I can now derive from the case study what the essential elements of a plan for dispersed energy require. The key components of a plan for dispersed energy are summarised, before moving on to consider whether the institutional arrangements are in place to develop this plan.

This thesis deduces that the ‘methodology technique for a coherent dispersed energy development system’ (RO2) should consist of an 11-step planning process or principles, as follows:

1. **Resource appraisal**: The spatial distribution of the resource needs to be identified and understood. For shale gas this is indicated by the Andrews study for the Bowland basin (2013) and would become further refined through exploration, appraisal and production activities. For other geological-based resources, such as geothermal energy and compressed air storage (CAS), data on UK onshore resources are available through BGS mapping, although this requires further refinement (Stephenson et al 2019). For example, it is known that the Cheshire salt mines provide an opportunity for CAS. Data is also available for surface resources. For onshore wind comprehensive data exists (ETSU 1999, Global Wind Atlas 2020). The resource data for solar is straightforward (Global Solar Atlas 2020). The opportunity for carbon capture and storage is largely in existing expired hydrocarbon fields or in saline aquifers. Other nascent technologies, or development in countries that do not have comprehensive datasets available, may require new data at the resource appraisal stage (Hill et al 2021).

2. **Technical limitations and development**: Each resource has its own specific engineering or technical requirement for exploitation. The planning process needs to identify the technical requirement of each exploitation process, and the likely environmental and social impacts that arise from these. For example, for onshore wind this needs turbines to be constructed, vehicle access roads, perhaps over high ground, and local road use for transportation, as well as access to the electricity transmission system. The technical requirement for solar energy appears straightforward. For some other dispersed energy types, such as geological resources, the exploitation technologies may be complex, or yet to be developed fully. Care needs also to be taken to ensure that future developments in technology are incorporated. For instance, work on offshore wind has focussed on reducing the number of maintenance visits and the potential for floating turbines (accessing resources beyond 60m sea depth). If this technology is deployed in onshore wind, then the ongoing requirement for maintenance traffic may well reduce through time. Applying outdated or inappropriate technology assumptions can result in unrealistically inflated estimates of impact, as discussed in Bond et al (2014).
3. **Demand:** quantify the demand spatially and temporally, including diurnal and seasonal fluctuation, taking account of the energy vectors required, their relative efficiencies in relation to their ultimate purpose and likely future changes.
4. **Transport:** the requirement for transport of the energy produced, such as transmission to consumers, needs to be understood. The location and capacity of the extant infrastructure needs to be identified in order that the requirement for additional plant can be included within the planning process. Some transportation requirements might be simple whereas others may be complex. In part this is dependent upon the scale, extent and location of the energy development. For example, wind power energy developments in Northern Scotland requires far longer transmission lines than in the Thames estuary.
5. **Effects identification**: The general environmental effects need to be assessed in order to identify the key influential effects. This includes identification of potential human and environmental receptors. For some dispersed energy technologies these may be

very light and insignificant. For others, such as onshore wind, these may be significant but should be straightforward to distinguish.

6. **Receptors:** The disposition of receptors needs to be understood in detail, based on the effects distinguished at stage 4. The effect-pathway-receptor model needs to be established. For some technologies, such as onshore wind, this may simply involve landscape assessment, predicting noise and shadow flicker. For other technologies, such as seismicity from shale gas development, the pathways may be very complex and uncertain.
7. **Other restrictions:** General development restrictions need to be included. These may vary between jurisdictions. These might include administrative restrictions, such as exclusion of certain energy types from National Parks. Some restriction might apply to public safety and potential environmental risks. Others may be more high-level intangible choices, for the planning agent. An example of this is limiting offshore wind development in valuable fish stock areas.
8. **Effects assessment**: The local environmental effects need to be assessed in detail to identify the impact on receptors. This stage might consist of selecting adequate separation levels required to clear receptors. The end of this stage should establish environmentally significant effects, spatially and temporally.
9. **Spatial projection:** The resource, technical requirement, transport, significant effects, receptor and other restrictions need to be brought together in a spatial model. By situating and sieving each element this should combine to identify locations where development can occur, the consequent zone of local environmental effects and areas where receptor impact inhibit development. In the case study these were provided by combining development tracts and developable zones. The spatial modelling needs to take account of energy transportation and recognise the potential scale or accumulation of development.
10. **Options evaluation:** Having identified resource development areas, effects zones and receptors alternative planning scenarios are developed. This may require iteration. Particularly around different transportation and out of area options. The assessment of options should seek to optimise dispersed energy development so that local environmental effects are minimised, if not avoided. The trade-off choices for

development need to be explicit, partly so that this is clear to those undertaking the planning, but also for public collaboration.

11. **Plan:** the process should conclude with a plan for each dispersed energy type. This can designate areas suitable for dispersed energy development and set out the criteria of how these are selected. These criteria can be used to set out policy guidance for decisions on development proposals. The plan should also be used subsequently to judge whether the delivery meets the plan objectives.

A challenge for all planning processes is identifying an appropriate scale and spatial extent for the plan. This needs to be judged in the light of the resource coverage, the extent of likely local environmental effects, the distribution of receptors and the transportation requirement. An appropriate choice of scale is likely to be evident only at stage 6, once the broad prospect for the energy development is clear.

The above process makes no provision for assessing demand for the energy. Demand volumes need to be identified at a national and at the regional level. National planning needs to consider the potential ongoing requirement for energy and which forms of energy are required to meet the demand. This requires both temporal, including diurnal and seasonal fluctuation, and the spatial spread of demand and potential energy production. The national energy modelling needs to take account of substitutability of different energy types, the energy conversion rates and production efficiency.

The success of the offshore wind energy planning process appears to have arisen because it was a positive planning process undertaken by a single agency. However, it is notable that other stakeholders were engaged with the planning process. This industry stakeholder involvement appears to have contributed to the success. For example, by changing the sea depth criteria to 60m rather than 50m (Section 3.3.1). It also built confidence in the potential developers that the plan was coming to fruition. It is also notable that the offshore wind plan was coordinated with complementary government processes (BEIS 2020a, BEIS 2020e). These built supply chain capability, organised suitable funding and regulatory structures. Onshore planning for dispersed energy needs to learn from this positive example and engage with relevant stakeholders (Section 3.3.1). It also needs to be supported by extra-planning process coordination (BEIS 2020e). The local planning process should be viewed as part of a wider system of developing dispersed energy. The onshore stakeholder engagement might include developers and specialists who understand the technical requirements of the energy type. It would also be useful to engage with the public. Gaining early public appreciation of the criteria used during the plan development process can guide choices and lays a foundation for subsequent public collaboration. For example, the potentially affected public may have views on the separation requirement between dwellings and wind turbines.

Before engaging with the institutional requirements for dispersed energy planning the next section briefly summarises the key characteristics of each form of dispersed energy. The reviews of each type of dispersed energy are not intended to be comprehensive. Each highlights the possible variations in local environmental effects that might arise, the different technical requirements and the differing character of the energy. The purpose of these brief reviews is to provide an illustrative basis for the closing discussion on planning for dispersed energy generally. This reflects the different energy disposition, technical recovery needs and anticipated local environmental effects. These are grouped by primary characteristics. As explained in Section 3.1.2 biomass, anaerobic digestion, energy from waste, industrial cogeneration are all excluded from this assessment since they are aligned with agricultural or industrial activity. Whilst offering potential in other jurisdictions, hydropower is mature in the UK and unlikely to see much development (BEIS 2013) beyond tidal lagoons, which are seen as offshore developments. The UK is likely to see substantial hydrogen energy development but the form of this is unclear at the present time. Most likely it will be used to substitute for methane in the gas grid (National Grid 2021). This leaves onshore wind, solar and geological energy to be discussed.

6.2.3 PLANNING FOR ONSHORE WIND

The dispersed energy type of greatest significance to the UK is currently wind energy. “In 2019 wind generators became the UK’s second largest source of electricity, providing 64 TWh, almost one fifth of the UK’s total generation” (BEIS 2020g, p59). The UK has an extensive programme of and is a world leader in offshore wind energy (Section 3.3). Onshore wind development in Scotland has seen considerable growth (Table 3.1). However, onshore wind developments in England and Wales have proved more problematic (Section 3.1.2). The divergence, between the parts of the UK, is a reflection of the distribution of the wind resource (Figure 1.2) as well as the human and natural geography. Scotland has good wind resources from large upland or exposed areas with a low resident population. However, the influential determinant for onshore wind in England and Wales appears to the government's response to a lack of social acceptance of the local environmental effects (Smith 2016, SE-LES 2019).

The key local environmental effects of onshore wind are visual amenity and landscape, noise and shadow flicker. Noise effects are likely to only affect receptors within two kilometres of turbines. Shadow flicker should be addressable by technical systems which switch off turbines when neighbouring property would be affected by shadows. Visual impact is dependent upon turbine size and the surrounding local topography. Planning for onshore wind would need to take account of the variability of the extent of potential visual impacts and energy density. The size of wind turbines currently reaches up to 260m tip heights (14MW) with the smallest turbine, from mainstream manufacturers, of 67m tip height (0.9MW)(Enercon 2020, GE 2020, Siemens 2020, Vestas 2020). The likely visual impact varies approximately in proportion to turbine output, with higher turbines giving a larger swept area, having greater visibility (across a flat land area). This suggests that the planning for local environmental effects of wind energy needs to consider alternative scenarios of visual spread to power production ratios. These scenarios also need to recognise the clustering of turbines into wind farms and the efficient separation distance between turbines.

Given the density of residential property in England visual and noise impacts may present a challenge, particularly in the lowland rural areas of southern and central England (Harper 2019a). The wind resource and energy potential appear to be greater in upland areas of Wales and northern England. However, much of these upland areas are scenic with designation as National Parks or Areas of Outstanding Natural Beauty. These are valued landscapes where the visual effects of wind energy are unlikely to be suitable. The potential for onshore wind in England and Wales therefore needs careful assessment of the local environment effects.

The greatest opportunity for onshore wind in the UK is in upland and coastal fringes of Scotland (Harper 2019 – Fig 6a). The visual amenity effect on receptors is likely to be limited by low population density. Whilst some of these areas provide rare species habitats there is ample opportunity to avoid these (DGC 2017). However, the principal drawback of these Scottish locations is the substantial distance from the location of large energy demand. Developments of onshore wind energy in these locations are likely to require considerable infrastructure for power transmission (National Grid, 2017). This is needed to take the energy from often remote parts of Scotland to the core of the extant national electricity transmission system. Whilst the transmission system covers Great Britain, the largest capacity in the existing infrastructure follows the historic patterns of carrying (coalfired thermal) energy from South Yorkshire and the North-East Midland to South Eastern England. It is, however, noteworthy that, according to Harper (2019), the wind resources across all of England are economically viable. Overall, planning to take account of the local environmental effects of onshore wind development therefore needs to take account of the moderate energy resources and challenging environment restrictions over much of England and Wales, together with the extensive transport requirement but rich resources for onshore wind development in remoter parts of Scotland.

6.2.4 PLANNING FOR SOLAR ENERGY

Planning for Solar energy seems to offer a simple form of dispersed energy with only limited local environmental effects. The primary local effect of solar energy is a modest impact on visual amenity. Unlike the tall structures of wind turbines solar energy parks create a low visual profile, although this can be extensive across a large area. In an undulating topography solar energy can create a significant visual effect. Similar to other energy proposals on virgin sites (Cowell 2020), where solar energy proposals are introduced into open countryside with locally valued landscapes this can give rise to social acceptance challenges (NoToLongfield 2020). In remote flat area, such as coastal mudflats or levels, the visual impact is likely to less significant. However, solar panels appear to be well suited to being placed on the top of industrial and commercial buildings, where their visual impact would be limited (DECC 2014e, ReNews 2020). The economics of solar energy can be challenging although this may improve with technological improvements. With a load factor of only 11.2% (Statista 2020a) and a diurnal and seasonal energy production contrasting with the national energy demand pattern the potential role for solar energy in the UK appears restricted.

6.2.5 PLANNING FOR GEOLOGICAL DISPERSED ENERGIES

For the geological based energy types there are three core adaptions required. Like shale gas, appropriate resources may only occur in specific geological locations. There may be some restrictions around how these resources are accessed from the surface, but only within a limited area. Surface restrictions may arise due to local environmental effects / receptor conflicts. Consequently, there may be strict limitations on where these can be developed. The development form for most geological resources is likely to be concentrated. As the shale gas pads illustrate, to access subsurface resources usually requires a surface point of focus for the development. Some of the geological resources, such as CAS, are likely to cause only light local environmental effects and therefore easy to accommodate (King et al 2021).

7. Conclusions and Recommendations

This chapter draws together the closing observations on the thesis research. This research has examined the gap, which exists both in academic research and policy/planning practice, between energy policy and planning in relation to dispersed energy. This type of energy is critical to the energy transition and the need to move away from fossil fuel to sustainable energy. Traditional energy production required relatively little land and was able to choose locations dependent upon economics.

However, as set out in Section 1.1, dispersed energy requires substantially greater land area and is often tied to resource location. Therefore, there is a considerable potential to either adversely affect local environments, which may also result in a lack of social acceptance, or for local environmental factors to restrict dispersed energy development. Given the land requirement, it is in society's best interests that an appropriate balance is struck between provision of dispersed energy and local environmental effects. This research has examined this nexus.

The thesis has confirmed that the gap between energy policy and planning remains. The research has sought to find ways how this might be addressed, by asking the question 'how best to plan for dispersed energy'. The research has shown that it is possible to develop methodological technique (or plan) for the provision of dispersed energy which minimise or avoid local environmental effects. In practice, however, there are still doubts about whether the institutional arrangements are sufficiently aligned to facilitate suitable positive planning for dispersed energy.

This chapter starts with a summary of research value of the thesis (section 7.1). It summarises how this thesis adds insight to the existing body of research, what has been delivered against the research objectives and how the research aim has been met. The remaining sections of this Chapter set out recommendations for future practice (section 7.2) and recommendations for future research (section 7.3).

7.1 Summary of Research Value

This section sets out a summary of how this thesis meets its original 'research aims', what has been accomplished against each specific research objective and what value this research adds to existing literature. It also briefly summarises what in this research is innovative or new, where it confirms, contradicts and/or adds value to the existing literature and what has proved to be challenging. Whereas Chapter 6 discussed this research result in relation to the literature in detail, this section looks at the principal research value of this thesis.

The research ambition or purpose aimed to formulate a methodological technique, or at least set out the principles, for a coherent dispersed energy development system which balances the necessary construction of energy facilities, sufficient for demand, with minimal local and global environmental effects, and at minimum cost to consumers. This ambition is discussed in both this section (on research value) and the next (in respect to future practice).

The primary finding of this research is that it is possible to plan for dispersed energy in a coherent and holistic way taking into account of local environmental effects (Section 6.1). The case study exemplar demonstrates an analytical technique for guiding the spatial planning of dispersed energy facilities. "Positive planning" (Allmendinger et al 2016, p48) is an explicit conscious process of making a plan which sets out criteria for spatial provision, having assessed the potential, evaluated the alternatives and selected an optimal design (Section 1.2).

Against each research objective the following has been accomplished:

1. For the identification of the factors that requires to be considered in a whole-system spatial planning approach for dispersed energy (RO1): the thesis has established the essential components. This research has shown that the factors need to include: the overall level of energy demand, the requirement for particular energy vectors and the

location of consumers; the distribution and characteristics of the primary energy resources; the baseline spatial characteristics of the area being planned for; the existing energy production patterns and characteristics; the capability, limitations and potential side or environmental effects of the exploitation technology (including vector conversion and storage); to get the energy to consumers, the energy transportation requirement and consequent effects of each vector; the cost and viability including optimum level of each element, but also recognising the 'externalities' cost; take account of the policy circumstances and market structures; lastly, but by no means leastly, the local environmental effects arising from all elements of the dispersed energy facilities.

2. For the development and setting out of the principles for a spatial planning methodology for the coherent holistic development of dispersed energy (RO2): the research has shown that this is achievable. The principles for the methodology are set out in the eleven-step planning process or principles, detailed in Section 6.2.2. In summary the principles are: resource appraisal, technology potential, demand quantification, transport capability, effects identification, receptor consequence, other issues consideration, effects assessment, spatial projection, alternatives evaluation, and plan resolution.
3. In terms of making constructive use of actual rather than proxy data (RO3): the research has applied and demonstrated the value of this in the case study. Using actual, rather than proxy or surrogate data, is an important element in making the analysis and planning of dispersed energy facilities meaningful. It is necessary to consider the real geography, for resources, consumers and transport, while effects need to be identified for actual, rather than notional, receptors.

As well as delivering the research objectives, this thesis adds insight to the existing literature. A key unavoidable consequence of the development of dispersed energy, with its inevitably increased level of local environment effects, is the increased impact on receptors. Unsurprisingly this has raised issues of social acceptance. Others have identified this as the 'social gap'. Many in the literature respond to this situation by calling for collaborative planning as a means of ameliorating the social consequences. Others suggest bottom-up thinking with the deployment of engagement with the receptor public who incur the effects. The approach shown by this research is importantly different.

I have argued that the adverse environmental effects on the receptor public arise in large part because of the incrementalist approach to decision making on dispersed energy facilities in combination with substantially heighten presence of energy facilities due to the essential dispersal. It may have been that an incrementalist approach was tolerable when the local environmental effects of energy (rather than dispersed energy) were much lower. But the scale of effects from dispersed energy, allied to incrementalism, leads to uncoordinated development and an unnecessarily increased level of local environmental effects. By its very nature this is likely to give rise to higher levels of nuisance for higher levels of affected public. I have shown that a coherent holistic method of spatial planning for dispersed energy reduces the accumulated local environmental effects. Rather than replacing top-down with bottom-up, the research here has shown that adaptions are required to top-down thinking, so that it takes full and proper account of local effects. This approach should substantially reduce the level of local effects and the nuisance to the public at large.

This research shows that when we’ve reduced the local effects to the absolute unavoidable minimum, that that is the time to engage with the affected public. Rather than letting dispersed energy facilities go wherever their developers wish, we should be directive so as to minimise local effects and optimise the effects / cost trade off. There should be fewer affected receptors, but at least it would be possible to show the public still affected that as much as possible has been done to mitigate accumulated effects.

A second important value of this research comes from the attempt to bridge the two (or more) stools of energy policy and planning. I accept the energy policy / planning practice stools is a challenge which remains unresolved in this research. A solution, other than advocacy, has not been provided in this thesis. However, these two stools are also a product of the separate silos that arise with dispersed energy development. In the incrementalist system developers, who have the technical knowledge, put forward their siting proposals to planners, who have the environmental awareness and the public interest viewpoint. The research here has shown that a spatial planning process can fully recognise the technical and engineering needs of the exploiting technology and the resource distribution, and can be integrated with consideration of local environmental effects. The thesis has shown that the silos can be bridged and broken down. This research shows that a cross-disciplinary approach is viable. In so doing, a spatial planning approach should be able to optimise the exploitation technology and thus the energy resource while minimising the accumulated level of environmental effects.

I acknowledged the two stools of the energy policy/ planning practice gap as intractable. However, bridging the silos and combining the technical/engineering requirement of dispersed energy development with the planning/ environmental assessment considerations does noticeably aid energy policy. It's been observed that energy policy is largely aspatial. This inevitably results in problems and consequence for the delivery of the policy. This research has shown that by taking account of the spatial dimension the delivery of energy policy is considerably assisted. It's been reported that wind energy development in England has largely ceased, essential due to problems of social acceptance. Receptor acceptance arises due to adverse local environmental effects. By reducing these, through effective spatial planning the delivery of policy can be assisted. The value of this thesis is to show that the spatial dimension is an important element of energy policy. We not only need to decide what dispersed energy is required to meet society's need, we need to decide where to put it.

In the literature review there was extensive discussion of cumulative effects, environmental assessment, and their relationship to strategic planning. The literature was pointing to difficulties with cumulative effects assessment and that this is best placed within a strategic planning process. This research affirms this current observation in the literature. It however goes further. The conclusion of this research is that environmental assessment would be better being fully integrated into a strategic planning processes, rather than being merely an 'information provider' subordinated to dispersed energy development decision making. The current separation is artificial and really arises because of the distinct roles in incremental decision making. The lesson from this research is that environmental assessment is better as an integral part of a coherent spatial planning methodology.

7.2 Recommendations for Future Practice

This thesis has one overriding recommendation for future practice: apply meaningful positive planning for dispersed energy. As this research shows, it is deliverable. The UK, like all developed economies, undertook a major program of energy development in the post war period to meet the growing demands of a modern society. There is a pressing need now for something similar to facilitate the delivery of dispersed energy at the local level. This is critical to the energy transition and attaining net zero. The scale of importance of the current requirement is at least similar to that of the earlier post-war need, arguably more important.

The case study has shown that there are no systematic or structural reasons why dispersed spatial energy planning could not take place. Confirmation is provided by dispersed energy planning offshore (Section 3.3). The lack of delivery of dispersed energy planning onshore appears to be a blend of institutional and social issues. Social because it is the anxiety about social acceptance which is seen as obstructing dispersed energy development (Section 2.2.3). Institutional because UK government has shied away from addressing the challenge (Sections 1.3 and 1.4). The institutional difficulties of the residual divide between energy policy and planning are enduring (Breukers & Wolsink 2007).

In terms of how best to resolve this difficulty and fill the gap between energy policy and planning practice in the UK, it appears that the planning system offers the best prospect for solving this problem. The planning system has the statutory capability to identify and designate areas suitable for dispersed energy development. It also has the expertise to assess need, weighing local environmental effects and reaching evidence-based choices. Alternatively, the soft space entities could take on the role. However, regional energy strategies need to be strengthened to make them worthy of being called regional energy strategies. A third option is a blending of the two, combining comprehensive energy strategies and statutory powers of designation of areas for development, to direct development.

Where the planning system will struggle with this responsibility is in three areas. Firstly, there is need for political recognition that positive or strategic planning, in some form within or associated with the planning system, is needed. Rather than relying on reactive decision making and ‘the market’ a full-blown strategic planning process is required. This requires a cultural sea-change at the policy level, to let planners plan. Secondly, the planning system would need to move beyond ‘local’. The thesis has demonstrated that planning for dispersed energy is best undertaken at the regional level. Being confined to restricted local authority boundaries is not sufficient for the spatial vision and perspective required. Thirdly, the dispersed energy planning process needs to fully integrate the technological/ engineering requirement of each form of energy. In some cases, such as shale gas, this requires complex specialist engineering know-how. In other cases, such as solar and even wind, this can be much lighter. In all cases, the technological element needs to include the transmission of energy arising from inter-regional energy flows.

7.3 Recommendations for Future Research

This thesis has explored the scholastic territory of the gap between energy policy and planning practice, in relation to the provision of dispersed energy. As has been recognised (Section 2.2.3), in academic research these are seen as two separate fields of study. This nexus between energy policy and planning practice deserves greater investigation, especially due to the importance of delivering the energy transition. From the energy policy perspective, it would be useful to understand why delivery of some forms of dispersed energy are so problematic. The usual response in research is social acceptance, but this could be refined. The UK government's move to give control over wind energy to the local level, allied to the moving of the focus of mainstream wind energy development offshore, suggests that UK policy accepts this perspective and has eschewed confronting the issues. This interplay between initial policy goals and the consequence of social acceptance, is worthy of further research. Not merely from the social acceptance perspective but also into the politics of implementing policy. Research on why government backs away from the headline challenge rather than seeking a more nuanced policy adjustment would be interesting. This thesis has suggested that rather than simply accepting social acceptance as an obstruction, research on direct rather than implied or surrogate effects could add value.

There is considerable scope for further research from the planning perspective of dispersed energy. It would be informative to understand whether the planning discipline could take on the challenge of planning for dispersed energy. At present planning literature largely eschews energy. Yet, with its remit for sustainable development; with the considerable need to accommodate dispersed energy at scale; with its core visioning and forward-thinking approach; and with planning's traditional cross-disciplinary skillset; planning research seems ideally positioned to investigate this field. Planning research also sits at the coalface of social acceptance and the adjudication of where public objections have merit and where this lacks genuine substance. Planning research could get behind the issues of social acceptance, where it arises, who objects, who remains quiet and why, whether there is consistency across communities and why on some issues the public is vocal but on others is not.

Perhaps the central question for future research arising from this thesis, combines energy policy and planning fields, is who is going to identify locations suitable for dispersed energy development? The UK Government has placed the responsibility for the preparation of regional energy strategies with soft space entities who do not have statutory power to decide locational choice. These energy strategies are worthy of in-depth research to measure their worth and, if evolved, their potential. It would be useful to consider what the relationship is between the soft space entities and the statutory authorities responsible deciding locational choices; particularly on how these can be combined to produce meaningful regional strategies, with powers to set planning criteria and direct dispersed energy development to acceptable locations. Related to this, this thesis shows there is a requirement for research on which forms of dispersed energy development can be accommodated in a densely populated country (such as England).

In looking at these recommendations it also important to place these suggestions for future research in context and consider what has been achieved. This thesis identified the crucial importance of delivering dispersed energy to the fulfilling of net zero and the energy transition. It reminds us that in the past and currently offshore, coherent planning approaches have delivered fundamental change in energy provision. The thesis highlighted the considerable challenge of providing dispersed energy onshore in the current era. The problem seems to be a lack of capability or will to plan appropriately and adequately to take account of local environmental effects. In turn these have adverse effects on receptors. Through the case study this thesis has shown that it is possible to plan for dispersed energy in ways which adjust for local environmental effects and avoid or minimise impact on the public and the environment. This positive or strategic planning approach also deals with cumulative or area wide effects inherently and shows how cumulative effects can consciously be evaded. The thesis has also shone a light on the institutional arrangement for dispersed energy planning. It is these arrangements which need to be addressed next to ensure adequate provision of dispersed energy. Resolving these can play a vital role in the energy transition and in finding the most efficient solution to achieving net zero.

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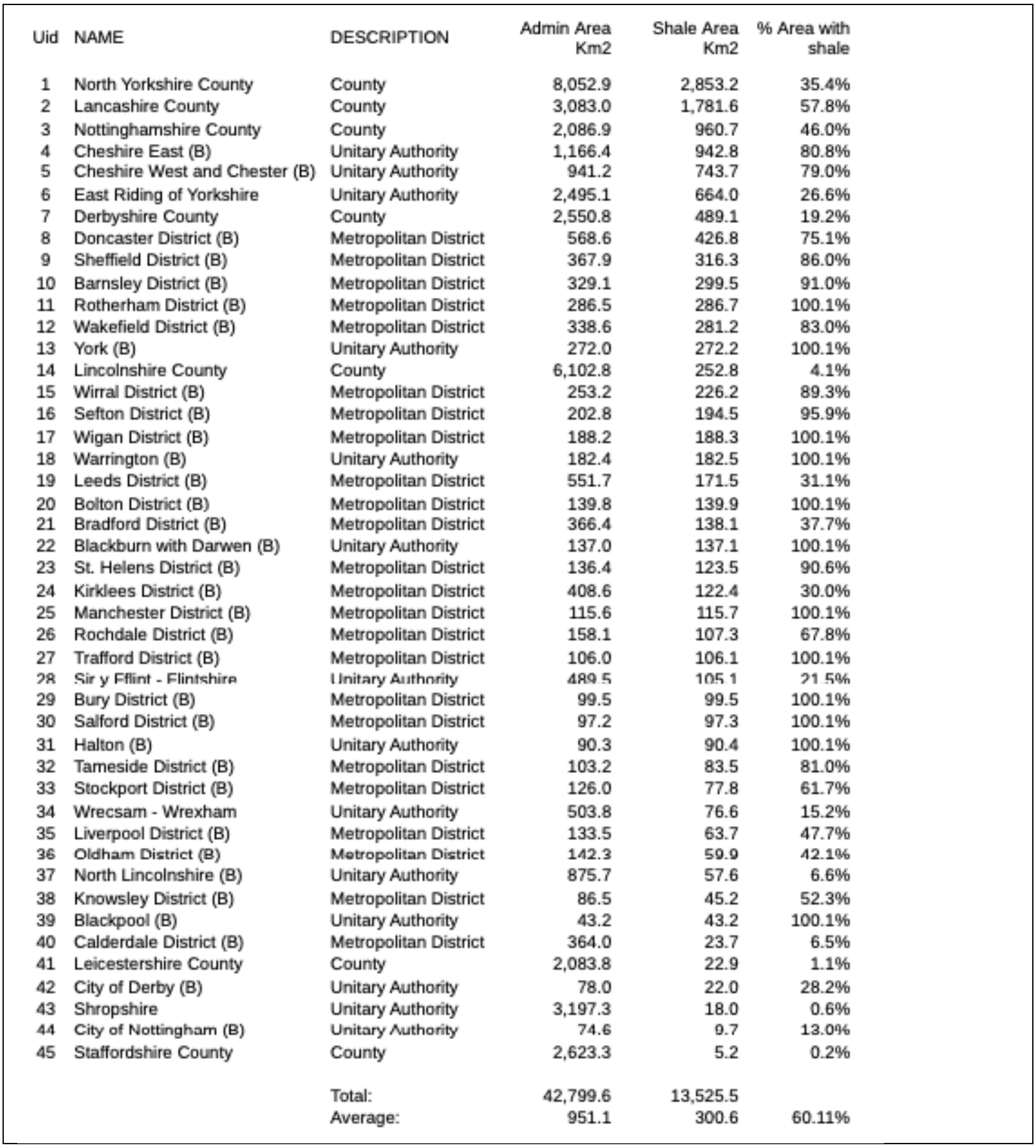
Appendix A: Local Planning Authorities with Bowland Shale Unit

Table A.1 Local Planning Authorities with Bowland Shale Unit (excluding National Parks), ordered by the Size of the Shale Unit Area.



Uid	NAME	DESCRIPTION	Admin Area Km2	Shale Area Km2	% Area with shale
1	North Yorkshire County	County	8,052.9	2,853.2	35.4%
2	Lancashire County	County	3,083.0	1,781.6	57.8%
3	Nottinghamshire County	County	2,086.9	960.7	46.0%
4	Cheshire East (B)	Unitary Authority	1,166.4	942.8	80.8%
5	Cheshire West and Chester (B)	Unitary Authority	941.2	743.7	79.0%
6	East Riding of Yorkshire	Unitary Authority	2,495.1	664.0	26.6%
7	Derbyshire County	County	2,550.8	489.1	19.2%
8	Doncaster District (B)	Metropolitan District	568.6	426.8	75.1%
9	Sheffield District (B)	Metropolitan District	367.9	316.3	86.0%
10	Barnsley District (B)	Metropolitan District	329.1	299.5	91.0%
11	Rotherham District (B)	Metropolitan District	286.5	286.7	100.1%
12	Wakefield District (B)	Metropolitan District	338.6	281.2	83.0%
13	York (B)	Unitary Authority	272.0	272.2	100.1%
14	Lincolnshire County	County	6,102.8	252.8	4.1%
15	Wirral District (B)	Metropolitan District	253.2	226.2	89.3%
16	Sefton District (B)	Metropolitan District	202.8	194.5	95.9%
17	Wigan District (B)	Metropolitan District	188.2	188.3	100.1%
18	Warrington (B)	Unitary Authority	182.4	182.5	100.1%
19	Leeds District (B)	Metropolitan District	551.7	171.5	31.1%
20	Bolton District (B)	Metropolitan District	139.8	139.9	100.1%
21	Bradford District (B)	Metropolitan District	366.4	138.1	37.7%
22	Blackburn with Darwen (B)	Unitary Authority	137.0	137.1	100.1%
23	St. Helens District (B)	Metropolitan District	136.4	123.5	90.6%
24	Kirklees District (B)	Metropolitan District	408.6	122.4	30.0%
25	Manchester District (B)	Metropolitan District	115.6	115.7	100.1%
26	Rochdale District (B)	Metropolitan District	158.1	107.3	67.8%
27	Trafford District (B)	Metropolitan District	106.0	106.1	100.1%
28	Sir y Fflint - Flintshire	Unitary Authority	489.5	105.1	21.5%
29	Bury District (B)	Metropolitan District	99.5	99.5	100.1%
30	Salford District (B)	Metropolitan District	97.2	97.3	100.1%
31	Halton (B)	Unitary Authority	90.3	90.4	100.1%
32	Tameside District (B)	Metropolitan District	103.2	83.5	81.0%
33	Stockport District (B)	Metropolitan District	126.0	77.8	61.7%
34	Wrecsam - Wrexham	Unitary Authority	503.8	76.6	15.2%
35	Liverpool District (B)	Metropolitan District	133.5	63.7	47.7%
36	Oldham District (B)	Metropolitan District	142.3	59.9	42.1%
37	North Lincolnshire (B)	Unitary Authority	875.7	57.6	6.6%
38	Knowsley District (B)	Metropolitan District	86.5	45.2	52.3%
39	Blackpool (B)	Unitary Authority	43.2	43.2	100.1%
40	Calderdale District (B)	Metropolitan District	364.0	23.7	6.5%
41	Leicestershire County	County	2,083.8	22.9	1.1%
42	City of Derby (B)	Unitary Authority	78.0	22.0	28.2%
43	Shropshire	Unitary Authority	3,197.3	18.0	0.6%
44	City of Nottingham (B)	Unitary Authority	74.6	9.7	13.0%
45	Staffordshire County	County	2,623.3	5.2	0.2%
		Total:	42,799.6	13,525.5	
		Average:	951.1	300.6	60.11%

Appendix B: The Shale Gas Development Process

Central to the case study of planning for shale gas is the shale gas development process. This appendix provides an overview of the technical shale gas development process. Development of sites for production of gas and oil from shale are largely similar to conventional hydrocarbon production (Hyne 2001). There are four main differences:

1. The sites are likely to require longer boreholes to provide the more extensive coverage required for shale.
2. The completion process by hydraulic fracturing is likely to be more extensive and time consuming.
3. The working time on site overall is likely to be greater.
4. Whereas with conventional hydrocarbons wells are optimised to reach the target resource with shale resources a more complex boreholes plan is required.

Table B.1 provides a summary of the five main stage of the shale gas development process together with a description of the activity and main materials required at each stage. Given the focus of this thesis on shale gas, the most significant shale resource in the UK, all subsequent coverage focuses on gas production rather than oil.

As well as drilling a borehole, stage 2 entails casing to be inserted into the open bore which is then cemented to the surrounding rock. Four steel casings are typically installed: a ‘conductor’ for the first 50m from the surface to stable surface ground, a ‘surface’ casing to approximately 300m to reach below any potable aquifers to protect groundwater, an ‘intermediate’ casing for approximately 3,000m down to the target shale strata, and a ‘production’ casing for the full borehole length. Thus, near the surface there are four cemented steel barriers between the inner borehole core and the surrounding subsurface rock or soils. The borehole is drilled in stages with a cutting bit proportionate to the borehole diameters required for each of the casings. Once the depth for the casing is achieved drilling ceases, the casing is inserted and then cemented into place. The drill bit is lubricated and cooled by circulating drilling fluid. This drilling fluid also stabilises the wellbore walls until the hole is cased. The drilling fluid also controls the subsurface fluid column, which is naturally under high pressure within the rock formation (Hyne, 2001). For shale wells, the borehole the drill is turned though a low-angle arc to run out horizontally along the shale, when the vertical

Box B.1: Summary of the Shale Gas Site Development Process

Phase	Description	Plant & Materials
Stage 1: Site Construction	Requires site preparation (stripping back topsoil), erecting security fencing, laying a geotechnical membrane across the site, laying and compacting an aggregate work base, forming bunds for surface water handling and preparing the concrete cellar(s) for the drilling platform	Groundworks machinery. Geotechnical membrane. Aggregate for base. Security fencing. Concrete for cellar.
Stage 2: Drilling	Applies the industry conventional process for hydrocarbon wells, with rotary and mud drilling, to create four cemented-in steel casings (conductor, surface, intermediate and production). For shale wells the borehole is initially drilled close to vertical, to reach the target depth, but then curves to intersect and track horizontally along the target shale reservoir (the horizontal in-shale section is referred to as ‘laterals’), to maximise the amount contact between the borehole and the reservoir.	Drilling rig and associated machinery. Drill string and bits. Drilling muds. Casings and cement. Monitoring equipment. Production tubing.
Stage 3: Completion	For shale gas hydraulic fracturing is the principal method of completion. This requires injecting fracture fluid at high pressure to create a fracture zone around the lateral borehole. This is undertaken in sections along the lateral.	Pumps and associated machinery for hydraulic fracturing. Extensive volumes of water for fracture fluid. Sand and some chemicals for fracture fluid.
Stage 4: Production	Gas is exported via a pipeline. Pipeline works are excluded from modelling due to poor data availability.	Pipeline to connect production pad to gas network.
Stage 5: Site Remediation	Includes capping boreholes, site clearance, removing all materials and reinstatement to prior condition	Groundworks machinery. Clear of all materials and site.

Source: Devereux 1998, Society of Petroleum Engineers 2019c, Donaldson et al 2013, King 2012, Zendehboudi & Bahadori 2017.

bore reaches the target formation. Figure 4.4 shows this arrangement with a borehole through a cut away cross section. Also note the increasing thickness of the borehole near the surface as a consequence of the various casings.

For all hydrocarbon sites the intense process of site construction is likely to take a few weeks whilst drilling could take several months for a simple site. The completion process of hydraulic fracturing is likely to take a few months, depending on the complexity and size of the shale areas covered by the site (Arup, 2014). Like any hydrocarbon, assuming gas is proven and viable, a pipeline is required to distribute the production of gas. Production of gas is likely to occur over several years. Re-working is possible to re-stimulate the well to improve the flow of gas later in the life of a well. Once the site has exhausted the viable production of gas from the site, all boreholes are capped and the site is remediated back to prior land use. Site remediation is like de-constructing the site and is likely to take a few weeks. Figure B.1 shows a typical pad for shale gas development during the drilling phase. Shale gas pads typically cover between 1 and 4 hectares.

Figure B.1: Typical Shale Gas Development Pad.

Note: the large structure in the centre of the pad is a drilling rig surrounded by acoustic barriers. The blue ISO containers around the pad contain equipment and materials. **Source:** (Cuadrilla 2016).

One of the key differences with extraction from shale is the shale and organisation of boreholes. The mechanics of hydraulic fracturing require sufficient pressure from the liquid to be exerted to overcome the inherent strength of the shale formation. The shale, lying with several kilometres of overburden above it and confined by the rock around it, is subject to extant in-situ stress. The “magnitude and direction of the principal stresses are important because they control the pressure required to create and propagate a fracture” (Society of Petroleum Engineers 2017, p1). When sufficient pressure (typically over 15,000 psi) is applied to the shale, internally from the fracture fluid, fractures will tend to occur along the direction of minimum stress. At shallow depth this is likely to be vertical but at depth in excess of one thousand feet (300m) the least principal stress will be horizontal. The orientation of maximum horizontal in-situ stress is determined locally by the surrounding tectonic forces. To maximise the hydraulic fracturing efficiency laterals are therefore best aligned perpendicular to in-situ maximum horizontal stress (SHmax) (Society of Petroleum Engineers, 2017). Thus, to cover an area of shale a series of laterals is required all parallel and perpendicular to the maximum in-situ horizontal stress (SHmax).

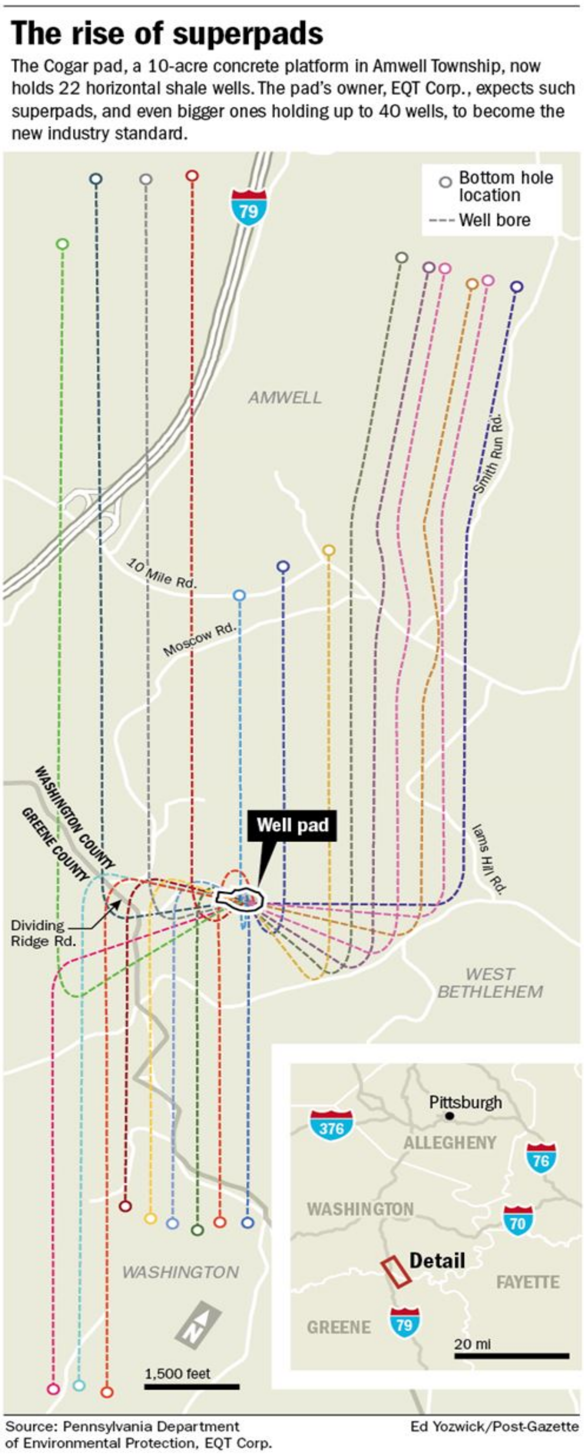
Overall efficiency of fracturing across an area is maximised by avoiding overlap between fracture zones. To optimise full coverage of shale a series of parallel laterals are requires separated by the horizontal extent of fracture zones. Figure 4.6 shows two three-dimensional arrangements of the possible organisation of boreholes to cover an area of shale.

The hydraulic fracturing, stage 3, is engineered to overcome poor porosity and permeability of the gas bearing shale to facilitate gas flow. It starts by perforating the production casing and surrounding cement to access the formation. Water, with up to 2% chemical additives, is then pumped under high pressure into the shale formation to fracture the surrounding shale rock. Having initiated fractures in the shale rock immediately surrounding the wellbore pumping is continued to extend the fracture zone for up to 100m around the wellbore. Proppant, often sand or silica, is pumped in to attempt to maintain the open micro-fractures. Following the release of pump pressure, water will flow back to the surface due to the natural hydrostatic pressure (referred to as flowback fluid). The fracturing results in a network of fine cracks around the wellbore, through which gas can flow up through the wellbore to the surface, after the flowback water has cleared (Donaldson, et al., 2013).

In recent years the length of borehole and the potential area covered from a single shale gas development (SGD) site has increased. In the 1990s Wytch Farm in Dorset England set a world record for the length of hydrocarbon production boreholes with a well length of 11.5km (Meader 2000). In 2017, Eclipse Resources drilled a horizontal or ‘super-lateral’ through shale with a 6.0km borehole for shale gas production (Nieto 2016). Traditionally pads were constructed with one or two boreholes per pad. This resulted in a patchwork of pads covering a local area, as shown in Figure B.2. In recent years there has been a trend towards increasing the number of wells drilled from a single pad. These multiple-well pads, or super-pads, are more efficient for the developer as well as less disruptive to the environment. Dembecki et al explains that these super-pads: “reduce the land required to develop the area; increase efficiencies from manufacturing style operations; allow for artificial lift using gas lift; enable the ability for high pressure field gas gathering and transmission;” and improve the rig and other machinery utilisation time (2015, p1).

Figure B.2: Drilling Pads in West Virginia USA at a Density of One Well per Pad and 6 Pads per Square Kilometre.
Source: WVSORO 2019.

Figure B.3 shows wells for a multi-well pad. By combining longer boreholes and multiple wells pads developers, such as EQT Corporation, expect to be able to cover an area of up to 150 km^2 from a single pad. As well as the efficiencies outlined by Dembecki et al (2015) this reduce the number of access roads required to pads and the overall environmental footprint in an area of shale (Litvak, 2018). One pad is planned to have sixty-four wells (Braziel 2019).



The rise of superpads

The Cogar pad, a 10-acre concrete platform in Amwell Township, now holds 22 horizontal shale wells. The pad's owner, EQT Corp., expects such superpads, and even bigger ones holding up to 40 wells, to become the new industry standard.

Source: Pennsylvania Department of Environmental Protection, EQT Corp.

Ed Yozwick/Post-Gazette

Figure B.3: Configuration of a Multi-Well Drilling Pads in West Virginia USA.

Note: The diagram shows 22 boreholes from one pad. Also note that the laterals are all aligned in two opposing directions, perpendicular to the maximum horizontal in-situ stress (S_{Hmax}). **Source:** Litvak 2018.

Appendix C: Modelling Base Block and Spatial Transposition Across to Other Study Blocks

The objective of the model is to assess what local environmental effects might arise with a full-scale development of the Bowland shale basin, and to consider whether and how a strategic planning process can optimise this. It also considers what accumulated and cumulative affects might arise. Three key environmental effects, of noise, traffic and visual amenity (see Section 4.4), have been identified as the likely most significant effects. It is these effects which need to be assessed in detail. The noise and visual amenity effects arise when the receptors of a residential population are present. This only occurs when residential areas are taken into account. The traffic effect is complex and need to be considered at all levels within the modelling. Section 4.8 outlines the process for laying out fracture zones and laterals, for applying five different pad densities whilst section 4.10 explains the core traffic assessment. This Appendix briefly sets out the fundamental need to achieve consistency across the basin by the use of a base block and the transposition of this base block across the basin.

C.1 Consistent Modelling Across the Basin

Before going into detail as to how the model is run it is useful to understand how the basin wide effects are assessed. As explained in Sections 4.2.3 and 4.5, the model operates on the principle that it is applied consistently across the basin. Consistent specification, norms and standards are used across the basin. To implement this through the model, base principles are established and then rolled out across the basin. Since the model analysis is conducted by comparing different blocks within the Bowland basin the consistency is achieved by setting out the norms and standards for a ‘base block’. Having established the operating principles of the model for the base block these are then duplicated in all 96 study blocks to roll out a consistent approach across the basin. In the later stages of the model these operating principles are then adapted to local circumstances. For example, in the early levels of the model it is assumed that the shale unit fully covers all of the 96 studied blocks. From level 3, (subsurface geology) onwards, when the disposition of the Bowland shale unit is considered, the model adapts to known circumstances of the shale unit. As stated, in Section 4.3, the studied blocks have at least 70% shale unit coverage. For units with 100% coverage the operating principle of the base block are applied. For blocks with less than 100% shale coverage the base block principles are adapted to the local circumstances.

C.2 Base Block and Spatial Transposition Across the Basin

This subsection explains the computation of the base block and the transposition to all other study blocks. The modelling is spatially based. Each study block is a rectangular square box or grid. When operating on the base block locational calculations are based on a simple XY grid, with location in metres calculated in relation to a datum in the south west corner of the grid square. This follows the Ordnance Survey grid arrangements (Ordnance Survey 2019). The grid applied to the base block is a ten-kilometre square. The same size as the assumed licence blocks. Using an eight-figure referencing system the centre of the grid would have a location reference of 5000 for the X dimension and 5000 for the Y dimension. This is 5km east and 5km north from the datum. These XY positions are also known as ‘eastings’ and ‘northings’, referring to how far east and north from the south-west datum point.

This system enables an easy transposition of locations from the base block to duplicate these equivalent positions in all study blocks across the basin. The OS National Grid is based on hierarchical kilometric-based grid with 500km and then 25km grid being distinguishable by a letter character pair, across the UK. However, these can be transposed into a numerical identifier. So TL63 transposes to 5623 (Ordnance Survey 2019). This 5623 point represents a set position at the 10km scale. The full reference, in metres, is 560000 230000, in an XY format.

This system facilitates a ready transposition from the base block across the basin by simply adding the base block reference to national grid full block reference. So, to duplicate the centre point of the base block across all study blocks the position is simply added. For the example for the centre point of any block, the centre point of the base block 5000 for X, 5000 for Y is added to the block reference 560000 230000 to give a resulting reference of 565000

235000. Table C.1 shows how the position of Ben Nevis, the UK’s highest point, within its 10km block can be transposed to identical relative positions within other 10km blocks.

Table C.1: Applying Base Block Locations Across the Basin

Example based on Ben Nevis	eastings	northing
Position of Ben Nevis with the local 10km Block (as in a Base Block) -	6692	1274
Ben Nevis lies within the National Grid character block reference-	NN17	
This transposes to numerals National Grid as-	21	77
The full metre-based position of this block is-	210000	770000
Full metre-based position of Ben Nevis is-	216692	771274
Full metre-based position of a different example block-	440000	330000
Ben Nevis relative position within its block transposed to another example block.	446692	331274

Appendix D: Key Steps in the Model

This appendix summarises the key steps in the model. It is prepared as a high-level instruction set on the computation process that produces the final results of the model. It assumes data is available for the disposition of the shale unit (Andrews 2013), the 10km Ordnance Survey national grid (OS), the road network (OS), residential areas (OpenStreetMap) and administrative restriction (National Parks, AONB & SPZ1). In brackets it states what software is used. Qgis is a Geographic Information System software whilst 'Ss' refers to a spreadsheet.

The modelling process for planning the development of shale gas consists of the following steps:

1. For the base block (assuming 100% shale coverage), identify the position of the laterals to cover all of the study blocks, perpendicular to the maximum horizontal in-situ stress (S_{Hmax}) of 150-330-degree orientation, applying a standard fracture zone width of 333m. (Ss)
2. Divide the cross-block laterals into sections, appropriate for each pad density (Ss).
3. Identify the position of the lateral heels for each lateral section (Qgis or Ss).
4. Divide the heels into groups with the minimum overall separation. The number of groups is set by the pad density – one group for each pad in the block (e.g., 10ppb = 10 groups in a block) (Qgis).
5. Determine the centroid of each group of heels. Set this as the preferred or notional pad position (nPP). (Qgis). (NB.: the pad position on the surface is directly above the centroid of heels at the depth of the shale).
6. Transpose the base block date (laterals, heel, groups & preferred pad positions) to all study blocks (as described in Appendix C) to produce notional pad positions (nPP)(Ss).

7. For blocks without 100% shale cover, apply the lateral, heels and notional pad points to the cover of shale area available. Adjust as appropriate to maximise the access to shale with a number of pads proportionate to the shale coverage. Revise or remove nPP as appropriate (Qgis).
8. Identify residential areas across the basin (Qgis).
9. Establish buffer zones, at the appropriate distance, around residential areas (Qgis).
10. Identify National Parks, AONBs and SPZ1 across the basin (Qgis).
11. Sieve out residential areas and their buffer zones, together with National Parks, AONBs and SPZ1, to identify the areas outside these, designating these area as 'developable zones' (Qgis).
12. Generate areas around all notional pad points, at the appropriate radius for each pad density, designating these as 'development tracts' (Qgis).
13. Sieve out developable zones and development tracts to identify 'area suitable for pad development', also referred to as 'landing zones' (Qgis).
14. Filter the road network data for the basin, to identify the major roads and local roads, from other roads in the hierarchy. Establish each of these as dataset (Qgis).
15. Sieve the roads data to identify major and local roads within study blocks and a 5km buffer around study blocks (Qgis). (NB.: this reduces a large data set to the minimum necessary for modelling).
16. Identify all junctions between major roads and local roads within the study blocks and the 5km buffer (Qgis).
17. For each nPP, identify the possible all sections of major roads in the landing zone and their individual development tracts (Qgis).
18. Where there is a major road with the development tract, find the nearest point on the nearest major road to the nPP. Mark this location as the final pad position (fPP) for the respective pad (Qgis).
19. For all local roads within the study blocks and 5km buffer, subdivide these by distance from a major road junction, to find the nearest major road junction for each section of local road. In practice these are divided into 250m sections for the first 6km from a

major road junction, then into 500m sections up to 10km. For local road sections which are over 10km from a major road junctions individually calculated (only three found in the modelling). (Qgis).

20. Sieve the local roads against developable zones to identify local roads in developable zones (Qgis).
21. For pads without access to major roads in their development tracts (pads left over from step 18), find the local road with the lowest distance from a major road junction in the developable zone, within their development tract. Mark this location as the final pad position (fPP) for these pad. Where there are two or more sections of local road with the same distance from a major road junction use the local road section nearest to the nPP (Qgis).
22. Calculate the distance on the local roads from the nPP to the nearest major road junction. This will be in 250m or 500m sections plus the distance to the start of the section. Where the distance is over 10km this requires calculation to the 10km point. Record the distance against the pad identity (Qgis & Ss).
23. For pads without access to major roads (step 18) or local roads (step 21) within the development tracts, extend to development tract by 1 km radially. Exclude any residential areas or areas in a line drawn from the notional pad point beyond residential areas (Qgis).
24. Sieve these extended development tracts against the major and local roads network within developable areas (Qgis).
25. Where there is a major road in the extended development tract, find the nearest point on the nearest major road. Mark this location as the access point for the pad (Qgis).
26. Draw a straight line from the notional pad point to the access point. Where this line intersects with the perimeter of the actual development tract mark this as the final pad point (Qgis).
27. Where there is no major road in the extended development tract find the nearest point of the nearest local road. Mark this location as the access point for the pad (Qgis).

28. Draw a straight line from the notional pad point to the access point. Where this intersects with the perimeter of the actual development tract mark this the final pad point (Qgis).

29. Identify the pads using these extended development tracts as pads using access tracks. Measure the distance from the final pad position to the access point and set this distance as the length of the access track (Qgis).

30. For pads using access tracks with access points on local roads, calculate the distance on the local roads from the access point to the nearest major road junction. This will be in 250m or 500m sections plus the distance to the start of the section. Where the distance is over 10km this requires calculation to the 10km point. Record the distance against the pad identity (Qgis).

31. All pads should now be identifiable as having either: (i) direct access to a major road, or (ii) using direct access of a local road to a major road junction, or (iii) using an access track (via either a major {mr} or local road {lr}), or (iv) nPPs which are not developable because they do not have any access to the roads network.

32. For all final pad points, with access to the roads network (31: i, ii & iii) calculate the distance to the lateral heels served by the pad (Qgis).

33. Calculate the distance of the lateral sections served by the pad (Ss).

34. Derive the length of each bore by combining the lateral section and the distance from the pad to heel (Ss).

35. Calculate the goods vehicle load factor based on the weight and size limits of the vehicles and the parameter of the materials used in the boreholes drilling, hydraulic fracturing and pad development. (Including the access track length where appropriate). (Ss).

36. Identify the materials needed to develop the pad based on the length of the borehole, the length of the lateral sections, the required casing and the size of the pad (Ss).

37. For each pad, calculate the number of goods vehicles loads by applying the material required to the goods vehicle load factors (Ss).

38. For each developable pad using local roads (31:ii) or local roads with access tracks (31:iii lr), calculate the distance travelled on local roads by multiplying the number of

loads required by the distance from the final pad position (or the access point) along the local roads, by two (for outward and return journeys). (NB.: that pads with final pad positions or access points on major roads do not generate any traffic on local roads) (Ss).

39. For each developable pad calculate the aggregate length of lateral sections on the pad. Multiple this by 0.333 to produce the area of shale which developable (Ss).
40. Aggregate the distance travelled on local roads for each block (for each pad density) (Ss).
41. For each pad density, aggregate the area of shale developed for each block (Ss).
42. For each pad density, aggregate the distance travelled on local roads and the area of shale developed for each block for the whole of the basin (Ss).
43. Extract the other figures produced in the Results Chapter 5 (Ss).

Appendix E: Data Sources and Data Quality

This appendix sets out the data sources used in the modelling and briefly discusses issues around data quality.

E.1 General Issues of Data Quality

Table E.1 shows the data sources used in the modelling of the Bowland basin shale gas development planning process.

The data quality of the roads data is vital to the modelling process. Throughout the analysis the OS roads data proved to be exceedingly accurate. It soon became apparent that if errors arose this was due to some issues with logic. Unfortunately, OS data for residential areas is in an inappropriate format. Hence, the OSM data was used for residential land use.

Table E.1: Sources of Data used in the Assessment

Data type	Data Source
UK Roads network	Ordnance Survey Open Roads (https://osdatahub.os.uk/downloads/open).
Disposition of the Bowland shale unit	Andrews 2013/ OGA / BGS.
UK Coastline	Ordnance Survey Open-Map – Local (https://osdatahub.os.uk/downloads/open).
OS 10km National Grid	Ordnance Survey Open-Map – Local (https://osdatahub.os.uk/downloads/open).
Residential land use areas	Open Street Map (https://www.openstreetmap.org).
Data on size and weight of drilling and hydraulic fracturing components	Society of Petroleum Engineers (2017, 2019 & 2020), Hyne 2001, Azar & Robello Samuel 2007, American Petroleum Institute

Table E.1: Sources of Data used in the Assessment

Data type	Data Source
	(https://www.api.org/products-and-services/standards/).
Vehicle Load capacity	UK Government (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211948/simplified-guide-to-lorry-types-and-weights.pdf.
Fracture zone and lateral sizes	Warpinski & Zimmer 2012, & UKOOG 2018.
High value scenic areas	National Parks UK (https://secure.nationalparks.uk/students/whatisanationalpark/maps).
Extant Onshore Oil and Gas Licenses	OGA (https://www.ogauthority.co.uk/data-centre/).
Aggregate compaction weight & volume	Various, including: Primary aggregates (https://www.primaryaggregates.co.uk/aggregates/aggregates-calculator), Ineos Marsh Lane Screening Report, Cloburn Quarry (https://www.cloburn.co.uk/how-to/aggregate-calculator), and Calculator Soup (http://www.calculatorsoup.com/calculators/construction/roadway.php).
Ground Water Source Protection Zone 1	Environment Agency (http://apps.environment-agency.gov.uk/wiyby/37833.aspx).
General verification of Pad development	Arup (2014)/ Cuadrilla (2016 & 2018).
Noise radius from pads	Aurora Energy (2020).

E.2 Provision for the Shale Unit Variations

During the modelling process an attempt was made to consider the disposition of the shale units in greater detail. It would have useful to consider the variability of thickness and depth of the shale units, any known faults and any data on porosity, permeability and known percentage for total organic carbon. Some of this data was used in the Andrews (2013) study. Two approaches were taken to this. Firstly, by seeking the data that had been used in the Andrews (2013) study, from BGS/OGA. It is clear that to achieve the results of calculating the volume of shale and the gas producing potential, that Andrews (2013) must have used or generated some considerable details of depth, thickness and the disposition total organic content. Unfortunately, this data was not available (Harvey 2019). Secondly, an altogether more imprecise approach of scanning the raster images of expected thickness and depth of the shale unit, produced in the Andrews (2013) report, then overlaying these on the model GIS projection and attempting to extract the thickness and depth information from Andrews (2013). Supplementary information is available in the fence diagrams (Andrews 2013, Figures 42). Figure 3.4 shows the merged Andrews study (2013) image overlaying the model projection. Whilst this technique produced a reasonable fit between the two projections (verified by comparing the UK coastline) extraction of the data from the Andrews (2013) colouring proved problematic. The data was found to have very poor accuracy. Given the accuracy available, together with the time available for the research for this thesis, it was decided that this approach was not viable.

Consideration was given to treating the Upper and Bowland units (Andrews 2013) distinctly as two rather than one merged shale unit. To take full account for the thickness, depth, porosity and permeability of the Bowland Hodder disposition requires a considerable amount of time and computing power. Whilst this would have provided greater refinement to the subsurface aspects of this study it was concluded that this degree of refinement was not a priority for this study. The emphasis of this study is the planning approach and the surface environmental effects which might arise with full scale Bowland basin shale gas development. From this perspective detailed refinement of the subsurface data is not a priority, particularly given the time and resources required to consider it. For a study focused on surface environmental consequences the key feature of the subsurface data is the area extent of the shale unit to be exploited. The modelling in this study therefore focused on the area extent of the Bowland shale units. It treats the Upper and Lower Bowland shale unit as one single shale unit with an assumed depth of 3km. The study also assumes a standard thickness, porosity, permeability, total organic content and absence of faults throughout the shale unit. The Bowland shale unit (Andrews 2013) is therefore assumed to be homogeneous with only the spatial extent recognised.

Appendix F: Explanation of Important Steps in the Modelling

This Appendix sets out how the particular challenges in the case study modelling are addressed. It is intended to supplement the modelling process described in the Methodology Chapter 4. The description of the modelling process set out in the Methodology Chapter does not follow the method used to conceive and build the model. The Methodology Chapter presents the method in a coherent way to enable the reader to understand the salient stages in the model's operation. Due to word limits the Methodology Chapter is a summary and not intended to be comprehensive. The description of the modelling in this Appendix broadly follows the method used to build the model. This follows the conception set out in Figure 4.5 of a four-level model. This starts with a simplified version of the model and then adds complexity arising in each level. In sequence this deals with the engineering level, the surface geography, the subsurface geology and then the social factors. This Appendix is not comprehensive on every aspect of the methodology employed in the modelling. Its purpose is to provide detail on the most complex aspects of the model. These are omitted from the Methodology Chapter primarily to enable that Chapter to give a clear overview of the modelling process. Also, so that the Methodology Chapter is not excessively long and difficult to digest. Appendix D provides an overview of the computational steps applied in the model, whilst Appendix B summaries the shale gas engineering development process. Any reader unfamiliar with the oil and gas for production process may find it useful to read the synopsis provided in Appendix B of the Shale gas Production Process, before reading this Appendix.

In the planning discipline plan preparation often incorporates modelling of different options. In the case study the modelling was used to plan for mitigation of environmental effects and forecast where development could take place. To identify areas suitable for development and to set criteria for how development can be decided. The approach deployed in the case study modelling follows the government guidance of planning for dispersed energy (DHCLG 2015), described in section 3.1.2.

When first conceived, to contend with the complexity, the model was broken down into different component. These different components are referred to as levels (Figure 4.5). Having separated the levels, the overall complexity is addressed by starting with the first level, addressing this and then building on this in subsequent levels, evolving the model in stages. The first component or level to be addressed was the petroleum engineering or technical level, looking at how the petroleum engineering is deployed to exploit a shale resource. This level considers what production resources, such as plant and materials, are needed to extract the shale and what steps are required. This includes considers the arrangement of laterals, fracture zones and pads to access the shale, albeit in straight forward form. At the first level this is addressed as if in an ideal world. As if everything else was perfectly suited to what petroleum engineering requirements need to be met and how would a developer undertake the development. At this level it was assumed that the shale unit and the road network were idealised whilst there is no residential population or other surface feature to complicate delivery.

The second level builds on the first level by adding the complexity of incorporating the real-world road network of the Bowland basin, but without residential land use and any social consequences. The third level builds further by adding the subsurface circumstances of the actual extent of the shale unit and its geological orientation. The final level builds in the remaining factors by recognising the presence of the existence of the human population in residential settlements. These levels follow the image set out in Figure 4.5. Organising the process of addressing the system complexity in this way gives preeminent importance to planning to meet the need of avoiding adverse effect on the human population. Tables 4.2 summarises the factors taken into account at each level.

In addressing this overall complexity, the modelling starts by applying the concept of a base or standard block at the opening engineering level. The base block becomes the core unit upon which the model is built. Since there are no surface and subsurface factors to consider, at the first engineering level the modelling is only applied to the base block. In the second, third and final levels the modelling analysis is applied to all 96 study blocks. Common principles, derived from the base block, are applied across all blocks. An explanation of the base block and the transposition across all study blocks is provided in Appendix C.

The modelling seeks to predict and then, as much as possible, plan to avoid local environmental effects. Three local environmental effects were identified as significant, before modelling commenced, from the study of real-world decision making on shake gas development decisions (Section 3.5). The identified significant effects are noise, visual amenity and traffic. Analysis of these local effects identified that the effects are asymmetrical in their impact (see section 4.9.1). From the analysis of these effects, in the preliminary stages of a plan preparation process, it was always understood how each of these effects could be mitigated. For noise and visual amenity set back or clearance distances are used to provide mitigation. This is only necessary when human receptors are introduced in the fourth level. Given the ability to mitigate away the noise and visual amenity effects, much of the effort of the modelling is needed to calculate, predict and plan for the traffic effect. The modelling therefore gives emphasis to the need to contend with the traffic effect. This treatment of local effects, particularly around the important influence of the traffic effect, reflects the real-world decision making on shale gas proposals, where traffic was the only effect which led to the rejection of a SGD proposal (Section 3.5). Accordingly, much of the modelling is given over to contending with the traffic effect of SGD.

This Appendix next looks modelling of the engineering level, then consider the challenges of contending with the surface real-world road network. The third section of this Appendix gives a detailed explanation of the challenges of addressing the authentic shale unit and how the idealised engineering level is transposed to take account the disposition of the Bowland shale unit. The final section of this Appendix looks at how the environmental effects of residential receptors are addressed.

F.1 Modelling of Engineering level Components

For the first level the prime focus is on the petroleum engineering, of how to, most efficiently, exploit the shale unit. Particularly how to best exploit the laterals and fracture zones within a $10km^2$ block. The engineering level applies a system of fracture zones, lateral, boreholes and the organisation of pads, set out in section 4.8, without the need for any adjustment to any other factors. Because of this idealised situation the engineering level only needs to be applied to a base block. Like all other levels, the engineering level modelling is applied for all five pad densities. The shale unit is assumed to fill the block, with a comfortable east-west alignment of maximum in-situ stress (S_{Hmax}).

In many ways the engineering level is a basis for developing the principles of the model. It also provides a worked example for validating the core model processes and principles. The calculation of work required for drilling and hydraulic fracturing are set out for the base block development arrangements explained in sections 4.8. Section 4.8.2 explains the principles of applying the details of fracture zones, laterals, heels, pads.

F.1.1 PAD GRID REFERENCE POSITIONS FOR THE BASE BLOCKS

The application of the principles for fracture zones, laterals, heels and pads results in pads located with the base block, with the number of pads appropriate to pad density. The follow a geometric pattern. These result in fixed positions for the pads, for each pad density. Using the system of grid referencing explained in Appendix C, the grid reference positions for each pad, for each density, is set out on Box F.1. These locations are mathematically derived to balance: the tessellation of the fracture zones across the block; allowing for the heel positions to be optimised (for laterals in each opposing direction); and the equalised grouping of heels, to be served by each pad, so as to minimise the length of cross-fracture-zone bores form the pad to the heels.

F.1.2 ASSESSING TRAFFIC AT THE ENGINEERING LEVEL

Whilst the focus of the engineering level is the efficiency of petroleum engineering it is instructive to consider what the theoretical traffic effects would be. Whilst this is not necessary for the modelling results it helps the evolution of the methodology. Considering the traffic effect at the engineering level also assist with evolution the principles of the core traffic assessment (Figure 4.16). Consequently, the core traffic effects assessment is also applied to the engineering level.

The obvious problem with applying the traffic assessment at this level is that there are no roads. To overcome this, it is assumed that roads are available wherever needed. These notional roads are conjured up simply to meet the engineering need of the shale development. To emulate the roads network, applied later in the modelling, the model

Box F.1: Grid References for Pads for the Base Block, for Each Pad Density

1 Pads Per Block		
Pad Number	Grid Position X Easting	Grid Position Y Northing
1	5	5

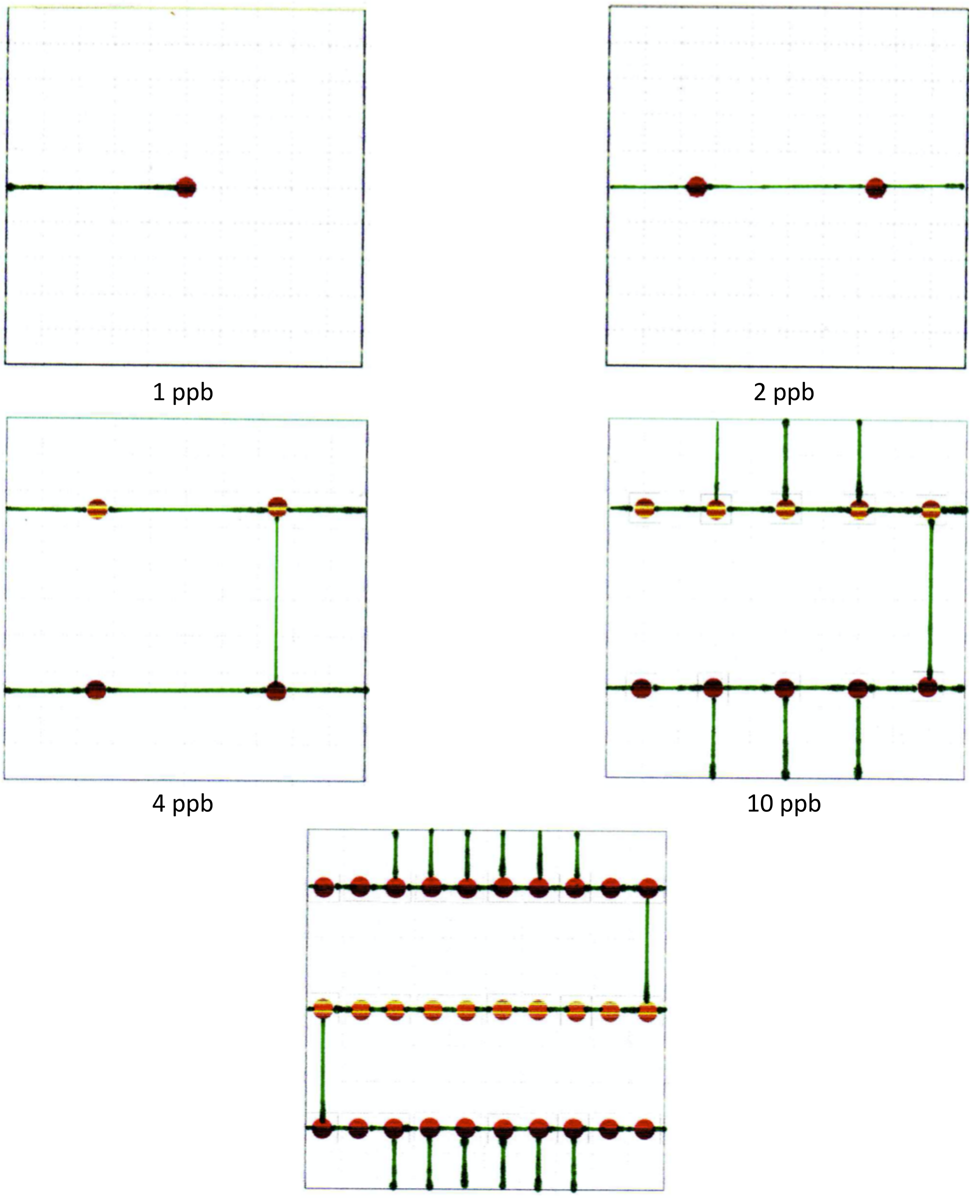
2 Pads Per Block		
Pad Number	Grid Position X Easting	Grid Position Y Northing
1	2.5	5
2	7.5	5

4 Pads Per Block		
Pad Number	Grid Position X Easting	Grid Position Y Northing
1	2.5	2.5
2	2.5	7.5
3	7.5	2.5
4	7.5	7.5

10 Pads Per Block		
Pad Number	Grid Position X Easting	Grid Position Y Northing
1	1	7.5
2	3	7.5
3	5	7.5
4	7	7.5
5	9	7.5
6	1	2.5
7	3	2.5
8	5	2.5
9	7	2.5
10	9	2.5

30 Pads Per Block		
Pad Number	Grid Position X Easting	Grid Position Y Easting
1	0.5	8.33
2	1.5	8.33
3	2.5	8.33
4	3.5	8.33
5	4.5	8.33
6	5.5	8.33
7	6.5	8.33
8	7.5	8.33
9	8.5	8.33
10	9.5	8.33
11	0.5	5
12	1.5	5
13	2.5	5
14	3.5	5
15	4.5	5
16	5.5	5
17	6.5	5
18	7.5	5
19	8.5	5
20	9.5	5
21	0.5	1.67
22	1.5	1.67
23	2.5	1.67
24	3.5	1.67
25	4.5	1.67
26	5.5	1.67
27	6.5	1.67
28	7.5	1.67
29	8.5	1.67
30	9.5	1.67

applies two types of roads: local roads and major roads (Section 4.10 and Table 4.6). For the purposes of modelling, all roads within the 10km^2 block are treated as local roads. The perimeter boundary of the 10km^2 block is treated as major roads. Hence, following the principles of significant effects of traffic, set out in section 4.10, only traffic within the block is treated as environmentally significant. This provides a way of relating the imaginary engineering level roads network to the real-world roads network used later in the modelling. The imagined local roads within the block are the minimum required to connect the pads and the perimeter. They are therefore straight lines connecting the pads to the block perimeter (for materials) and to each other (for plant and materials). Consequently, the road network is unique for each pad density. Figure F.1 shows the required road network, for each pad density. Having evolved this imaginary road network, the calculation of the traffic effect for the engineering level applies the core traffic effect assessment, set out in Section 4.10. The results of this are not given, but were useful in the conceptualisation and development of the model.



1 ppb

2 ppb

4 ppb

10 ppb

30 ppb

Figure F.1: Local Roads Network Required for the Base Block in Frack-land, Level 1

Notes: Showing pad locations for 1, 2, 4, 10 and 30 pads per block. Dots = pad locations. Green lines = Local roads required for accessing all pads from the perimeter. For materials roads are required to connect each pad to the perimeter, at the closest point. For plant movement, which takes place between pads, the shortest route for the vehicles is (i) closest point on the perimeter to the pickup pad, (ii) shortest route to the next pad, and (iii) closest point on the perimeter to leave the drop-off pad. The plant needs to travel between the rows of pads for pad densities of 4, 10 and 30 ppb. The assumed production sequence for plant starts in the North West, then on to the next nearest undeveloped pad. The pad positions conform the grid reference points in Table F.1.

F.2 Contending with a Real Road Network at the Surface Level

The next step up in the model, at the second level, is to take account of the real-world roads network at the surface. At this stage the residential areas remain excluded and the shale unit is assumed to be retained from the engineering level. Consequently, the shale is still assumed to fill in all blocks, with an east-west alignment of laterals. The analysis moves beyond the base block to take account of the 96 study blocks. Since traffic may require to use roads outside the study blocks the analysis at this level is basin wide.

The roads network applied is the authentic road network for the Bowland basin covering Northern England. Following the process set out in section 4.10, 'A' class roads in Northern England are designated 'major roads', whilst 'B' and 'C' class roads are designated 'local roads'. The motorways and access roads are excluded from analysis (Table 4.6). In accordance with the Core Traffic Assessment process, significant traffic effects are assumed to arise only on local roads whilst the major roads are assumed to be of sufficient standard that any traffic from SGD is not environmentally significant (Section 4.10). Figure F.2 shows the major and local roads network for the Bowland basin in Northern England.

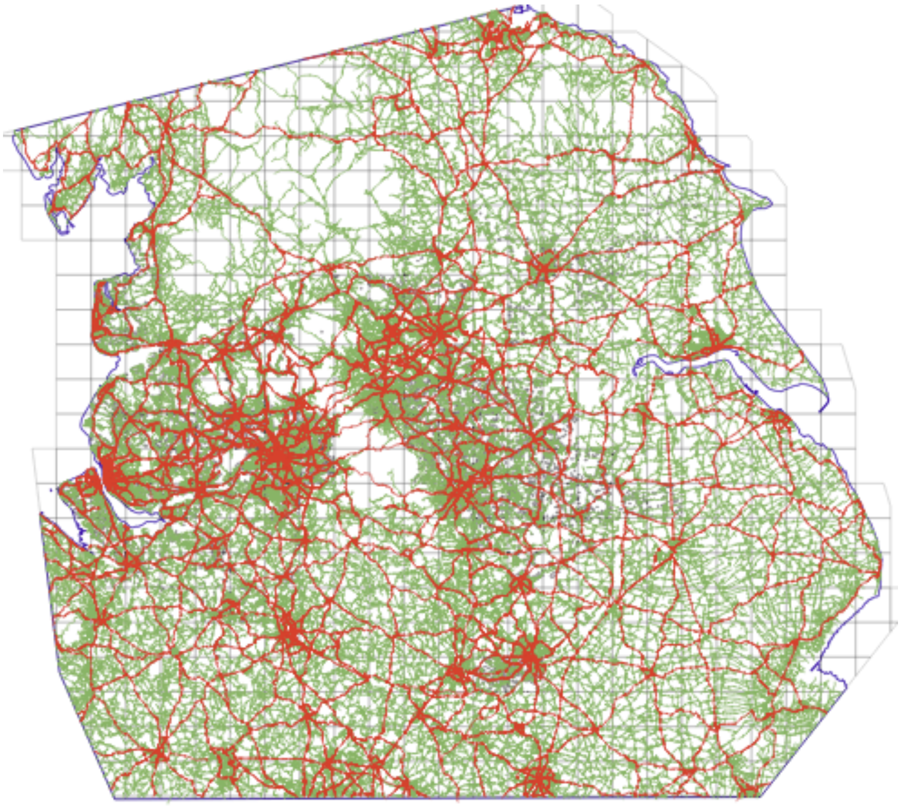


Figure F.2: Major and Local Roads Network across the Northern England

Key: Red lines = Designated as Major Roads. Green Lines = Designated as Local Roads. Grey Grid Lines = OS 10km National Grid. Blue Line = UK coastline and area cut off.

F.2.1 SURFACE LEVEL PAD LOSS DUE TO THE COASTLINE

The position of pads, laterals, heels and fracture zones for the second level are initially based on the engineering level. The base block and the pad positions are transposed onto all 96 study blocks, in accordance with the process described in Appendix C. The Bowland basin identified by Andrews (2013) extend into the sea beyond the coastline. A few of the 96 study blocks also reach out beyond the coast. Whilst laterals can reach out under the sea, pads cannot be located offshore. To identify any pads not located onshore the pads for the 96 study blocks are sieved against the UK coastline to identify the retained onshore pads. Table F.1 shows the resulting pads data for each density.

Table F.1: Pads per Block Adjusted for Surface Level Coverage

	30 ppb	10 ppb	4 ppb	2 ppb	1 ppb
Notional number of Pads per Block	30	10	4	2	1
Number of Blocks	96	96	96	96	96
Notional number of Pads across the Basin	2880	960	384	192	96
Number of Onshore Pads	2867	958	384	192	96
% of Basin Covered	99.5	99.8	100.0	100.0	100.0

For onshore pads the core traffic assessment (Sections 4.10 and 4.11) is applied to assess and quantify the traffic effect at level two.

F.3 The Challenges of an Authentic Subsurface Shale Unit

The next stage in the modelling, at level three, is to take account of the geology of the shale unit. This is the subsurface level of modelling. Up to this point the model used a simplified version of the shale unit, with an assumed 100% shale coverage for every study block, with a uniform shale thickness and depth throughout and a convenient orientation of maximum horizontal in-situ stress (S_{Hmax}). For the subsurface or geological level, the shale unit is changed to reflect the authentic coverage of the Bowland Hodder shale unit identified by Andrews (2013). For this level the Upper and lower units, identified by Andrews, are combined. The assumed uniform shale thickness and depth are retained. The depth is assumed to be 3,000m and the thickness is the height of the fracture zone. Despite this still being a simplification of the real-world Bowland-Hodder shale units, the consequences of introducing a more realistic disposition of the shale unit are substantial. Three principal changes arise in the modelling with introduction of an authentic shale unit: (a) the shale coverage is amended from the assumed full coverage of shale across all 96 blocks to the actual area or spatial coverage identified by Andrews (2013); (b) rather than the comfortable east-west alignment of maximum in-situ stress (S_{Hmax}) the authentic alignment of the in-situ stress in the Bowland-Hodder shale unit is applied; (c) as a consequence of the reorientation of the fracture zones (to comply with in-situ stress) the ends of these zones do not align at the block boundary.

To take account of the coverage of shale identified by Andrews (2013) the pad coverage has to be adjusted. Whilst 60 study blocks have full coverage of the authentic shale unit some 36 blocks do not. Figure F.3 shows the study block and the shale unit. Taking account of the authentic alignment maximum horizontal in-situ stress (S_{Hmax}) of the Bowland basin requires an extensive reorganisation of fracture zones, laterals, pad coverage and pads. Within the Bowland shale unit the orientation of maximum horizontal in-situ stress (S_{Hmax}) varies slightly

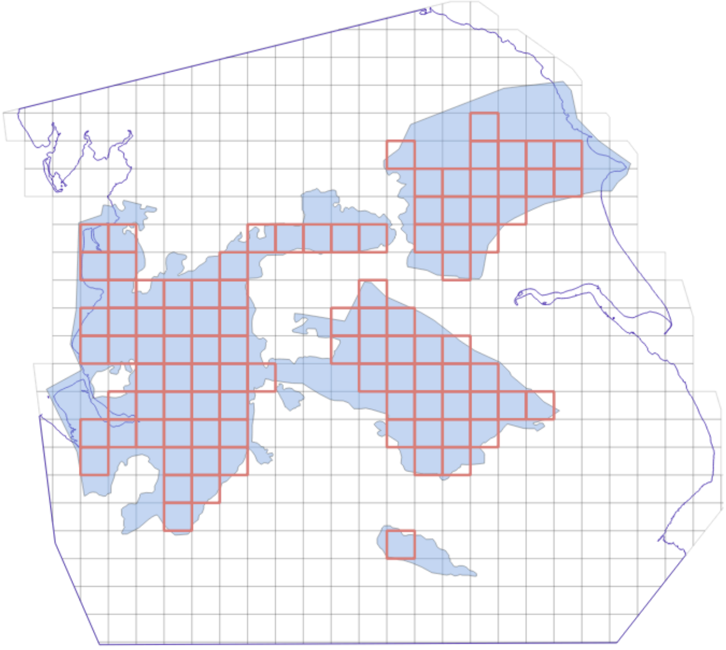


Figure F.3: 96 Study Blocks with Authentic Shale Unit Coverage

Key: Pale Blue Area = Bowland Shale Unit identified by Andrews. Red Squares = 96 Studied Blocks. Grey Grid Lines = OS 10km National Grid. Blue Line = UK coastline and area cut off.

across the basin, with a general orientation in ENE-WSW direction. The studies of maximum horizontal in-situ stress for the Bowland basin have identified an average orientation of maximum horizontal in-situ stress (S_{Hmax}) across the Bowland shale unit of 150.5 degrees, with a standard rotary deviation of 13.1 degrees (Kingdon 2016). For the case study modelling the authentic average maximum horizontal in-situ stress (S_{Hmax}) is applied to the whole Bowland basin and all studied blocks. To adjust for this the orientation of laterals (which needs to be perpendicular to the maximum horizontal in-situ stress) is set on an orientation of 60-240 degrees. Figure F.4 shows a 10km^2 base block with laterals aligned at 60-240 degrees. Rather than the thirty laterals of a standard length employed in the base block, in the earlier stages of model, the revised reorientation requires forty laterals to cover a block. These laterals across the block vary in length. The maximum length of the central laterals, which run across the full width from the western to eastern side of the block, is 11.55 km. The shortest lateral within a block, situated in the north east corner, is 0.76km. The average length of all forty laterals within a block, for the realigned laterals, is 7.5km.

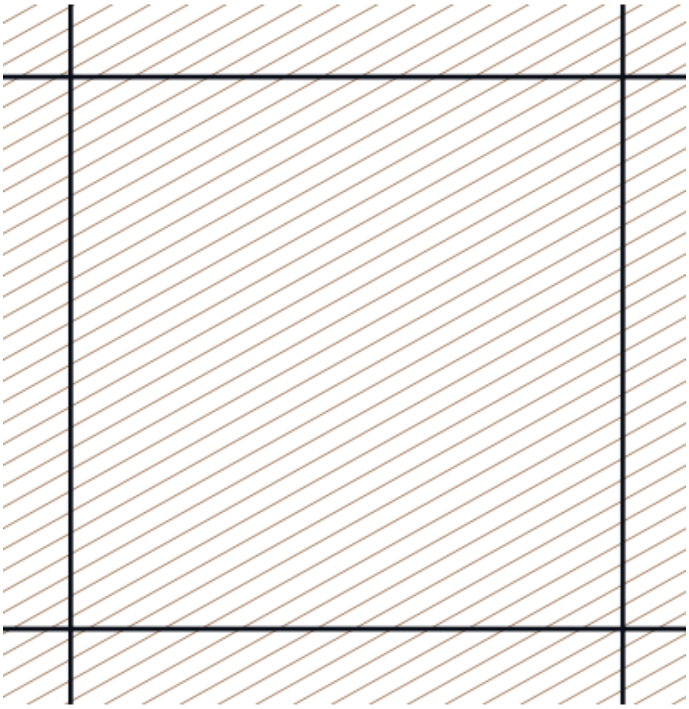


Figure F.4: Laterals Across a Block with a 60 - 240 Degrees Orientation

Key: Black Lines = OS 10km^2 Licence Block. Brown Lines = Laterals at a 60-240-degree orientation.

The realignment of laterals creates a hiatus when dividing the cross-block laterals into subsections, and therefore also in creating an efficient fracture zones pattern, which cover the block effectively. The earlier comfortable fit of pads coverage and fracture zones falls away when the laterals and fracture zones are aligned obliquely to the rectangular boundaries of a block. The following subsections explain how this hiatus is handled in the modelling.

F.3.1 Coping with Fracture Zones Overlapping the Block Boundary

Before considering the ramifications of this fracture zone hiatus, however, it is necessary to consider the situation at the point where the laterals intersect with the perimeter boundary of the block. In the first and second levels of the model, in sections F.1 and F.2, the fracture zones around a lateral have effectively been treated as a rectangle with the laterals running centrally along their length. Where these fracture zones ended at the perimeter of a block, they have previously been perpendicular to the block boundary. Consequently, the ends of the fracture zones aligned neatly along the edge of the block. However, when the laterals are orientated at 60-240 degrees the fracture zone ends are oblique. Thus, the ends of the rectangular fracture zones are at a 30-degree angle to the eastern and western block boundaries and 60-degrees of the northern and southern boundaries. If laterals were to run to the block boundary the rectangular fracture zones would extend out beyond the block. This would create a breach of licence arrangement for blocks. To address this issue the laterals and fracture zones need to be withdrawn at the block boundary. Figure F.4 shows a schematic of the fracture zone overlapping the boundary, in the north east corner of the base block. It shows the fracture zones when lateral runs to the block boundary. It also shows the extent to which laterals need to be shortened so that the fracture zones stay within the block.

Shortening laterals at the block boundary reduces the area of coverage of production of gas from the shale unit. Table F.2 summarise the details and total length of laterals across a block when the laterals are turned to an 60-240-degree orientation, to take account of the authentic maximum horizontal in-situ stress (S_{Hmax}) for the Bowland basin. It also gives the total length of laterals when they are shortened to avoid fracture zones overlapping the block boundary. This shows that shortening the laterals, to avoid fracture zones overlapping the block boundary, results in a reduction of the total fracture zones coverage for a block by 4.4%. This 4.4% area of shale, equivalent to 4.4km^2 or 440 hectares, is lost from the production area

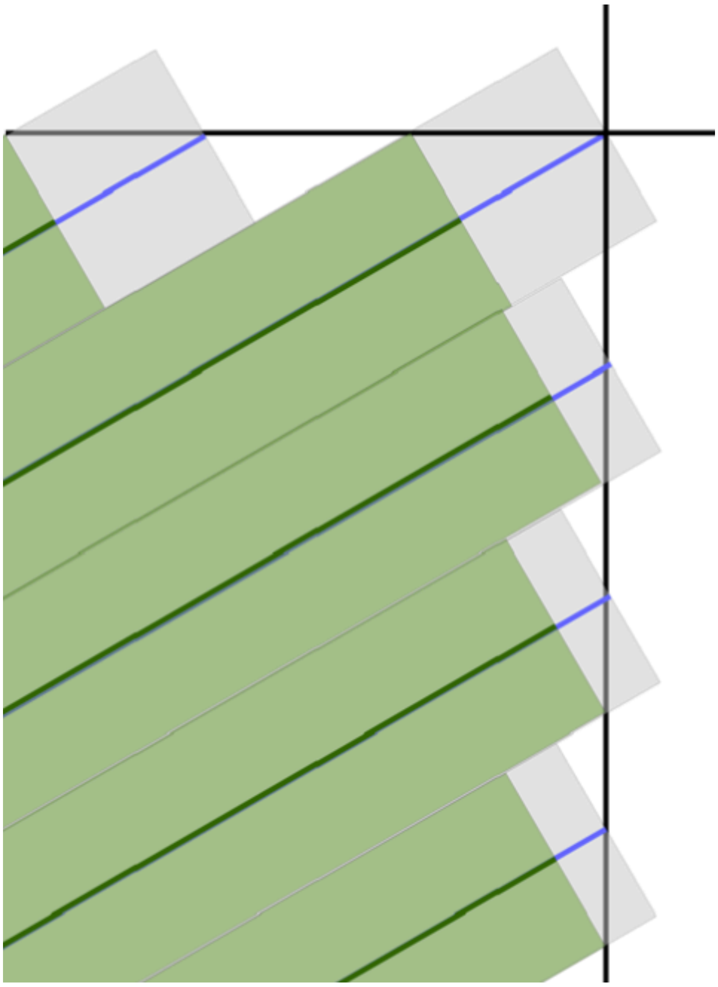


Figure F.5: Issues with Fracture Zones and Laterals at the Block Boundary

Key: Black Lines = Licence block boundary in the North East corner of a block. Blue Lines = Laterals at a 60-240-degree orientation, reaching the edge of the licenced block. Grey Area = Fracture zone accessed from blue line lateral. Green Lines = Laterals at a 60-240-degree orientation, withdrawn from the edge of the licenced block boundary so that the fracture zone does not overlap the block boundary. Green Area = Fracture zones accessed from green line laterals, within the Block Boundary. **Notes:** This schematic shows the North East corner of a block with the Laterals orientated at 60-240-degress. Where the laterals reach the block boundary (blue line intersect with black lines) the fracture zone extends beyond the block boundary as well as leaving some areas of the shale in the block unserved. The lateral therefore need to be withdrawn from the boundary (green lines) so that fracture zones (green areas) do not exceed the boundary. This results in a loss of coverage of the shale unit by fracture zones.

of the shale unit, when the shale unit fully covers the block, as a result of the oblique alignment of laterals to the block boundary. The loss will vary when the shale unit does not fully cover the block.

Table F.2: Block Coverage when Laterals are Oriented and Shortened for Authentic Bowland Maximum Horizontal In-Situ Stress

MHISS = Maximum Horizontal In-Situ Stress (S_{Hmax}). FZ = fracture zone.		Data	Percentage
East West MHISS (from Table F.3)	Number of laterals	30	
	Average lateral length	10 km	
	Total length of laterals in block	300 km	
	Total coverage @ 333m FZ width	100 km^2	
MHISS @ 150 degree, (laterals @ 60-240 degrees)	Number of laterals	40	
	Average lateral length	7.5 km	Of east west orientation:
	Total length of laterals in block	300 km	100%
	Total coverage @ 333m FZ width	100 km^2	
MHISS @ 150 degree, shortened to avoid overlapping block	Number of laterals	40	
	Average lateral length	7.17 km	Of 60-240 orientation
	Total length of laterals in block	286.7 km	95.6%
	Total coverage @ 333m FZ width	95.7 km^2	

F.3.2 ROTATING FRACTURE ZONES AND REORGANISING PADS

With the orientation of laterals at 60-240 degrees the new challenge is how to best fit the positions of pads to optimise efficient access to the fracture zones and laterals. Figure F.6 shows a comparison of the situation between pad densities when the pad pattern deployed in the engineering level are rotated to fit the reorientation of the laterals at a 60-240-degree orientation. The rotation is centred on the block centroid. As can be seen, whilst the rotation does not affect the pad at a density of 1ppb, when rotation is applied at the 30ppb density some pads fall outside the block. Any solution is likely to need to vary for each pad density. The pads at intermediate and higher pad densities do not appear to be positioned to balance and optimise the required access to laterals and fracture zones. Figure F.7 confirm this by showing the fracture zone coverage from centrally rotated pads, for 10 and 30 ppb. The fracture zone coverage spills outside of the block whilst leaving the corners of the block not covered by fracture zones.

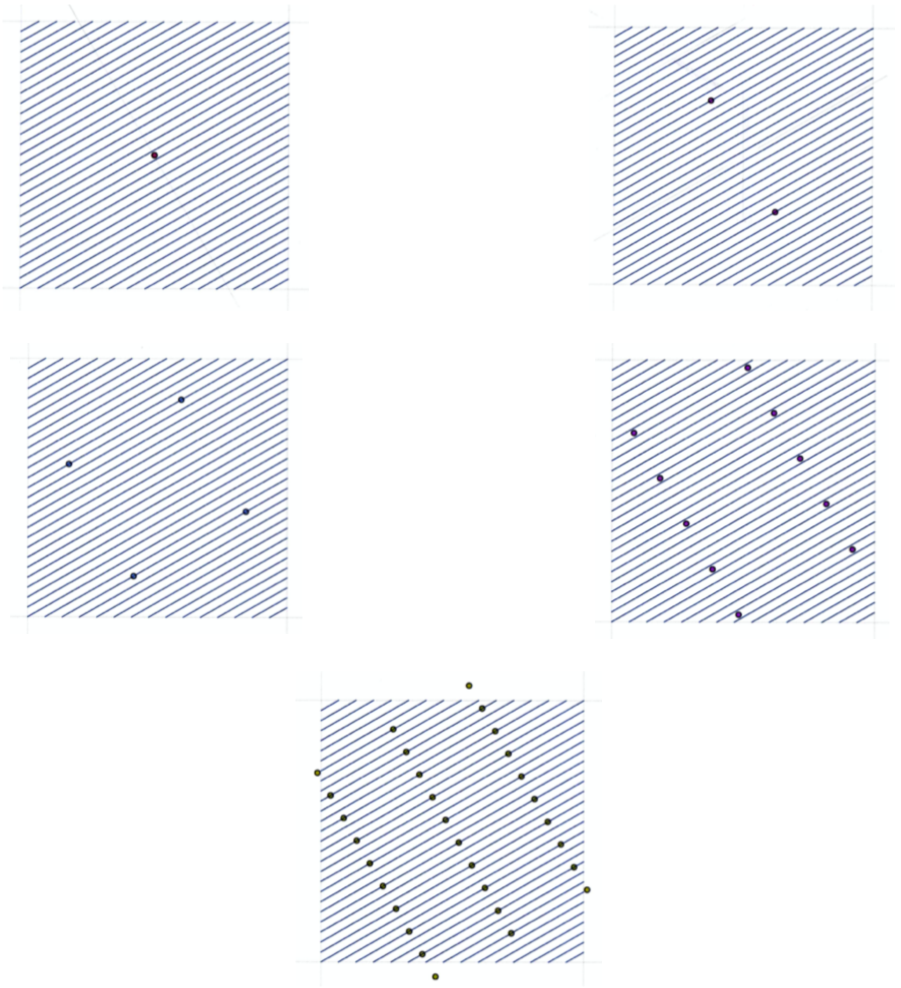


Figure F.6: Pad Patterns from Level 1 Rotated in an Attempt to Comply with the Orientation of Laterals at 60-240- Degrees.

Key: Sequence of Pad Densities at 1, 2,4, 10 and 30 ppb. Blue Lines = Laterals stretch across the Block. Black Dots = Pads. **Notes:** Pads complying with prior level pad patterns for each pad density, when turned to suite the reorientation of laterals across the block. The pad pattern rotation is centred on the middle of the block.

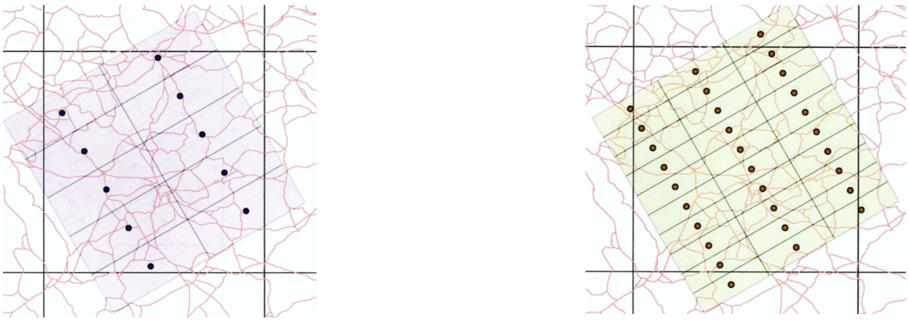


Figure F.7: Coverage when Level 1 Pad Pattern is Rotated, for 10 and 30 ppb.

Key: Main Black Lines = OS 10km^2 Licence Block Boundary. Black Dots = Pads. Coloured pale purple and green areas = fracture zones. Red lines = roads. **Notes:** Shows the fracture zones from pads across the block, for 10 and 30 ppb pad densities, complying with prior level pad patterns for each pad density, when turned to suite the reorientation of laterals across the block.

Analysis of these pad locations, for each pad density, using Voronoi Polygons show that the tessellation is inconsistent (Senechal 1993). Figure F.8 shows the Voronoi tessellation for 10 and 30 ppb densities. For the 30 ppb, the middle eight pads of the central row provide a common shape of coverage, but this is not reflected in the fracture zones and lateral at the block perimeter. Apart from this only a few resulting pairs of polygons are identical, mirroring either side of the block. Overall, there is a very poor tessellation with considerable variation in the size of the area covered from each pad. Another approach is required to achieve consistent and balanced tessellation and coverage from pads.

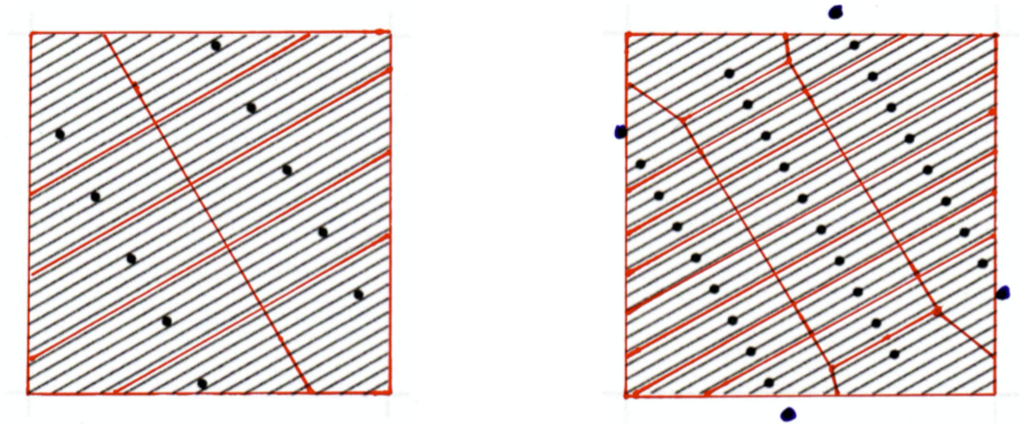
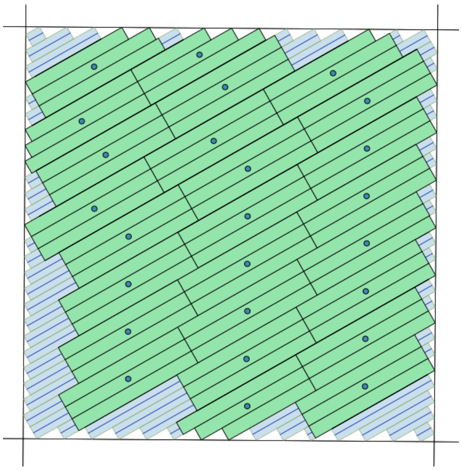


Figure F.8: Voronoi Polygons for Pads where a Simple Rotation of Level 1 Pad Patterns has been Applied, for 10 and 30 ppb Densities

Notes: Left - 10ppb, Right - 30ppb. Black Lines = Laterals at a 60-240-degree orientation. Red Lines = Separation lines of Voronoi Polygons for coverage of laterals. Blue Dots beyond the block (30ppb only) = Excluded pads falling outside the block.

An alternative option is to relocate the pads, and the fracture zones served by each pad, to provide a better organisation of the pads. This approach involves moving pads, where the bulk of the area covered falls outside the block and repositioning them in the large empty areas not covered by a pad. Where a row of pads, for example some of the middle rows of Figure F.8 30-ppb, are offset from the centre of the block largely to the west or to east these could move eastward and westward, respectively, to better fit the block. However, even this process is unlike to provide an effective solution to optimise the coverage from pads. Figure F.9 shows the results of this process, for the 30ppb density, overlaying the target cross-block laterals and fracture zones. The pads are positioned to maximise the coverage of the related fracture zones. Yet it is clear the combined facture zones do not fill the block and the target shale cover. Large areas of uncovered cross-block fracture zones and laterals remain. Using the arrangement shown in Figure F.9 it is only possible to fit 25 out of a possible 30 pads under this arrangement.



30 ppb

Figure F.9: Best Fit Fracture Zones and Pad for 30 ppb Densities

Key: Black Lines = OS 10km^2 Licence block boundary. Blue Area = Shortened target fracture zones (mostly covered). Blue Lines = Shortened cross-block laterals (mostly covered). Green Area = Pad coverage area, at Level 1 specification, reoriented to accommodate authentic maximum horizontal in-situ stress. Blue Dot = Pads positions to serve reoriented fracture zones. **Note:** Whilst the pads and coverage are from the 30ppb density there are only that there are only 25 pads. Due to the poor alignment of the fracture zones with block boundaries it is not possible to fit in all 30 pads and their coverage.

F.3.3 REORGANISATION BASED ON 'CROSS-BLOCK LATERAL SUBDIVISIONS'

An alternative approach to position the pads for the subsurface level is to consider the requirement by looking at the laterals and fracture zones. The changed and variable length of laterals create a significant discrepancy in the way that laterals in the earlier levels of the model are subdivided into suitable equal lengths. Table F.3 shows the variable length of the cross-block laterals and the division into the section lengths used earlier, in earlier levels of the model. With the cross-block laterals shortened, to avoid fracture zones overlapping the block boundary (Section F.3.1), the longest laterals across the block are 11.35km long. After adjusting to prevent fracture zones exceeding the block boundary, the shortest lateral is only 0.38km long. Table F.3 also shows the division of the laterals across the block by the lateral sections used in engineering level, in the first row of data. For each pad density two columns of data are given. The first of these columns shows the number of lateral sections, or part section, required to fill the new cross-block laterals at the appropriate length of the

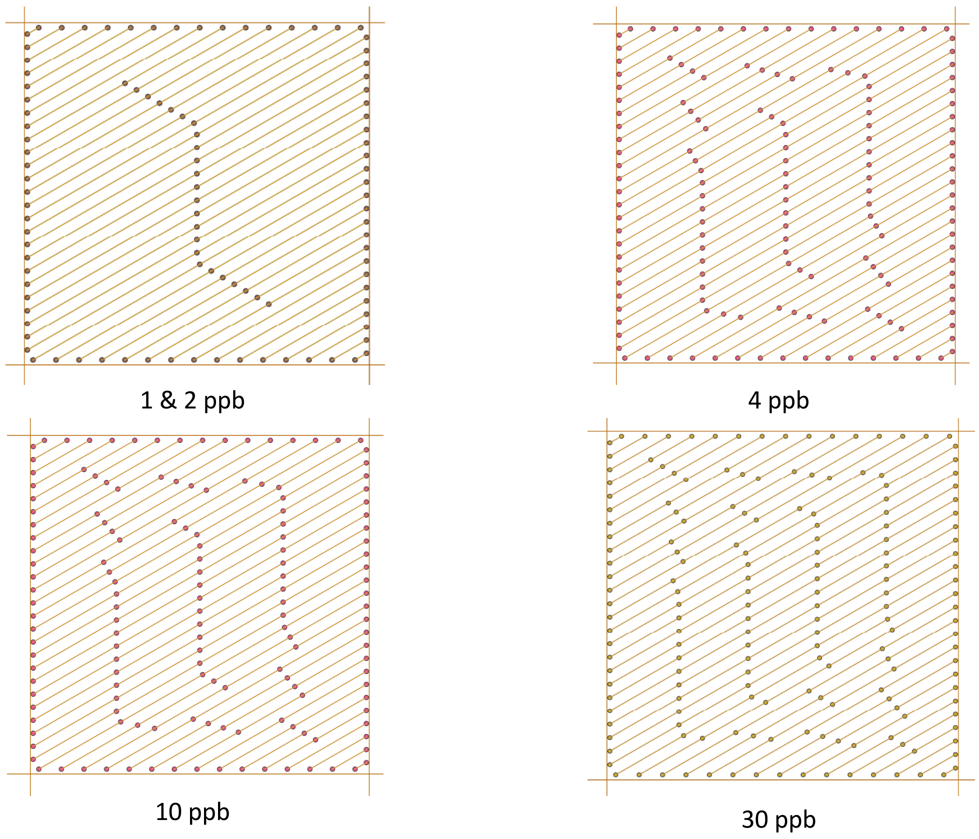
Table F.3: Cross-Block Shortened Lateral Lengths and Subdivision of Laterals into Sections, by Pad Density

	Lateral Identity Number	Length across the Block (km)	30 ppb		10 ppb		4 ppb		2 ppb		1 ppb	
			No	Len (km)	No	Len (km)	No	Len (km)	No	Len (km)	No	Len (km)
Cross Block Laterals based on 90-270 degree laterals	All	10	6	1.666	4	2.5	4	2.5	2	5	2	5
Cross Block Laterals based on 60-240 degree laterals	1	0.38	1	0.38	1	0.38	1	0.38	1	0.38	1	0.38
	2	1.15	1	1.15	1	1.15	1	1.15	1	1.15	1	1.15
	3	1.92	1.1	0.32	1	1.92	1	1.92	1	1.92	1	1.92
	4	2.69	1.6	0.45	1	2.69	1	2.69	1	2.69	1	2.69
	5	3.46	2	0.58	1.3	0.87	1.3	0.87	1	3.46	1	3.46
	6	4.23	2.5	0.71	1.6	1.06	1.6	1.06	1	4.23	1	4.23
	7	5.00	3	0.83	2	1.25	2	1.25	1	5.00	1	5.00
	8	5.77	3.4	0.96	2.3	1.44	2.3	1.44	1.1	2.89	1.1	2.89
	9	6.54	3.9	1.09	2.6	1.64	2.6	1.64	1.3	3.27	1.3	3.27
	10	7.31	4.3	1.22	2.9	1.83	2.9	1.83	1.4	3.66	1.4	3.66
	11	8.08	4.8	1.35	3.2	2.02	3.2	2.02	1.6	4.04	1.6	4.04
	12	8.85	5.3	1.48	3.5	2.21	3.5	2.21	1.7	4.43	1.7	4.43
	13	9.62	5.7	1.60	3.8	2.41	3.8	2.41	1.9	4.81	1.9	4.81
	14	10.39	6.2	1.73	4.1	2.60	4.1	2.60	2	5.20	2	5.20
	15	11.16	6.6	1.86	4.4	2.79	4.4	2.79	2.2	5.58	2.2	5.58
	16	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	17	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	18	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	19	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	20	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	21	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	22	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	23	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	24	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	25	11.35	6.8	1.89	4.5	2.84	4.5	2.84	2.2	5.68	2.2	5.68
	26	11.16	6.6	1.86	4.4	2.79	4.4	2.79	2.2	5.58	2.2	5.58
	27	10.39	6.2	1.73	4.1	2.60	4.1	2.60	2	5.20	2	5.20
	28	9.62	5.7	1.60	3.8	2.41	3.8	2.41	1.9	4.81	1.9	4.81
	29	8.85	5.3	1.48	3.5	2.21	3.5	2.21	1.7	4.43	1.7	4.43
	30	8.08	4.8	1.35	3.2	2.02	3.2	2.02	1.6	4.04	1.6	4.04
	31	7.31	4.3	1.22	2.9	1.83	2.9	1.83	1.4	3.66	1.4	3.66
	32	6.54	3.9	1.09	2.6	1.64	2.6	1.64	1.3	3.27	1.3	3.27
	33	5.77	3.4	0.96	2.3	1.44	2.3	1.44	1.1	2.89	1.1	2.89
	34	5.00	3	0.83	2	1.25	2	1.25	1	5.00	1	5.00
	35	4.23	2.5	0.71	1.6	1.06	1.6	1.06	1	4.23	1	4.23
	36	3.46	2	0.58	1.3	0.87	1.3	0.87	1	3.46	1	3.46
	37	2.69	1.6	0.45	1	2.69	1	2.69	1	2.69	1	2.69
	38	1.92	1.1	0.32	1	1.92	1	1.92	1	1.92	1	1.92
	39	1.15	1	1.15	1	1.15	1	1.15	1	1.15	1	1.15
	40	0.38	1	0.38	1	0.38	1	0.38	1	0.38	1	0.38

Notes: 1) Lateral Identity No. are taken from Figure F.5 working from north-west to south-east. 2) The column "No" shows the number of subdivided laterals sections required of the cross-block laterals, to meet the standard length of lateral sections used in Level 1 of the model, for each pad density. A minimum requirement of one section applies. 3) The column "Len" shows the length of laterals sections required to meet the number of subdivisions of the cross-block laterals deployed in Level 1 (shown in the top row of data under 'No'). These are either shorter (at the low and high lateral identity numbers) or require a 13.5% increase in section lengths (for the middle lateral numbers which cross the full width of the block). E.G. the cross-block lateral, Identity No 20, requires to be 1.89km rather than 1.666km for 30ppb, 2.84km rather than 2.5km for 10ppb and 4ppb, and 5.68km rather than 5km for 2ppb and 1ppb (1.89/1.66≈1.135, 2.84/2.5≈1.135, 5.68/5≈1.135).

engineering level laterals sections, with a required minimum of one lateral section per cross-block lateral. The second column, for each pad density, shows the length of lateral sections required to fill the reoriented cross-block laterals with the number of lateral sections employed in Level 1.

This cross-block lateral subdivision process shows that the length of sections across the block, used in engineering level, need to be increased by 13.5%, from the level one 10km laterals, to match the longest cross-block laterals. This 13.5% increase is consistent across all densities. The spatial application of this approach is illustrated in Figure F.10. This illustrates the cross-block laterals divided into sections to provide the number of subdivisions applied to laterals. Figure F.10 also shows the heels and toes of all possible lateral sections. The subdivision for 1 and 2 ppb densities and 4 and 10 ppb densities are common to both pairs of pad densities.


1 & 2 ppb

4 ppb

10 ppb

30 ppb

Figure F.10: Cross-Block Laterals Subdivided into the Number of Sections from Level 1.

Key: Black Lines = OS 10km^2 Licence Block Boundary. Coloured Lines with Dots at Ends = The ends of subdivided lateral sections, showing both the heels and toes of lateral sections. **Notes:** The lateral sections for 1 and 2 ppb density are common to both. For 4, 10 and 30 ppb densities it is notable that the middle latitude cross-block laterals can be conveniently subdivided whilst in the north-west and south-east parts of the block the cross-block laterals subdivide into three, two or one sections with varying section lengths.

The implications of the variations in length of lateral sections appears to undermine the efficiency of the exploitation of the shale unit. There appears to be three significant consequences of the reorientation of the laterals to take account of the authentic maximum horizontal in-situ stress (S_{Hmax}). These are:

- When the number of subdivisions of cross-block laterals applied in Level 1 is deployed the length of sections exceeds the standard length of lateral sections applied in engineering level. To cover all the laterals within a block effectively, particularly for mid-block laterals (LIN 14 to 27)(Lateral Identity Number = LIN in Table F.3) it appears the lateral sections need to be increased in length. For example, looking at the 1ppb density, without increase the lateral section it would not be possible to cover all the shale within a block. This shows 27% of the remaining 95.6%, from shortening the laterals, of the shale unit within a block, would be inaccessible. Table F.3 shows that the number of lateral sections subdivisions, applied in level 1, need to be increased by 13.5% to cover the shale unit (remaining after shortening). Without this extension of lateral sections, the authentic orientation of maximum horizontal in-situ stress results in a considerable reduction in the accessible shale unit.
- The lateral sections at the north-west and south-east parts of the block are exceedingly short. To reach them requires a considerable length of unproductive cross-reaching borehole, giving a poor ratio of productive length to overall borehole length. Whilst multilateral completion could be employed to access adjoining laterals from a common vertical borehole (Society of Petroleum Engineers 2017) the shortest laterals (LIN 1 and 40) appear unviable. These lateral sections are removed from subsequent analysis.
- The organisation of fracture zones into viable groups to be accessed by a pad appears to be problematic. Whilst the mid-block laterals (LIN 13 to 28) appear to be capable of being grouped conveniently, the lateral in the north-west (LIN 1-12) and south-east (LIN 29-40) appear irregular. Whilst this does not of itself present a problem, as boreholes can transverse in any direction, the overall efficiency the shale gas production may be affected. Whilst the overall economic viability of basin wide development is not considered in this thesis it seems appropriate to consider whether some rationale of productive length to the overall borehole length should be applied.

F.3.4 GROUPING OF HEELS EFFICIENTLY FOR ACCESS FROM PADS

If the cross-block lateral subdivision process is to be applied, consideration needs to be given to the grouping of lateral sections and fracture zones, and the way these can be organised to balance the access from pads. To investigate how these might be organised into groups to be accessible from a pad, Figure 4.12 shows the laterals sections (from Figure F.10) highlighting the heels with a dot. The lateral toes are not shown since the object is to link the pads to the lateral heels. In Figure 4.12 pairs of heels which are sited at the same point are only shown once. For the 1-ppb density the obvious location of a pad remains the centroid of the block. For the 2-ppb density the optimum pad locations appear to be close to the central line of heels, somewhere around the quarter laterals (LIN 10 and 30). For the 4-ppb and 10-ppb densities there are 112 lateral sections suggesting that at 4-ppb each pad should connect to approximately 28 lateral heels, whilst for 10-ppb each pad should connect to 11 or 12 heels. For the 4-ppb the optimum pad locations appear to be one pad on each of the two vertical columns of heels at LIN 20 or 21, with one pad each centrally within the other areas of heels in the north-west and south-east. This leaves the two pads (on LIN 20) connecting to 32 sections and two pads (centrally on LIN7 and LIN33) connecting to 24 sections. For the 10-ppb density the optimum pad locations appear to be three pads on each two vertical columns of heels (at LIN 13, 20 and 25 for the west row and LIN 14, 20 and 27 for the east row), with two further pads in each of the north-west and south-east corners (centrally at LIN 5 and 36, covering the single direction section north-east of LIN 10 and south-west of LIN30). For the 30-ppb density there are 168 lateral sections within the block, suggesting 5 to 6 heels per pad are required. The optimum grouping appears to be a line of eight pads down each side of the block and four or five centrally connecting six heels each. This leaves two group of sections, along the north and south of the block, which can be grouped into four pads each in the north and south. For the northern and southern groups two pads have six heels whilst two pads have a pair of heels together with three single heels. In all of these possible pad organisations LIN 1 and 40 have been excluded.

Table F.4 shows the parameters for lateral section coverage resulting from the alignment of laterals to suit the authentic maximum horizontal in-situ stress (S_{Hmax}) for the Bowland basin, for each pad density.

Table F.4: Parameter for Laterals Coverage for Pads, for Subsurface Level

	30 ppb	10 ppb	4 ppb	2 ppb	1 ppb
Number of Laterals across Block	40	40	40	40	40
Number of Active Laterals across Block	38	38	38	38	38
Total Active Laterals Length -km	285.44	285.44	285.44	285.44	285.44
Number of Lateral Sections	166	120	120	64	64
Average Lateral Section Length -km	1.72	2.38	2.38	4.46	4.46
Maximum Lateral Section Length -km	1.89	2.84	2.84	5.86	5.86
Number of Pads Per Block	28	10	4	2	1
Average Number of Lateral Sections per Pad	5.93	12	30	32	64
Average Number of Boreholes per Pad	5.93	12	30	32	64
Total Number of Boreholes per Block	166	120	120	64	64
Fracture Zone Width – km	0.333	0.333	0.333	0.333	0.333
Total Area Coverage – km^2	95.15	95.15	95.15	95.15	95.15

Close study of this information, for example Table F.3 and Figure 4.12, shows that some cross-block laterals are divided into an even number of laterals sections whilst other are divided into an odd number of sections. Where the sections are even this results in pairs of heels overlapping. However, where the number of lateral sections is odd this results in one heel on the lateral without an overlap. For example, in Figure 4.12 for 1&2-ppb all the central heels are pairs whilst the outer heels, near the northern and southern block boundary are single heels. Pairing heels is generally advantageous to efficiency as this focuses the mean coordinates and result in closer proximity of pad locations. In the cases where heels do not overlap in a pair, as along the boundary of Figure 4.12 1&2-ppb, the heels could be located at either end of the lateral sections. They could be at either the south-west or north-east ends.

Figure F.11 illustrates the cross-reaching boreholes which connect the pad/heel groupings, for at the 2-ppb density, where some heels near the northern and some near the eastern boundary used. These are grouped to show the difference for the northern and southern pads. These pad positions provide the shortest aggregate length of cross-reaching bores to connect the pad with all the heels within each group. By applying weighting, the calculation recognises that some heel locations provide access to two laterals whilst other only account for one. Table F.5 shows the resulting distances of cross-reaching boreholes for the northern and southern pads. Using 'mean coordinates', it is shown that positioning the heels for these are optimised by being on the northern and southern boundary, rather than eastern and western, as shown in Figure 4.12 and other Figures. When the heels are positioned near the northern and southern boundary the arrangement is 19% (58/48.8) horizontally more efficient than placing the heels near the east and west boundary. However, this differential is reduced to 4% when the near-vertical boreholes are considered to connect the heels at 3km depth (115.4/110.7). This process of optimisation, using mean coordinates, is applied throughout the remain process of finding the optimum position for pad locations.

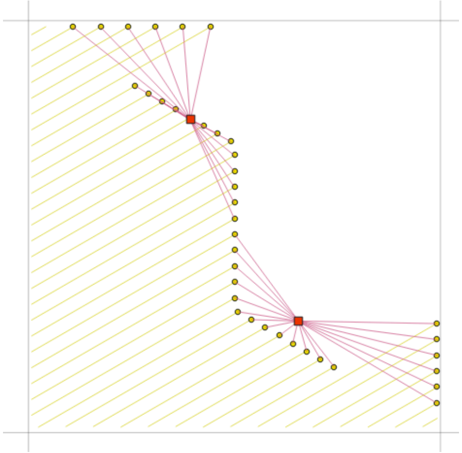


Figure F.11: Lateral Section Heels, Pads and Cross-Reach Near-Vertical Borehole Pattern Options, for 2ppb Density.

Key: Grey Lines = OS 10km^2 Block. Yellow Lines = Laterals Sections (orientated at 60-240 degrees, running south-west of the central line of dots only, for clarity). Yellow Dots = Heel of Lateral Sections. Red Square = Optimised Pad Positions. Red Lines = Cross-reaching near vertical boreholes. **Notes:** The shortest laterals 1, in the northwest, and 40, in the south east, are not connected.

Having assessed the potential grouping of heel/pads the grouping and optimum positions for pads is determined by applying mean coordinates analysis. Appropriate weighting is given where heels overlap in a pair to serve two lateral sections. This approach, of cross-block lateral subdivision and then grouping heels served by pads so that the block wide mean coordinates of all groups is minimised, is applied to all pad densities. This is the most efficient approach to spatial organisation of fracture zones, laterals, heels and pads, when the orientation of maximum horizontal stress is at 150-330 degrees. Figure 4.13 shows the positions for pads, for the base block at each pad density, which optimises both the heel groupings and the pad position for the group. This Figure also shows the cross-reaching near vertical bores connecting pads to the group of heels.

Table F.5: Distance of Horizontal and Cross-Reaching near Vertical Borehole to Connect Pads and Heels, for 2ppb Density

Cross-Block Lateral Identity	Horizontal Distance between Pad and Heel Point				Distance of Near-Vertical Borehole from Pad to Heel, at 3km depth			
	North Pad		South Pad		North Pad		South Pad	
	West Column	East Column	West Column	East Column	West Column	East Column	West Column	East Column
Lateral 2	3.64				4.72			
Lateral 3	3.14				4.34			
Lateral 4	2.72				4.05			
Lateral 5	2.41				3.85			
Lateral 6	2.27				3.76			
Lateral 7	2.31				3.79			
Lateral 8	1.58	1.58			3.39	3.39		
Lateral 9	1.19	1.19			3.23	3.23		
Lateral 10	0.81	0.81			3.11	3.11		
Lateral 11	0.43	0.43			3.03	3.03		
Lateral 12	0.05	0.05			3.00	3.00		
Lateral 13	0.35	0.35			3.02	3.02		
Lateral 14	0.73	0.73			3.09	3.09		
Lateral 15	1.12	1.12			3.20	3.20		
Lateral 16	1.37	1.37			3.30	3.30		
Lateral 17	1.64	1.64			3.42	3.42		
Lateral 18	1.95	1.95			3.58	3.58		
Lateral 19	2.28	2.28			3.77	3.77		
Lateral 20	2.63	2.63			3.99	3.99		
Lateral 21			2.61	2.61			3.98	3.98
Lateral 22			2.31	2.31			3.79	3.79
Lateral 23			2.04	2.04			3.63	3.63
Lateral 24			1.81	1.81			3.50	3.50
Lateral 25			1.65	1.65			3.42	3.42
Lateral 26			1.48	1.48			3.35	3.35
Lateral 27			1.13	1.13			3.21	3.21
Lateral 28			0.81	0.81			3.11	3.11
Lateral 29			0.58	0.58			3.06	3.06
Lateral 30			0.56	0.56			3.05	3.05
Lateral 31			0.76	0.76			3.09	3.09
Lateral 32			1.07	1.07			3.19	3.19
Lateral 33			1.42	1.42			3.32	3.32
Lateral 34				3.37				4.51
Lateral 35				3.40				4.53
Lateral 36				3.47				4.59
Lateral 37				3.58				4.67
Lateral 38				3.73				4.79
Lateral 39				3.91				4.93
Total – km	48.8		58.0		110.7		115.4	

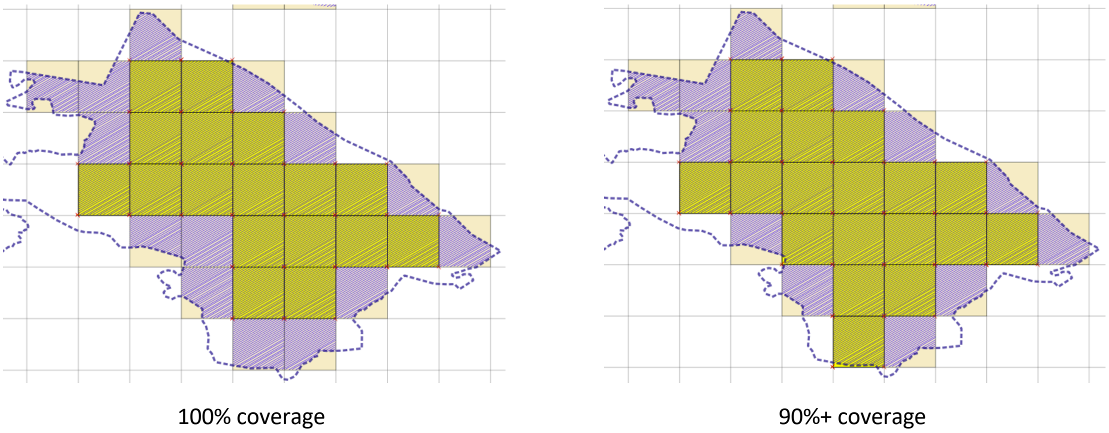
Notes: Lateral 1 and 40 are omitted due to lack of viability.

F.3.5 ADDRESSING THE COVERAGE OF AN AUTHENTIC SUBSURFACE SHALE UNIT

The pad pattern arising from these heel groupings, established under the process set out in section F.3.4, provides the most efficient coverage of the shale unit for the base block. This approach is applicable where a block has full shale cover. However, 36 of the 96 study blocks

(37%) do not have full coverage of the shale unit. There is therefore a need to address how the fracture zones, lateral sections and pad pattern will be adapted where there is only partially shale unit coverage within a block. This section addresses this issue.

Figure F.4 showed the locations where study blocks have only partial shale unit coverage. Figure F.12 illustrates a typical coincidence of the shale unit with 10km^2 blocks which have at least 50% coverage of shale unit, in more detail. Is shows a small selection of the shale unit and the overlap of the 10 km national grid block. Whilst blocks with at least 70% shale coverage have been selected for study, this Figure illustrates the general coincidence of blocks and shale unit. Whilst the central body of blocks have full coverage the blocks at the perimeter of the shale unit are limited in cover. Some blocks have almost complete cover. The right image in Figure F.13 shows block which have at least 90% shale unit coverage. For study blocks which have 100% shale unit and for study blocks with at least 90% shale the base block pattern of organisation is applied with minor modification to allow for the slightly reduced coverage.


100% coverage

90%+ coverage

Figure F.12: Typical Area of Shale Cover and Coincidence with 10km^2 Study Blocks.

Key: Grey Lines = OS 10km^2 Block. Blue Dotted Line = Extent of the Shale Unit. Coloured Blocks = Study Blocks. White Blocks = Non-Study Blocks. Yellow Highlighted Blocks = Blocks with High Shale Coverage - Left image with 100% shale coverage, Right Image with 90% or more shale coverage. Purple Area = Shale Unit coverage within study blocks with less than 100% coverage (left) and 90% coverage (right). **Notes:** Blocks with less than 50% shale unit coverage are excluded from the study. Out of the 31 study blocks shown 17 have 100% shale unit cover and a further 2 have at least 90% cover, leaving 12 with between 50% and 90% cover. The white block within the shale unit, to the west, is excluded from the study as it lies within a restricted high value scenic area.

Where study blocks have less that 90% shale unit cover a three-step process is applied to adjust the fracture zones, lateral sections, heels and pad positions, for each pad density. This process consists of:

1. The cross-block laterals from the base block, as in Figure F.10, are overlaid across the affected blocks. The shortened cross-block laterals are used to avoid fracture zones overlapping blocks. This is then sieved against the shale unit coverage to remove any part of the lateral which is not engaged with the shale unit.
2. The remaining engaged lengths of cross-block laterals are then reorganised and subdivided according to the maximum lateral section lengths, for each pad density (from Table F.6). Any lateral section lengths below 0.5km are removed.
3. The process outlined above for organising lateral heels, groups of heels and the optimum location for pad, using mean coordinates (Section 4.16) is applied to each block. In a few cases parts of cross-block laterals and lateral sections become isolated. These are removed. Data is then extracted on the area of shale coverage as well as the boreholes and laterals lengths, for each pad.

F.3.6 COMPLETING THE SUBSURFACE ASSESSMENT

Having established the position of pads across the Bowland basin, which recognise the partial coverage of the shale unit and the authentic orientation of maximum horizontal in-situ stress (S_{Hmax}), the final steps are required to complete the assessment for the subsurface level. This section outlines these final steps.

Since there is no residential population in this third level, the noise and visual impact are not significant. However, this level does require the traffic effect to be assessed. This involves two steps: the calculation of the level of traffic and the distance which the traffic needs to travel. Since the pad locations have been changed from the previous level, both of these need to be recalculated. The materials used for each pad varies as the length of laterals and boreholes will have changed as the length of lateral sections, size and organisation of fracture will have all changed. In particular the length of laterals section has been increased significantly. Table F.6 shows the data on length of lateral sections and boreholes for a base block arrangement (which apply to 60% of the 96 study blocks). Since surface level requires an entirely new arrangement of pad locations, the data on the distance from pad to major road junctions need to be fully revised. The one except to this is the 1-ppb pad density, where the single pad per block remains in the same location. To take account of the revised pad locations and the variance in the materials required the core traffic assessment (Section 4.10) is repeated for all pad densities, at this level.

Table F.6: Final Parameters for Laterals Sections and Boreholes for Subsurface Level for a Block with 100% Shale Cover

Parameters.	30 ppb	10 ppb	4 ppb	2 ppb	1 ppb
Number of laterals across block	40	40	40	40	40
Number of active laterals across block	38	38	38	38	38
Total active laterals length -km	285.44	285.44	285.44	285.44	285.44
Number of lateral sections	166	120	120	64	64
Average lateral section length -km	1.72	2.38	2.38	4.46	4.46
Maximum lateral section length -km	1.89	2.84	2.84	5.86	5.86
Number of pads per block	28	10	4	2	1
Average number of lateral sections per pad	5.93	12	30	32	64
Average number of boreholes per pad	5.93	12	30	32	64
Total number of boreholes per block	166	120	120	64	64
Fracture zone width – km	0.333	0.333	0.333	0.333	0.333
Total area coverage – km^2	95.15	95.15	95.15	95.15	95.15

F.4 How the Residential Receptors Affects the Calculations

The next step up in the model takes account of the presence of local environmental effects arising on residential receptors. This is level four of the modelling. In the earlier stages of its development, the model has taken account of the petroleum engineering, in first level, the surface geography with the real-world roads network in second level, and added an authentic disposition of the shale unit by including the subsurface in the third level. In all of these earlier stages the presence of the residential population has been omitted. This meant that environmental effects of noise and visual amenity were not considered. Without the presence of human receptors, these effects were not significant. In this final step up in the model the presence of a human residential population is incorporated and the environmental effects of noise and visual amenity need to be taken into account. This section explains how these factors are taken into account, what adjustments need to be made to the earlier levels of the model and how the model is adjusted to recognise the presence of a human population.

It is instructive to appreciate how extensive the area occupied by the residential areas is as it shows the scale of the potential for interaction between SGD activity and residential receptors. The land area occupied the local residential population is provided in Table F.7. This gives details on the extent of the residential land use areas within the 96 model study blocks. The block with the greatest residential land use has 49.5% cover whilst the block with the lowest residential land use has just 0.028% cover. The average residential land use within the study blocks is 11.5%. Whilst this is not a heavily populated area there is clearly potential of interaction between the SGD activity and the local population.

Table F.7: Residential Area Coverage for 96 Study Block.

	Number of Blocks	% Average Coverage
Blocks with more than 40% residential area coverage	2	46.5%
Blocks with 30% to 39.9% residential area coverage	7	33%
Blocks with 20% to 29.9% residential area coverage	16	24%
Blocks with 10% to 19.9% residential area coverage	30	14.6%
Blocks with 5% to 9.9% residential area coverage	20	7.0%
Blocks with less than 5% residential area coverage	47	2.5%
All Blocks	96	11.5%

A key requirement for adding the human receptor component to the model is data on the disposition of the population within the Bowland basin. Typically, this would be shown in the form of residential land use zones. Much of the generic base spatial data used in this modelling has been taken from Ordnance Survey Open Data (Ordnance Survey 2020).. Many OS maps show residential property and details on places. However, unfortunately these maps do not provide data on the disposition of the human population in a suitable format for processing within this model. In contract Open Street Map (OSM) (OSM 2020) provide spatial data on land use which includes residential land use areas. Figure F.13 illustrates an OSM map giving land uses, including residential areas. This data has been assessed, against OS mapping, and is found to have a high-level of accuracy. The OSM residential land use areas can be extracted from OSM maps as a separate vector dataset. The subsequent modelling is therefore based on OSM residential land use area data. It should be noted that this data provides residential land use areas and does not distinguish individual properties.

Consequently, individual residential properties in other land use zones, such as farmhouses located in agricultural areas, are excluded from the subsequent analysis.

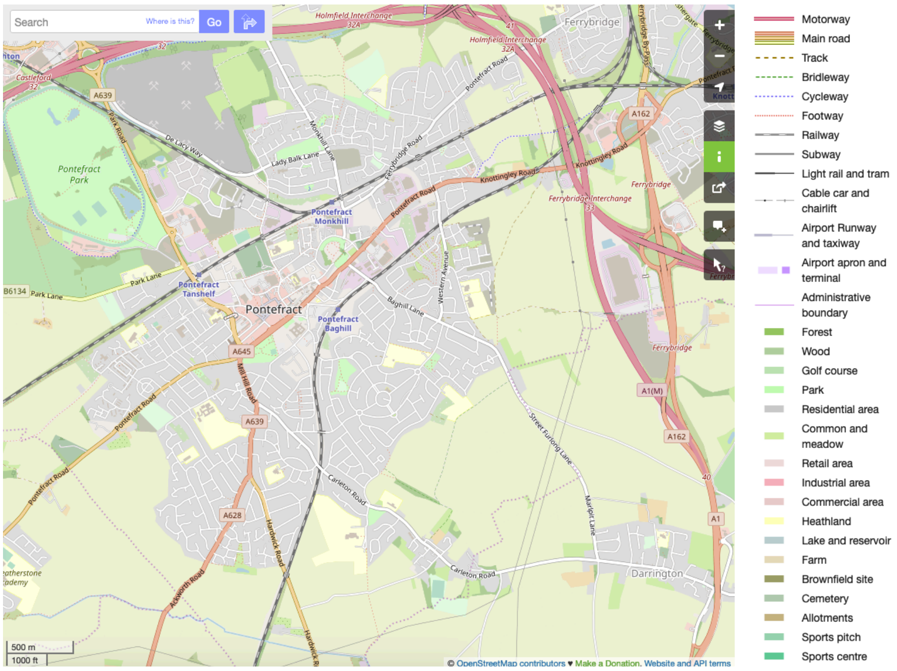


Figure F.13: Residential and Other Land Use Areas on Open Street Map.

Notes: Screenshot showing Open Street Map land use zones in and around a settlement, together with the legend (on the right). The residential land use areas are shown in light grey. **Source:** OSM 2020.

This final level of the model assesses the effects of noise and visual amenity on the residential population together with the engineering arrangements, the real-world road network for Northern England and an authentic disposition for the subsurface shale units. The following sections detail how the effects of noise and visual amenity on the residential population is taken in account. This results in the need to relocate pads, to mitigate the effects on the population. The following sections sets out how the adjustments to the model and explains how recalculations of the model are made.

F.4.1 TAKING ACCOUNT OF NOISE, VISUAL AMENITY EFFECTS AND THE RESIDENTIAL POPULATION

Details on the environmental effects of noise and visual amenity have been discussed in Chapter 3 and in Chapter 4. These showed that the effects of noise and visual amenity broadly decline with increasing distance from SGD sites. Whilst there are periods where SGD sites produce no or very little noise, during the site construction, drilling and hydraulic fracturing phases (see Section 3.5 for details) noise is a significant environmental effect. Similarly, for much of the time of the existence of an SGD site the pad is screened by medium height (approx. 10m) security and screen fencing. During the drilling and hydraulic fracturing phases tall rigs are required, up to 60m high, to facilitate the operation. Figure F.14 shows the comparative radial spread of the noise effect for each phase of SGD operations. Except for the access track, which runs from the pad to the south west, the noise profile consistently declines radially around the site. The colour coding, representing levels of noise generated, is consistent between phases. As can be seen the hydraulic fracturing phase (bottom left) shows the greatest spread of noise, followed by the site construction phase (top left), well testing phase (bottom right) and the drilling phase (top right). The boundary between the brown and yellow colouring marks the boundary the 50dB noise level. For the hydraulic fracturing phase this is some 350m from the pad. For the drilling phase it is within 100m of the pad.

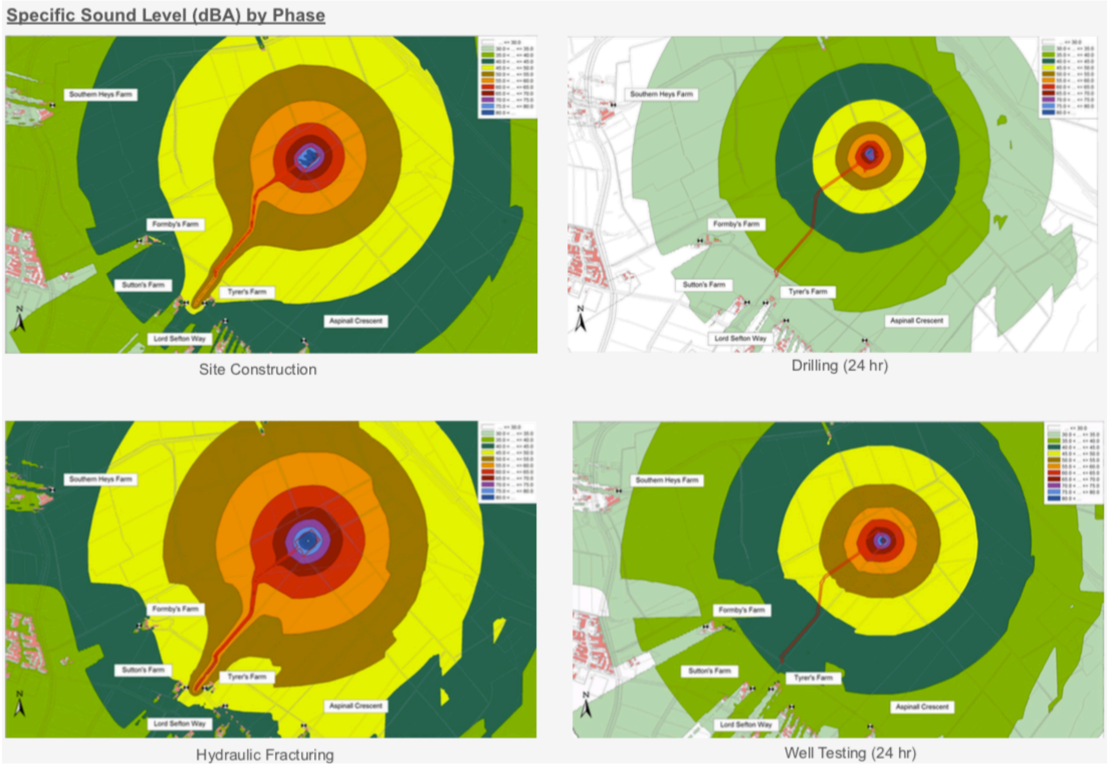


Figure F.14: Radial Decline Effect of Noise from a Shale gas Development Site.

Notes: Noise Assessment for main phases at Altcar Moss, Lancashire. Radial extent of noise levels from fracking site in a flat topography shows the decline of noise as distance increases. The finger out to the South West reflects traffic use of an access track whilst barrier of buildings in the outer areas is also visible. Reproduced by permission from Aurora Energy and RPS Group. Base map with Crown Copyright Ordnance Survey 2019. **Source:** Aurora Energy 2019.

Whilst part of the environmental effect of noise relates to the level of noise a receptor incurs a second component of the noise effect from its duration. A short period of noise is likely to have a less detrimental effect than a noise continuing over a long duration. During the earlier levels of the model no consideration has been given to the duration of SGD activity. However, it is reasonable to deduce that the duration of activity will vary on any single pad, with pad density. It is not unreasonable to assume, for modelling purposes, that drilling and hydraulic fracturing activity takes place at the same rate across all pad densities. So, for example, for drilling activity a given rate of metres drilled per day would apply. Where there are pads with greater lengths of borehole to drill, which occurs at lower pad densities, then the activity on pads will be more protracted than on a pad on higher pad densities with less drilling activity. Table F.9 estimates the duration of drilling activity for pads at each assessed pad density. The data on the aggregate length of boreholes for each pad is taken from Table F.8. The impact of visual amenity is also likely to be more significant with a greater duration of activity. Similarly, any visual intrusion into the landscape from SGD activity is likely to increase in environmental significance if it last considerably longer.

Table F.8: Estimate of the Duration of Drilling Activity Per Pad, by Pad Density

Parameters.	30 ppb	10 ppb	4 ppb	2 ppb	1 ppb
Aggregate length of all borehole per pad -km	10.2	28.5	71.4	142.7	286
Production rate (with one drilling rig and one HF pump set per block) – metres per day	100	100	100	100	100
Duration required for production rate - days	102	285	714	1,427	2,854
Duration required for production rate (@ 240 workdays per year) – years	0.4	1.2	3.0	5.9	11.9

To address the environmental effects of noise and visual amenity consideration of mitigation needs to recognise both the spatial and duration effects that arise. The potential receptors on both noise and visual effects are the human population that maybe within the area of coverage of the effect. The appropriate form of mitigation would be spatial separation between the SGD site and the human population. For modelling purposes, mitigation is applied using a setback distance to separate pads from residential areas. To recognise the duration component of the noise and visual effects, the setback distance for pads with longer activity are increased. The separation distances, for each pad density, applied in this level of the model are stated in Table F.9. These are based on the approximated distance of the 50dB level shown in Figure F.14.

Table F.9: SGD Site Separation Distance from Residential Areas, by Pad Density

	30 ppb	10 ppb	4 ppb	2 ppb	1 ppb
Expected duration of production activity – years.	0.4	1.2	3.0	5.9	11.9
Site separation or setback distance between pads and residential areas (m).	200	275	350	425	500

F.4.2 MITIGATING ADJUSTMENT TO PAD LOCATIONS TO AVOID THE RESIDENTIAL POPULATION

To avoid a noise and visual amenity effect of residential areas a minimum clearance or setback distance is required from pads to residential areas. The first step to achieving this within the model is to assess whether any pads from the previous level are situated within or less than the minimum clearance distance of residential areas. This is established using the GIS. Residential areas, from OSM, are replicated across the Bowland basin and then a buffer zone is set up around residential areas, appropriate to the clearance distances required for each pad density (from Table F.9). Figure F.15 illustrates the typical result with buffer zones around residential areas. Many pads, from level 3, are situated outside the buffer zones and are therefore have no significant noise of visual amenity effects. Pads falling within residential areas and the surrounding buffer zones will produce significant noise and visual amenity effects. To avoid the effect from these pads, the pads need to be relocated to outside the buffer zones.

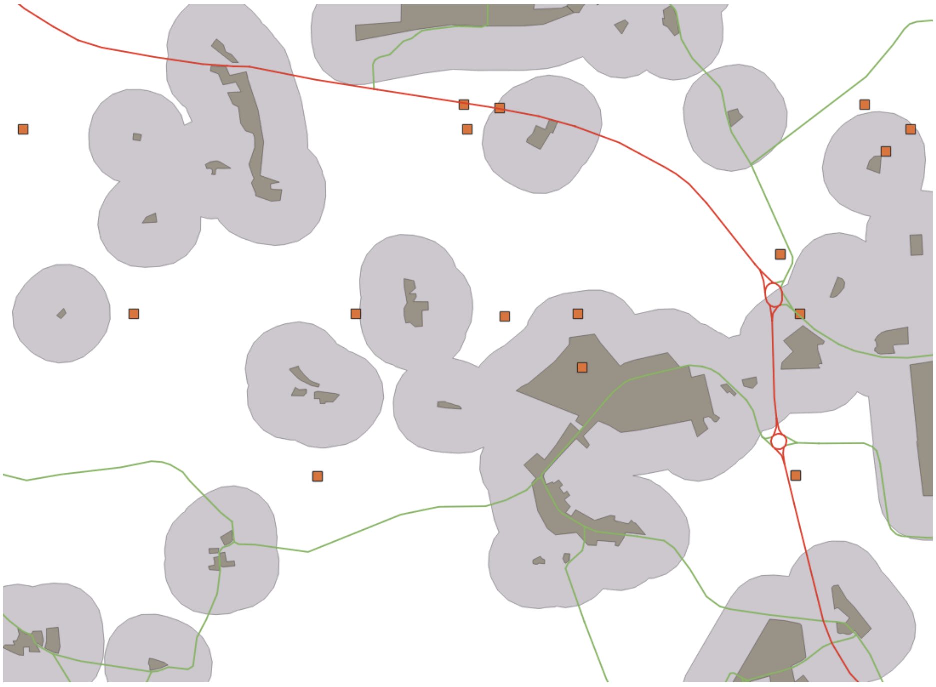


Figure F.15: Pads, Residential Areas and Setback Zones

Key: Orange Square = Pads. Dark Grey Area = Residential land use areas. Light Grey Area = Buffer or setback zones around residential Area. Red Lines = Major Roads. Green Lines= Local Roads. White area = Developable zone. **Notes:** Whilst several pads are outside buffer zones some pads fall with residential areas or buffer zones.

The pads which need to be considered for relocation are identified using GIS. For modelling purposes, the relocation of pads is based is based on the process set out in section 4.9.2. Areas outside the residential areas and their appropriate buffer are distinguished as 'developable zones'. Pads must be located within both the developable zones and a pads own development tract. Details on how development tracts are established is set out in Section 4.9.2. Table F.10 sets out the extent of development tracts each pad density. This limit is set taking account of the expected angle of near vertical boreholes in the earlier levels of the model. As might be expected, the scope for horizontal adjust is lowest amongst high densities as the angle of boreholes is more restricted.

Table F.10: Scope for Relocating Pads Whilst Retaining the Fracture Zone Coverage from Level 3.

	30 ppb	10 ppb	4 ppb	2 ppb	1 ppb
Horizontal limit of development tracts -km	0.510	1.010	1.991	2.450	4.441

Where study blocks are affected by pads that require significant adjustment after the location of residential areas have been taken into account a three-step process is applied. This process adjusts the fracture zones, lateral sections, heels and pad positions for each affected block, taking account of the parameters for each pad density. In some cases, only the vicinity around the affected pad is reorganised. In a few cases, this requires a complete reorganisation of activity across the whole block. This three-step process is:

1. The cross-block laterals from the base block, as in Figure F.10, are overlaid across the affected blocks. The shortened cross-block laterals are used to avoid fracture zones overlapping blocks. This is then sieved against the residential area buffer coverage to remove any part of the lateral which cannot be access from areas outside the residential buffer zones.
2. The remaining engaged lengths of cross-block laterals are then reorganised and subdivided according to the maximum lateral section lengths, for each pad density (from Table F.6). Any lateral section lengths below 0.5km are removed.
3. The process outlined above for organising lateral heels, groups of heels and the optimum location for pad, using mean coordinates (Section F.3) is applied to each block. In a few cases parts of cross-block laterals and lateral sections become isolated. These are removed. Data is then extracted on the area of shale coverage as well as the boreholes and laterals lengths, for each pad.

Appendix G: Goods Vehicles Load Factors

This appendix sets out how the goods vehicles load factors are calculated. Table 5.11 in the Results Chapter 5 sets out the vehicle load factors in proportion to an identified unit of the shale gas development process. For example, for aggregates (material used for creating the base of a pad in the site construction category) requires a set number of loads per hectare. These load figures are important in determining how many journeys are made by vehicles involved in the shale gas development process and therefore are a key determinant of the SGD traffic effect. They reflect the amount of work effort required to develop the shale gas on each pad, as a direct consequence of the scale of development on each pad such as the length of all bores drilled and hydraulically fractured. The volume of traffic is a major contributor to the 'Distance travelled on Local Roads' results (Table 5.16).

The figures in the 'Loads' column of Table 5.11 are the result of a calculation of the load factor which is not shown in the table. This Appendix explains how these 'load' figures are composed and give details on the data sources used. Against each row in the table a reference (ref) number is provided in the right-hand column. The information given here is organised according to these reference numbers. Several of the load factors are based on the information provided by the developers who submitted planning applications for recent proposed shale gas development and exploration sites in the Bowland basin (Section 3.5). Rather than repeating this for each item this information is simply referred to as the 'developer information'. Some of the load factors information require technical specification for petroleum engineering equipment. These include borehole casings and linings as well as the drill string used to bore the boreholes. These petroleum engineering equipment technical specifications are taken from the Society of Petroleum Engineers (2020).

Details of the load calculation from Table 5.11 are as follows:

Site Construction: The site construction requires: machinery to clear and construct the pad; a geotextile is laid to provide a waterproof and chemical seal to prevent pollutants from running off the site; an aggregate based is laid and compacted to allow vehicles personnel and requirement to move around the site; the site needs to be secured for public safety and security; and site offices and storage are needed for the duration of the pad's operations. Where access tracks are required the ground is cleared by the onsite machinery and an aggregate base laid as a roadway. Loads to carry materials for access tracks are added in proportion to the aggregate base assuming a track width of 4m. Site construction load calculation detail as follows:

1. Plant: 10 loads per pad- It is assumed that the machinery, such as excavators and bulldozers, required to construct the SGD site, or pad, is common across all pads, even though the time taken will vary according to the size of the pad. Based on developer information.
2. Geotextile: 5 loads per hectare of the pad- Estimated at: 80m2 coverage per geotextile roll gives 125 rolls per hectare; assumed 25 rolls per load. (Arup 2014).
3. Aggregate for base: 320 loads per hectare of the pad – Assumed that approximately 9,000t of aggregate per hectare are required, based: on 100m x 100m @ 0.622m depth; 1.4t of un-compacted gives 1 cubic metre compacted; delivered using 4 axle tipper truck with a gross vehicle weight of 36t provides a carrying capacity of 20t payload. (Arup 2014, Cloburn 2019, DoT 2003).
4. Security fencing: 5 loads per hectare of the pad – Estimated at: fence boundary is 400m per hectare; 2.5m high by 3m long fence sections; give 133.3 section per hectare; assumed 27 sections per load.
5. Office & Storage: 10 loads per hectare of the pad – Estimated at 10 loads for offices, storage containers, water and wastewater storage tanks. Noting that some storage containers will be delivered with materials.

Borehole drilling: To drill the boreholes: a drilling rig and its associated equipment is required; the boreholes are cased to seal these from the surrounding geology; including a conductor casing to stabilise the ground, a surface casing to protect ground water, an intermediate casing to seal the bore for the vertical length to the heel and production casing for the length of the borehole. Chemical muds are used during drilling to lubricate and cool the drill whilst cements are used to tie the bore casing to the surrounding soils and rock. The drill string used to drill the borehole with a drill bit on the end. Drilling boreholes load calculation details are as follows:

1. Drilling rig & associated equipment: 40 per pad- Estimated that the drilling rig will be delivered in component form and erected on site. Associated plant required to support the drilling rig operation. Based on developer information.
2. Conductor casing: 0.9 loads per bore- Estimated at: casing unit size of 9.5m length by 0.4m diameter; at 50m casing length per bore requires 5.26 unit per borehole; number of units per load determined by size; trailer flatbed over 10m long and 2.5m wide; carries 6 units across the width and 7 units high gives 42 units per load.
3. Surface casing: 1.4 loads per bore- Estimated at: casing unit size of 9.5m length by 0.34m diameter; at 300m casing length per bore requires 94.7 units per borehole; number of units per load determined by weight; net payload of vehicle is 29t; weight per unit is 1082kg; trailer flatbed over 10m long and 2.5m wide; number of units per load is 23.
4. Intermediate casing: 3.3 loads per kilometre of vertical bore- Estimated at: casing unit size of 9.5m length by 0.24m diameter; casing length determined by length of vertical bore to heel; number of units per load determined by weight; net payload of vehicle is 29t; weight per unit is 775.5kg; trailer flatbed over 10m long and 2.5m wide; number of units per load is 32.
5. Production casing: 2.4 loads per kilometre of the overall borehole length- Estimated at: casing unit size of 9.5m length by 0.1778m diameter; casing length determined by length of bore; number of units per load determined by weight; net payload of vehicle is 29t; weight per unit is 565.5kg; trailer flatbed over 10m long and 2.5m wide; number of units per load is 44.
6. Drill string: bespoke- Estimated at: drill-string unit size of 9.5m length by 0.127m diameter; number of units per load determined by weight; net payload of vehicle is 29t; weight per unit is 404kg; trailer flatbed over 10m long and 2.5m wide; number of units per load is 61. The required length of drill string on a pad is determined by the length of the longest borehole on the pad plus 25% of the remain aggregate borehole length on the pad. The drill string needs to reach to the toe of the longest borehole and thereby will reach the toe of all bores on the pad. The 25% is to allow for drill

string wear and tear. The calculation takes account of the need to remove the drill string at the end of drilling at the pad.

7. Drilling muds, cement and consumable materials: 1 load per kilometre of the overall borehole length- Estimate based on developer information.

Hydraulic fracturing: To carry out the hydraulic fracturing operation a set of hydraulic pumps is required together with their associated equipment. Whilst the prime ingredient of the hydraulic fracturing fluid is water other chemicals and additives are added to this including sand and surfactants. Water used in hydraulic fracture and the wastewater remaining after fracturing operations is excluded from the load calculation due to uncertainty of the requirement. Since the pads are envisaged as production sites it is assumed that water will be supplied through pipes from the local potable water distribution network. The volume of wastewater depends on the level of flowback from the fracturing process and the level wastewater recycling. The load assumptions for hydraulic fracturing are as follows:

1. Hydraulic pumps and associated equipment: 40 loads per pad- Estimated that the hydraulic pumps and the associated equipment are based on developer information.
2. Fracturing materials: 2 loads per kilometre of lateral section- Estimate based developer information.

Gas production phase: Assumed that no loads arise.

Site remediation: At the end of gas production operations, the pad needs to be cleared and the site reinstated back to its prior use. Before doing this all boreholes need to be capped and sealed. Site remediation essentially requires a similar number of loads to site construction. The assumptions for site remediation are as follows:

1. Plant: 10 loads per pad- Similar to site construction.
2. Removal of base aggregate: 320 loads per hectare of the pad- Similar to site construction.
3. Removal of other materials: 12 loads per hectare of the pad- Similar to site construction.
4. Office & Storage: 10 loads per hectare of the pad- Similar to site construction.

The development of shale gas pads will require personnel to attend sites to carry out the necessary operations. It is assumed that these personnel with travel by car or light bus. Whilst this will also increase the traffic visiting each pad it assumed that this type of traffic is not significant to the local environmental effects arising from SGD as the local roads should be suitable.

Appendix H: Circumstantial Findings and Operative Outcomes – Study Block Result Tables

This Appendix provides details of the tables which are presented in a digital spreadsheet for the Circumstantial Findings (Section 5.1) and the Operative Outcomes (Section 5.2). The spreadsheet is called Appendix H-Results-CircumstantialOperative.xlsm. It should be possible to open this spreadsheet in Microsoft Excel, OpenOffice calc or LibreOffice calc. The spreadsheet was written and is best viewed in LibreOffice calc.

Chapter 5 of this thesis present Circumstantial Findings (Section 5.1) and Operative Outcomes (Section 5.2) aggregated for all 96 study block, across the whole basin. The spreadsheet provides Circumstantial Findings and Operative Outcomes for each individual study block. The workbook consists of the following tabs or spreadsheets:

- Blocks: Lists the 96 study blocks. It identifies these as national grid alphanumeric 4-digit identifiers, for example SD30 (TileName). The spreadsheet also provides the full grid reference for each block in GIS format (wkt_geom).
- Shale: Provides the percentage shale coverage for each study block.
- ResidentialLandCover: Provide the circumstantial results of the proportion of each block's residential land use cover, in cells A1 to E106. In cells B112 to F209 it also provides the residential land use cover ranked, in descending order, by extent. Cells G1 to K108 provide the extent of 'developable zones' for each block. These take account and the residential areas, the required buffer zones around residential areas at the appropriate distance according to pad density and the administrative restriction of National Parks, Areas of Outstanding Natural Beauty and ground water source protection zone one.
- Roads: Provides the length of A-roads and Local Roads for each block. These are also combined and the extent of areas beyond 1km from an A-Road is given. An exercise

of trying to establish the length of A-roads outside residential areas was carried out. The results for this test are also shown.

- RoadResCorrelate: This provides the data and results for the correlation, with each block, between roads length and residential land coverage.
- Laterals: Provides the results for the aggregate length of laterals in each block. These are calculated after taking account of shale coverage, the orientation of lateral to 150-330 degrees and whether the pad is developable under the modelling.
- PadTracts: Provide the results for the area of each block covered by development tracts, for each pad density.
- TractIntsectZone: Provide the extent in each block of overlap between developable zones and development tracts. It is this area which can potentially accommodate pads whilst being outside residential areas buffer zones and within reach of the lateral heels which each pad needs to serve. For comparison purposes the results for developable zone and development tracts is repeated.

Appendix I: Analytical Results – Pads, Bores and Shale – Study Block Result Tables

Appendix I provides details of the tables which are presented in a digital spreadsheet for the Analytical Results, of section 5.4.3. Chapter 5 presents aggregated results for the whole Bowland basin. The spreadsheet present the results for each individual study block. The spreadsheet is called Appendix I - Results-Analytical-PadsBores&Shale.xlsm. It should be possible to view this spreadsheet in Microsoft Excel, OpenOffice calc or LibreOffice calc. The spreadsheet was written and is best viewed in LibreOffice calc.

The workbook consists of the tabs or spreadsheets for each applied pad density (1, 2, 4, 10 & 30 ppb). Each pad density tab provides the number of pads developed, the aggregate length of the bores from the pad to the heels, the aggregate length of lateral sections, the overall length of the boreholes and the consequent shale area developed, for each block. These results are pad which are deemed as developable under the modelling process.

Appendix J: Analytical Results – Distance travelled on Local Roads – Study Block Result Tables

Appendix J provides details of the tables which are presented in a digital spreadsheet for the Analytical Results, of section 5.4.5. The Chapter 5 presents the results for all study block aggregated for the basin. The spreadsheet presents the equivalent results for each individual study block. The spreadsheet is called Appendix J - Results-Analytical-LR_Dstances.xlsm. It should be possible to view this spreadsheet in Microsoft Excel, OpenOffice calc or LibreOffice calc. The spreadsheet was written and is best viewed in LibreOffice calc.

The workbook consists of the tabs or spreadsheets for each applied pad density (1, 2, 4, 10 & 30 ppb). For each density the spreadsheet provides the following results:

- The shale area developed.
- The number of pads developed in the block.
- The number of pads accessing the roads network directly via an A-Road.
- The number of pads accessing the roads network directly via a Local Road.
- The number of pads accessing the roads network via a Local Road but using an access track
- The aggregate access track length (where appropriate).
- The total number of loads required within the block.
- The aggregate distance of the local roads used within the block. Note that where two or more pads use the same roads each length is calculated for every time the road section is used.
- The aggregate distance travelled on local roads within the block.
- Where local roads are use, the distance travelled on local roads in each block, using local roads as a proportion of the area of shale developed.

A summary table is also given, which combines the pad density's' results for comparative purposes.