Department of Mechanical and Aerospace Engineering

Utilising GIS mapping to identify areas of opportunity for Photovoltaic Power Station deployment in an urban environment

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination, which has led to the award of a degree.

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Nomenclature

Abbreviations

AC	Alternating current
AHP	Analytical Hierarchy Process
CAA	Civil Aviation Authority
CEDA	Centre for Environmental Data Analysis
DC	Direct Current
DC	Direct Current
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
ESRU	Energy Systems Research Unit
EU	European Union
EV	Electric Vehicles
GCC	Glasgow City Council
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GOMap	Geospatial Opportunity Mapping

GSHP	Ground Source Heat Pump
GUI	Graphical User Interface
LiDAR	Light Detection and Ranging
MCDM	Multi-Criteria Decision Making
OS	Ordnance Survey
OUV	Outstanding Universal Value
PV	Photovoltaic
PVPS	Photovoltaic Power Station
QGIS	Quantum Geographic Information System
RET	Renewable Energy Technology
SEC	Scottish Exhibition Centre
SEPA	Scottish Environment Protection Agency
SNH	Scottish Natural Heritage
SPEN	Scottish Power Energy Networks
SSLI	Site of Special Landscape Importance
SSSI	Sites of Special Scientific Interest
STA	Solar Trade Association
UNESCO	United Nations Educational, Scientific and Cultural Organization
VDL	Vacant and Derelict Land

Symbols

GW	Gigawatt
GWh/y	Gigawatt-hours per year
km	Kilometre
kV	Kilovolt
kW	Kilowatt
$kWh/m^2.y$	Kilowatt-hours per square metre per year
m	Metre
m/s	Metre per second
MW	Megawatt
MWh/y	Megawatt hours per year
W/m^2	Watts per square metre

Abstract

At the present time there is much interest in deploying clean energy systems at the city level in the form of district heating, solar photovoltaics, ground/air source heat pumps and the like. Such deployments require consideration to be given to policy aspects that may affect the likelihood of receiving planning permission, and technical aspects that may constrain the economically achievable power production. The research reported here identified the factors underlying these policy and technical aspects and established scoring and weighting mechanisms derived from consultations with local authority planners and utility personnel. The high-resolution, city-wide information to result is represented as layers in a GIS tool for Geospatial Opportunity Mapping, named GOMap, which is applied to the city of Glasgow to investigate the potential for the deployment of PVPS throughout the city. It is found that utilising a portion of the city's VDL is equivalent to the heating energy requirement of the city.

This thesis describes the policy and technical aspects, the scoring applied to the factors underlying each aspect, the weighting method applied to the aspects, the functionality encapsulated within the GOMap tool, and the results from application of the tool at real city-scale.

Several scenarios are investigated with the focus on policy and technical changes intended to encourage the availability of greater land areas within the City of Glasgow and enable a comparison of alternative land use strategies – such as between VDL and other sites such as quarries. Scenario 1 is the base case in which all policy and technical aspects are active in the context of sites with the VDL designation. Scenario 2 is as Scenario 1 but with the future intention of community education programs and the disregarding of glare from PVPS by relaxing pertinent policy aspects. Scenario 3 is as Scenario 1 but with technical substation-related aspects disabled to reflect a future intention for radical infrastructure investment. Scenario 4 is as Scenario 1 but investigates new potential sites within the city in areas not previously designated VDL and meet certain conditions. Scenario 5 is a scenario that explores the deployment of PVPS on the roofs of multi-story car parks for the purpose of charging EVs. Scenario 6 explores the alternative use of VDL sites for house building to tackle the city's homeless issue. A land utilisation factor is set that allows for only a portion of an unconstrained land area to be utilised. This is required to reserve adequate space to

deploy and maintain the PVPS installation. To calculate the PVPS energy generation, the area of unconstrained land is passed to an in-built PVPS model where the potential energy yield is calculated as a function of solar geometry and hourly weather information.

GOMap can be specifically configured for other cities as the tool allows the scoring and weighting of the policy and technical aspects to be modified to reflect local policies and specific renewable energy technologies. The tool was rerun using irradiance data characteristic of these cities to indicate the potential supply for local heating/cooling and EV energy demand for PVPS deployment on sites designated for urban renewal development.

GOMap is made available under an open source licence and is free to download and apply. It has already been deployed in teaching and research context and has informed sustainable development planning within Glasgow City Council.

Chapter 1 – Introduction

1.1 Overview

This chapter introduces the principal themes of RET in urban environments, guidelines related to site selection, and the specific research objectives. There is an ongoing need to tackle rising energy demand and carbon emissions within cities with local governments driving policies towards sustainability. A number of site selection tools are utilised for large regions of land but few for urban environments. The focus of this thesis is to define a new evaluation method that combines policy and technical considerations relating to energy supply within the planning process for an urban city, encapsulate this method into a GIS tool, and apply it to a city.

1.2 Renewable energy systems in an urban environment

In many countries, there is legislative push towards sustainable energy supply solutions (Mirzania *et al* 2019, Papamanolis 2015, Erdiwansyah *et al* 2019, Castro *et al* 2019, Hua & Shiu 2018). This has resulted in initiatives to tackle climate change by investing in the renewable market to reduce carbon emissions. As ~37.5% of carbon emissions are due to the electricity supply sector, much of this could be reduced by sustainable means (Sims *et al* 2003, Scottish Government 2009, European Commission 2015). Further, energy from renewable sources allows for nearby communities to be provided for, reducing dependence on imported sources and providing greater energy security. Having diversity in energy supplies is also expected to reduce volatile fluctuations in the energy market and help to maintain stable energy prices (Correlje & Van Der Linde 2006). Investment in renewable energy projects could also provide a boost to the local economy by creating employment and a cleaner local environment (Dvořák *et al* 2017, Mitchell & Connor 2004). Such initiatives have given rise to significant developments such as the emergence of the EU Green Deal, which aims to reach net-zero greenhouse gas emissions by adopting policies that accelerate building renovation and reduce the waste produced by carbon-intensive industries such as steel, cement and textiles (European Commission 2019).

In recent times, cities have become aware of the need to tackle rising energy demand and carbon emissions and have accessed research funding to consider options for change. For example, the EU Horizon 2020 RUGGEDISED project (2016-2021) is generating sustainable energy exemplar districts within several cities, including

Glasgow, Rotterdam and Umeå (European Commission 2016), while Innovate UK funded Glasgow as a 'future cities demonstrator' of actions such as city-wide wireless networks, smart transport and intelligent street lighting (Innovate UK 2015). The drive towards sustainable cities has gained significant momentum, with reduced manufacturing costs and improved conversion efficiencies (Geldermann *et al* 2016), and it is possible that intra-city renewable energy technologies will become a major contributor to the energy needs of future cities in addition to overtaking the dominance of thermal power stations at the strategic level (Liu & Wang 2009). The underlying driver is that renewable energy is non-polluting, does not deplete natural resources and is sustainable (Baban & Parry 2001, Tsoutsos *et al* 2005, Asif & Muneer 2007, Pidgeon *et al* 2008).

1.3 Guidelines related to site selection

Smart technology rollout has led to the opportunity to move strategic power into cities in order to bring supply closer to demand and thereby reduce infrastructure costs and transmission losses (Fudge *et al* 2016). UK City Councils generally show interest in local energy solutions, especially where these are community based (Mirzania et al 2019). Identifying suitable deployment sites is the key to enabling local energy production that brings economic value (Kuiper *et al* 2013). Such Councils control the policy aspects that underpin city development in relation to site selection, urban expansion, natural resource management and regional integration (Li *et al* 2009, Bunruamkaew & Murayama 2011, Omitaomu *et al* 2012, Phuangpornpitak & Kumar 2007). However, the planning process generally excludes the technical aspects that underpin power production by dictating site suitability. For example, the planning process for Scotland in regards to project development is designed to support economic, environmental and social aspirations by balancing the benefits and costs over the long term (Scottish Government 2014). Various principles and decisions are enacted based on the following summarised guidelines in the policy document.

- Promote economic benefit and respond to economic issues and challenges.
- Make efficient use of existing land and building infrastructure.
- Support delivery of regeneration, housing, commerce and leisure projects.
- Support climate change mitigation and be aware of potential flood risks.
- Protect and improve the environmental landscape such as cultural and natural heritages and green spaces.

- Reduce waste by facilitating its management and promote resource recovery.
- Avoid over-development and protect the amenity taking into consideration the implications of development for soil quality, air and water.
- Offer opportunities to promote social interaction and development.

At the time of project commencement, it was common for renewable energy projects to have focused on technical constraints such as the energy resource potential, terrain suitability and access to power grid transmission lines (de Santoli *et al* 2019, Amjad & Shah 2020, Colak *et al* 2020, Pillot *et al* 2020). Other renewable energy projects have considered similar technical and additional policy constraints related to environmental, social and economic issues (Swofford & Slattery 2010, Messaoudi *et al* 2019, Marques-Perez *et al* 2020, Shao *et al* 2020). Although guidelines similar to the Scottish Planning Policy document are enacted elsewhere in the UK and beyond, a major issue observed in practice is that site identification for RET deployment in the UK typically does not consider detailed policy aspects provided directly by the local authority and detailed technical aspects provided directly by the local utility.

1.4 Research objectives

The central issue addressed in the present work is how to best relate policy and technical aspects in the context of site selection in the UK. While tools are available to evaluate the impact of energy systems deployments in new build and retrofit contexts (Charles *et al* 2019), there are a number of mapping tools used to identify site suitability that can be used to deploy new energy generation (these are discussed in Section 2.3). As these tools tend to focus on identifying site suitability in large regions of land and on single issues with limited information on other significant aspects, this gives rise to the need to develop a comprehensive evaluation method that encapsulates detailed information on the factors underpinning both policy and technical considerations in an urban environment.

The work reported here targeted the development and application of a new evaluation method that combines policy and technical considerations relating to energy supply within the planning process for any urban city. The primary and secondary objectives are specified as follows:

- To design a method to determine the renewable energy potential of any city utilising available land that is policy and technically unconstrained.
    - Gather information regarding policy aspects directly from the local government authority.
    - Gather information regarding technical aspects directly from the local utility provider.
    - Identify the relevant factors of policy and technical aspects that may affect site selection for PVPS deployment.
    - Design a grid system to create a spatial relationship between all policy and technical information.
    - Design a factor scoring system to differentiate between factors supporting, curtailing or remaining neutral in PVPS deployment.
    - Design a weighting system to determine the importance of each policy and technical aspect.
    - Design a PVPS model capable of calculating optimal parameters for deployment on sites based on local weather information.
    - Encapsulate this process in a GIS-based tool for use in city-scale sustainable development action planning.
- To apply this method to identify the unconstrained land within a city that is available for the deployment of PVPS.
    - Gather information regarding heating energy requirements for dwellings.
    - Gather information regarding electrical energy requirements for EVs.
    - Investigate the contribution such a deployment makes to the city's heating energy and EV energy requirements in future.
    - Investigate how the available land area can be increased through the adaptation of policy and technical considerations in future.
- To apply this method for an alternative use in identifying the unconstrained land within a city that is available for new build dwellings.
    - Gather information regarding density of dwellings within a city.
    - Gather information regarding population and homelessness within a city.
    - Investigate the contribution new build dwellings make to tackle the city's homeless issue.

- To apply this method to other cities of varying latitudes on sites available for urban renewal development for PVPS deployment.
    - Gather information regarding sites available for urban renewal development.
    - Gather information regarding weather.
    - Gather information regarding building heights and topography.
    - Investigate the contribution such a deployment makes to the city's heating/cooling and EV energy requirements.

To realise these objectives required the identification of myriad policy and technical factors that will dictate whether a given site will receive planning permission and be technology friendly. A factor scoring mechanism was required that is acceptable to both planners and developers, along with a weighting mechanism to accommodate the prioritisation of the policy and technical aspects as a function of development expectations. Finally, the developed method had to be encapsulated within a high-resolution GIS framework to support its routine application at the city scale.

The work reported here, undertaken within a study commissioned by Glasgow City Council as part of the Glasgow Future City Demonstrator project funded by Innovate UK (Energy Efficiency Demonstrator 2017), developed a GIS-based tool to enable the identification of land throughout a city that is both policy unconstrained and technically feasible in relation to the possible future deployment of renewable energy schemes (Clarke *et al* 2020). To date, journal and conference papers have been published and the findings of the project presented at the PLEA 2017 Edinburgh conference (Clarke *et al* 2020, McGhee *et al* 2017).

The next chapter introduces GIS technology and considers the methods developed to represent and rate the disparate factors that dictate the policy and technical aspects as applicable to a given city.

Chapter 2 – Literature Review

2.1 Overview

In Chapter 1, renewable energy systems and general guidelines used in the site selection process for RET deployment were introduced. This chapter introduces GIS technology, its importance to planning and developmental projects and the common methods used in existing site selection tools. Common themes between the examined tools are explored and include recurring aspects, the types of methods used, the weightings assigned to each aspect based on related studies, and the scope of the research conducted by the site selection tools. Research gaps are identified and information related to policy and technical aspects and their associated factors are collated. PVPS technology and inter-row spacing between arrays are also examined.

2.2 GIS technology

GIS technology is used to create, modify, analyse and visualise geographical data. It allows for basic data manipulation such as querying, editing and updating on two basic types of GIS data, vectors and rasters (Parker 1988). Vectors can be represented by discrete points (e.g. power stations, house locations); lines (e.g. power cables, roads); and polygons (e.g. building dimensions, regional areas). Information belonging to these vectors can be stored as textual and numerical values which allows users to populate the vector's underlying database. Rasters are image files which consist of pixels each containing a numerical value and is typically used to represent environmental, ecological and terrain information. Raster maps are also used for depicting aerial photographs, satellite imagery and thematic maps to represent multispectral data such as vegetation type. The term 'layers' is used to describe vector and raster maps loaded into a GIS software.

GIS technology has become a vital decision support tool for spatial analysis and planning. One of the biggest advantages of using such software in the planning stage is that it allows pre-defined criteria and constraints to be computed and visualised before any decisions are formally made (Eastman *et al* 1995). It also allows users to identify the specific policy and technical issues that might need to be managed or mitigated (Malczewski 1996).

GIS technology is also used increasingly in conducting spatial analysis and is widely considered as being an interdisciplinary and cross-industry platform (Luo *et al* 2012). Considering satellite imagery is available to anyone with access to GIS technology, many projects particularly those involving planning and development are no longer being conceptualised on pen and paper but instead represented computationally.

For this project, employing GIS technology would allow the development of a mapping tool to identify sites suitable for RET deployment. There are a number of tools developed to assess site suitability, some of which are examined in terms of the methods used and how the information is computed.

Many site selection tools use varying methods to create a final opportunity map but the information used as input for these tools play an important role in determining how accurate the final map is. Information can be sourced from various formats but some of the most commonly used are in the form of digital models: DSM, DEM and DTM (Jung *et al* 2021). These models are normally developed using remote sensing LiDAR technology attached to an airborne system which sends pulses of light towards the earth and by measuring the return time and combining other data such as the angle of pulses emitted, it is possible to create precise 3D models of the earth each depicting different types of high-resolution information with some as high as ~0.5 m (Novero *et al* 2019).

DSMs (raster) typically capture the natural and built features on the Earth's surface such as the rooftop of buildings, tree canopies, transmission lines etc. and due to this, plays a very significant role for a number of purposes (Ruzickova *et al* 2021). These purposes may relate to visual impact where urban planners use DSM to check how a proposed building would affect the viewshed of residents and businesses; or vegetation management to provide early warnings of vegetation encroaching areas of land in close proximity to transmission lines; or overshading by tree canopies and buildings which could drastically affect ground-mounted solar PV systems.

DEMs (raster) are topographic models depicting the bare-earth surface and excludes natural and built features (Liu *et al* 2012). These models are particularly beneficial when studying the topography of land including terrain stability where areas prone to avalanches are generally high slope areas with sparse vegetation; hydrologic modelling where hydrologists can delineate watersheds and calculate flow accumulation and direction; soil mapping where individual soil types can be mapped in relation to its surroundings.

DTMs (vector) are similar to DEMs as they represent the topography of the earth surface but only include elevation in the form of regular or irregular spaced points allowing the visualisation of contours (Ruzickova *et al* 2021). By incorporating contours, additional information can be extracted such as the sloping angle of land and its direction. Taking this new information allows new 3D models to be generated where terrain features are far more distinct and pronounced.

Outside of digital models, another common source of information is the shapefile (vector) which became the very first standard GIS vector format (Parker 1988). It is capable of storing 3 types of spatial information: points, lines and polygons; each feature can have many attributes associated with it to provide additional information to the user in the form of a database. One common use of shapefiles is determining protected buffer zones particularly for areas of sensitivity such as nature reserves, heritage sites or residential communities. Exploiting geospatial information from shapefiles can be used to calculate safe distances between potential sites and the buffer zone (Rylatt *et al* 2001). This method of creating new buffer zones can be included in a tool's workflow when generating the final opportunity map and has been used in site selection tools to discount areas where development is unfeasible.

It is important that the source information fed into these site selection tools is accurate and detailed to ensure the results are of equal quality. Regardless of the information type, there are many procedures of extrapolating new information from sources which can be done using GIS operations used extensively by tools to identify suitable site locations particularly for RET deployment. A number of these site selection tools are discussed in the next section.

2.3 Existing site selection tools

Utilising GIS technology, site selection tools are devised by researchers to assess site suitability when considering different pieces of information which itself is often grouped using various terminology. For this thesis, the following aspect names are used to collate associated factor information when reviewing the tools:

- Biodiversity (wildlife and plant information related to protection and conservation of special areas).
- Environmental (ecological and policy information related to protection and conservation of special areas and buildings).
- Proximity (distance information related to transport links, grid connection points, transmission lines and hydrological features).
- Terrain (topographical information related to slope, landcover and elevation).
- Visual impact (social information related to distance to and visibility from residential areas).
- Weather (climate information related to RET such as wind speed and solar radiation).

There are several methods used to process information for optimal site evaluation and coupled with weightings allows researchers to identify and prioritise aspects which are considered more significant than others, normally presented as decimal values or percentages totalling 1.0 or 100% respectively. Weightings are generally determined by the researchers following consultation with key investors, partners and policymakers (Günen 2021). The methods, aspects and weightings used in a number of site selection tools are described in the next section and summarised in Table 2.1.

2.3.1 MCDM

A number of tools involve the use of MCDM support allowing possible or alternative solutions to complex problems where multiple criteria affects a single goal (Kumar *et al* 2017, Abu-Taha 2011). This method normally involves the selection of restriction and evaluation aspects with regards to information which directly influence the desired RET and can be used in both vector and raster data models (Eastman 1999). In vectors, Boolean operators are often used if certain criteria are met such as the AND operator which involves combining or intersecting aspects; and the OR operator which involves either including or excluding aspects. For rasters, as it is a continuous grid-based representation, it can allow for more flexibility amongst aspects as those with low scoring criteria can be offset by another with a higher scoring criteria. Due to the different data model types, optimal solutions can vary allowing researchers to use a combination of GIS data models to control the degree of suitability.

Table 2.1. Site selection tools, methods and weighted aspects used for projects in various countries.

Site selection tools	RET	Method	Biodiversity	Environmental	Proximity	Terrain	Visual impact	Weather
Mauritius[1]	Wind	MCDM	-	-	0.090	0.400	-	0.510
Turkey[2]	Solar	MCDM/AHP	-	-	0.083	0.225	0.017	0.674
Iran[3]	Solar	MCDM/AHP	0.291	0.291	0.170	-	-	0.539
UK[4]	Solar	MCDM/AHP	0.069	0.065	0.328	-	0.049	0.489
	Wind		0.130	0.078	0.108	-	0.130	0.555
Spain[5]	Solar	MCDM/AHP	-	5.553	45.776	17.259	2.849	28.562
Indonesia[6]	Solar	MCDM/AHP	-	-	0.548	0.131	-	0.321
Saudi Arabia[7]	Solar	MCDM/AHP	-	-	0.131	0.271	0.032	0.565
Northern Ireland[8]	Solar	Weighted Overlay Analysis	-	0.112	0.081	0.370	0.036	0.400
USA[9]	Solar	Weighted Overlay Analysis	0.100	0.100	0.300	0.100	0.100	0.300
	Wind		0.100	0.100	0.300	0.100	0.100	0.300
Iran[10]	Solar	Weighted Overlay Analysis	-	-	0.080	0.320	0.100	0.500
UK[11]	Solar	Boolean Overlay Analysis	-	-	-	-	-	-
USA[12]	Solar	Boolean Overlay Analysis	-	-	-	-	-	-

[1] Cunden *et al* 2020
[2] Günen 2021
[3] Asakereh *et al* 2017
[4] Watson & Hudson 2015
[5] Sánchez-Lozano *et al* 2013
[6] Ruiz *et al* 2020
[7] Al Garni & Awasthi 2017
[8] Finn & McKenzie 2020
[9] Janke 2010
[10] Firozjaei *et al* 2019
[11] Palmer *et al* 2019
[12] Brewer *et al* 2015

For example, a wind farms project based in the island of Mauritius (Cunden *et al* 2020) included evaluation aspects regarding: environmental (nature reserves, permanent water bodies and Word Heritage Sites); proximity (grid connection points, roads); terrain (slope); visual impact (social); and weather (wind speed and direction). These aspects were weighted according to literature reviews conducted by the authors; however, it was found that there were no standards for prioritising the aspects as the importance of these differ from country to country. Consequently, the weather aspect was given the highest weighting (0.510) with the remaining aspects terrain and proximity given weightings (0.400 and 0.090 respectively) based on the context of the region being studied. The visual impact and environmental aspects were used to exclude regions protected by legal acts and were given no weightings. With this information and the level of flexibility coupled with buffer zones to narrow down the area of interest, the output of this tool yielded a wind resource map highlighting site locations for wind farms classified according to their potential wind power density. Although distances to transport links and grid connection points can play an important role in influencing the installation, operation and maintenance of wind turbines, they were considered least significant by the authors in determining optimum wind sites than weather factors such as wind speed or land suitability factors.

2.3.2 MCDM/AHP

Another method commonly used in conjunction with MCDM is AHP, a mathematical technique invented by Saaty in the late 1970s as a decision-making tool to resolve unstructured problems and employs a hierarchical or network-based structure where the upper level contains the primary objective of the analysis, and the lower level contains the main/sub-criteria (Saaty 1980). Each criterion is assigned a scale to determine the ideal weighting of each criterion in a given scenario. AHP is commonly used to split major problems into smaller individual problems that can be examined separately (Saraswat et al 2021).

The AHP technique is based on the pairwise comparisons method. The decision-maker forms a hierarchical decision tree and determines the importance of each individual criteria in comparison to all other criteria by using a 9-point scale system as shown in Table 2.2. The reciprocal values are used for inverse comparison. For example, a scale of 5 suggests a criteria has strong importance; an inverse scale of 1/5 suggests a criteria has weak importance.

Table 2.2. Scale for pairwise comparison (Saaty 1980).

Scale	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Values for inverse comparison

The pairwise comparison method incorporates the selected scale for each criterion, *a*, within a ratio matrix, *A*, in the following form (de Montis *et al* 2005):

$$A = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix} \quad (2.1)$$

where a_{ii} = 1 (the score of the ith alternative with respect to jth criterion), $a_{ji} = 1/a_{ij}$ (the inverse score), and $a_{ij} \neq 0$.

The weightings of each criteria are determined from normalising the ratio matrix by summing the values in each column of the ratio matrix (Malczewski 1999):

$$a_{ij} = \sum_{i=1}^{n} a_{ij} \quad (2.2)$$

where *n* is the number of criteria used.

Each element in the matrix is divided by its column total to generate a normalised pairwise matrix, X_{ij} (Malczewski 1999):

$$X_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ X_{n1} & X_{n2} & \ldots & X_{nn} \end{bmatrix} \quad (2.3)$$

The sum of each normalised column is divided by the number of criteria used to generate the final weighted matrix, W_{ij} (Malczewski 1999):

$$W_{ij} = \frac{\sum_{i=1}^{n} X_{ij}}{n} \begin{bmatrix} W_{11} \\ W_{12} \\ \cdots \\ W_{1n} \end{bmatrix} \quad (2.4)$$

An important procedure which typically follows the generation of the weighted matrix is to determine the Consistency Ratio, *CR*, to ensure the original preference ratings were consistent and is given by the following expression (Saaty 1980):

$$CR = \frac{CI}{RI} \quad (2.5)$$

where *CI* is the Consistency Index and *RI* is the Random Index.

The Consistency Index is a measure of inconsistency to determine how reliable the decisions were made in relation to several criteria of purely random judgments, and is equal to zero when $n < 3$ or when all judgments are perfectly consistent (Donegan & Dodd 1991, Kent & Williams 1988):

$$CI = \frac{\lambda - n}{n - 1} \quad (2.6)$$

where λ is the average value of the consistency vector, Cv_{ij} (Malczewski 1999):

$$\lambda = \sum_{i=1}^{n} Cv_{ij} \quad (2.7)$$

The consistency vector is calculated by taking the product of the weights and their respective columns of the ratio matrix (i.e. first weight and first column), summing the values for each row, and then dividing the weighted sum vector by the criterion weights.

The Random Index, *RI*, is the consistency index of a randomly generated pairwise comparison matrix of order 1–10 obtained by approximating random indices using a sample size of 500 as shown in Table 2.3 (Saaty 2000):

Table 2.3. Average random consistency index (RI) (Saaty 2000).

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

If *CR* < 0.1, then this indicates a reasonable level of consistency in the pairwise comparisons and the weightings for each criteria can be used for generating opportunity maps; alternatively, if *CR* >0.1, then this an indication of inconsistent results and the scales assigned to each criteria should be re-examined (Saaty 2000).

A project based in Turkey employed the AHP method in conjunction with MCDM to derive an opportunity map for proposed solar PV farms to tackle coal-fired power plant pollution in the province of Kahramanmaraş (Günen 2021). The developed tool used four aspects of information such as: proximity (rivers, roads and transmission lines); terrain (landcover and slope); visual impact (social); and weather (solar irradiance and temperature). Higher weightings were given to weather and terrain (0.674 and 0.225 respectively), and lower weightings given to proximity and visual impact (0.083 and 0.017 respectively). The author noted that during literature review, different weights were allocated to similar aspects such as access to solar PV farms to provide cleaning and repairs and observed that assignment of relative weightings is usually determined by researchers following consultation with investors and policymakers (Majumdar & Pasqualetti 2019, Colak *et al* 2020, Ruiz *et al* 2020). Several observations were made such as: site locations are generally barren, unused or dewatered; low-cost sites that are relatively far from the centre are preferred by investors; and land is either flat or flattened before construction.

A project based in the Khuzestan province of Iran (Asakereh et al 2017) used the MCDM/AHP combination with similar information as the project in Turkey such as: biodiversity (wildlife designations); environmental (conservation areas, local nature reserves, protected areas); proximity (railways and roads); terrain (elevation); visual impact (social); and weather (solar irradiance). There was greater focus on natural constraints compared to the previous project with higher weightings given to weather (0.539), environmental and biodiversity (0.291) and lower weightings given to proximity (0.170). The weightings applied were based on a similar study to the project as noted by the authors such as the availability of transport links being considered the least important by the authors (Mondino *et al* 2014). The results showed that parts of the province are suitable for PV deployment particularly in the southern regions where large areas of land have succumbed to desertification and are unused.

Another project which used the MCDM/AHP approach examined site suitability for both PV and wind farms in Southern England, UK (Watson & Hudson 2015). Aspect information included: biodiversity (wildlife designations); environmental (historically important areas and SSLI); proximity (grid connection points); terrain (landcover and slope); visual impact (social); and weather (solar irradiance and wind speed and direction). Two scenarios were devised for both RETs using weightings which were validated by consultations and anonymous expert stakeholders. For solar PV, the weather aspect received the highest weighting (0.489) with the second highest weighting given to proximity (0.328). This was followed by the visual impact (0.049), biodiversity (0.069) and the environmental aspect (0.065). The scenario for wind included high weightings for wind speed and direction (0.555). This was followed by proximity (0.131), visual impact (0.130) and biodiversity (0.130). The environmental aspect which comprised of historically important areas and SSLI was considered least significant with a weighting (0.078). Results of the tool showed that site locations identified as being suitable were better suited for solar farm developments than for wind farm development. The authors stated that the weightings were produced by experts and indicated that the distance to a network connection point was more important when siting a solar farm compared with a wind farm due to construction costs becoming more of an issue, hence the proximity aspect was deemed a higher priority to the environmental and biodiversity aspects.

A project based in Spain focused on solar RET with the proximity aspect receiving the highest weighting (45.776) (Sánchez-Lozano *et al* 2013). The authors noted that based on literature review, site location was to be of utmost importance followed by the weather (28.562), terrain (17.259) and finally environmental (5.553). The reasoning given for treating proximity with most significance was due to location factors becoming increasingly important to create a network of distributed energy generation that involves the reduction of losses in the transport of the energy generated. The authors originally grouped the distance to nearest settlements with all other distance-related factors, however, this was added to the visual impact aspect for this thesis to remain consistent with the examination of other site selection tools.

In Borneo island, Indonesia, a project assessed optimal sites for solar farms with the highest weighting given to proximity (0.548) (Ruiz *et al* 2020). The weather aspect received the second highest weighting (0.321) followed by terrain (0.131). The authors noted that due to the size and location of Borneo, both weather and terrain aspects were relatively similar in all areas of the island and was therefore not classed as top priority. Instead proximity was classed as significantly relevant with focus on the shortest distances between the proposed location for RET deployment to the nearest power transmission network and the major transport links.

Another tool utilised in Saudi Arabia assessed ideal locations for solar PV (Al Garni & Awasthi 2017). The highest weighting was received by the weather aspect (0.565) followed by terrain (0.271), proximity to transmission lines and roads (0.131) and visual impact (0.032). The authors noted that the weather aspect which consists of solar irradiation and annual average temperature were the most important criteria as they determined the output power of solar PV. This was subsequently followed by the terrain aspect which could determine the amount of irradiance received by the solar panels due to the steepness of the slopes and the orientation of the area. Areas facing in the southerly direction with milder slopes are considered ideal due to the country situated in the northern hemisphere. From an economic perspective, the proximity to the electricity grid and major roads could determine the infrastructure and transmission cost of installation and maintenance.

2.3.3 Weighted Overlay Analysis

The Weighted Overlay Analysis method avoids the setup of intricate systems for all criteria and instead analyses information stored directly in the raster source file (Finn & McKenzie 2020). Each raster depicts a certain criterion, the pixels in the raster are assigned a score and the raster itself is assigned a weighting depending on its importance to the project (Lentswe & Molwalefhe 2020). Multiple rasters are overlaid simultaneously and the final map contains the sum of multiplying the pixel scores of each raster by its weight. This is given by the following calculation (Parihari *et al* 2021):

$$S = \sum_{i=1}^{n} W_i A_i \tag{2.8}$$

where *S* is the final score of a pixel, W_i is the weight of the ith raster, *Ai* is the score of the ith raster, and *n* is the number of rasters.

A project based in Northern Ireland used Weighted Overlay Analysis in determining suitable site locations for PV farms (Finn & McKenzie 2020). Information included:

environmental (areas of outstanding natural beauty, conservation areas, local nature reserves, listed buildings, special protection areas, SSSI and Word Heritage Sites); proximity (hydrological features and transport links); terrain (landcover); visual impact (social); and weather (solar irradiance). Weightings were applied with the highest configured for weather (0.400) followed by terrain (0.370), environmental (0.112), proximity (0.081) and the lowest given to visual impact (0.036). The environmental aspect was classed as being restricted access and any land within this aspect was immediately excluded from the final map. It was noted by the authors that the weightings were based on their perceived importance in relation to solar farm development and could be refined on further expert judgement and direction from developers and policy makers.

A project in Colorado, US, used the Weighted Overlay Analysis method to develop a multicriteria GIS modelling tool for wind and solar farm site selection (Janke 2010). The following information were used: environmental (National Monuments, National Parks and Native American Reservations); proximity (roads and transmission lines); terrain (landcover); visual impact (social); and weather (solar irradiance and wind speed and direction). Weightings were applied with the highest given to weather and proximity (0.300) and the lowest weighting (0.100) given to all other aspects. The environmental aspect was used to discount all areas from the analysis with the remaining information overlaid with one another with areas of high solar and high wind potential identified. The authors noted that collaborative decision-making could be improved by combining different criteria or altering weights as this could create an environment that allows users to conduct a sensitivity analysis to understand the influence and effectiveness of each aspect.

In Iran, the Weighted Overlay Analysis method was used to identify site suitability for solar PV energy generation (Firozjaei *et al* 2019) and included information for: proximity (roads); terrain (landcover and slope); visual impact (social); and weather (solar irradiance). Weightings were configured with weather given the highest weighting (0.500) followed by terrain (0.320), visual impact (0.100) and finally proximity with the lowest (0.080). The authors noted that the analysis involved risk assessment and focused on a scenario to interest potential investors as they may be willing to pay more for the optimum location with the least risk to investment. Therefore, for these locations, the likelihood of a successful solar project was higher than other locations.

2.3.4 Boolean Overlay Analysis

One of the more simplistic methods is employing a Boolean Overlay Analysis where areas of land and various criteria are simply regarded as either supporting for RET deployment or curtailing it (Hassaan *et al* 2020). Advantageous maps are combined and exclusionary maps are subtracted resulting in a generated opportunity map showing areas which are suitable and those unsuitable. Despite its simplicity in evaluation and implementation, Boolean Overlay Analysis can be used as part of a conjunctive screening procedure capable of displaying suitable sites having met all considered criteria and avoids weightings which can be affected by subjectivity and individual viewpoints (Malczewski 2002).

A project based in mainland UK examined using the Boolean method for PV farm site location (Palmer *et al* 2019) and included information such as: environmental (moorlands, national parks and woodland regions); proximity (grid connection points); terrain (landcover and slope); and weather (solar irradiance). The Boolean process involved collecting and combining terrain with weather to create a single map, then creating a secondary map containing proximity buffer zones around known grid connection points. Both maps were then subtracted to reveal land which were at a safe distance away from a grid connection point. Finally, the land from the subtracted map was extracted where the slope was less than a given threshold and the final output highlighted areas that fit the chosen landcover criteria.

A project in the USA which employed the Boolean method also inspected suitable sites for PV farms (Brewer *et al* 2015) considering aspects such as: proximity (roads, rivers and transmission lines); terrain (slope); visual impact (social); and weather (solar irradiance). It was found that an in-depth preliminary siting analysis could be done that allowed for the avoidance of solar development from areas that could cause constructability and public issues. Suitability was assessed through several aspects to determine ideal areas that contained ideal terrain, proximity to features that reduced the cost of construction, and agreed with the environmental opinions of the public. The authors noted that using this method could help developers understand the limitations associated with current social opinion regarding environmental issues and costs associated with solar development could be avoided if negative public reaction was present.

After reviewing the existing site selection tools, some common themes are observed and discussed in the next section.

2.4 Common themes

From the tools examined, several observations arose to suggest that there are common themes between the site selection tools used to analyse geospatial information for RET deployment.

2.4.1 Recurring aspects

A number of recurring aspects appear for various site selection tools, one of which is weather where the information is normally contained within a raster data model. Based on the tools reviewed, solar PV and wind are two RETs commonly investigated.

- For solar PV, this aspect directly affects the RET in terms of the amount of available GHI, a metric for determining the feasibility of solar farm efficiency and its financial viability (Günen 2021). The GHI is the product of diffuse horizontal irradiance, direct normal irradiance and ground reflected irradiance and is discussed further in Section 2.7. Consequently, solar farms are better suited to areas with high levels of GHI radiation due to the solar energy output of PV being directly affected by incoming solar radiation (Giamalaki & Tsoutsos 2019).
- The weather aspect can also involve wind speed and direction as the average wind speed plays a pivotal role in both the technical feasibility and economic viability of wind farm installation sites (Saraswat *et al* 2021). Researchers have investigated various wind speeds for their analysis and found that areas with average wind speeds less than 3 m/s are classed as unsuitable and discounted; and areas with average wind speeds greater than 6 m/s are classed as highly suitable (Jangid *et al* 2016).

Terrain is a commonly used aspect which relates to the topographical features of the land and is normally contained within a raster data model.

- Landcover is one such feature and is often used to identify areas of land which can be utilised for RET deployment whilst still able to conserve natural resources and reduce environmental harm (Marques-Perez *et al* 2020). Land classified as barren or sparsely vegetated, dryland or shrubland are generally considered as highly suitable. Conversely, forests, wooded wetlands and built-up lands are generally considered as not suitable (Ruiz *et al* 2020).

- Another topographical feature is the slope and is relevant to investors due to its direct impact on solar PV farm sites as the cost of installation and levelling the land tends to increase the greater the slope with the cut-off range usually between 10° and 25° (Prieto-Amparán *et al* 2021).
- The terrain elevation feature is closely linked to flood risk zones where low-lying areas are typically more susceptible to flooding than those at a higher elevation (Zhang *et al* 2020).

The proximity aspect focuses on the distances from a site to the nearest features which may provide economic incentives or costs and is typically contained within a vector model.

- The transportation network is one such feature which provides an economic benefit predominantly in the form of existing roads or railways as this avoids unnecessary environmental damage and construction costs and facilitates the transportation of people and equipment (Yousefi & Astaraei 2017).
- Another distance feature which may provide financial benefits is power transmission lines as an existing power network minimizes the construction cost, ecological damage, and energy losses (Tercan *et al* 2021).
- A feature which may cause economical costs is the proximity to lakes, dams or rivers as this increases the risk of flooding and could damage or destroy the solid ground foundations of the land the RET is installed upon (Georgiou & Skarlatos 2016). A minimum distance should also be required to preserve the natural environment of water resources.

The previous aspects relate to the technical aspects of RET deployment as these can directly affect the output energy potential. The environmental aspect, however, relates to the policy perspective that may affect the likelihood of receiving planning permission and is commonly included in the site selection tools as it consists of various factors that can greatly influence any proposed development, and with careful planning can help mitigate negative environmental impacts (Watson & Hudson 2015). Although the definition of the following factors used in the examined site selection tools may differ amongst various countries, the definitions used in this thesis is based on the Scottish Planning Policy (Scottish Government 2014) and UK legislation.

- Conservation areas aim to preserve or enhance the character and aesthetics of the surrounding area. This includes the proposed demolition of unlisted buildings within a conservation area where consideration should be given to the contribution the building makes to the character and appearance of the area and if the contribution is positive, the building should remain. This definition is based on existing legislation (Planning (Listed Buildings and Conservation Areas) (Scotland) Act 1997).
- Historically important areas ensure the appropriate protection, enhancement and management of the area's heritage. Local authorities should aim to protect, conserve and improve the historic environment for the benefit of current and future generations in line with the Scottish Planning Policy and the Scottish Historic Environment Policy (Historic Environment Scotland Act 2014).
- Listed buildings have a close connection to conservation areas as they are both protected within the same legislation (Planning (Listed Buildings and Conservation Areas) (Scotland) Act 1997). Buildings designated by Historic Scotland which are of special interest, architecturally or historically, and which satisfy set criteria from the legislation are used to distinguish this significance.
- Local nature reserves are defined as areas of locally important natural heritage normally designated and managed by local authorities to provide opportunities for visitors to learn about and enjoy nature.
- The preservation of woodland is important particularly for woods classed as ancient semi-natural as this is considered an irreplaceable resource. Protections are given to these woods along with hedgerows and individual trees considered having high nature conservation and landscape value in the form of the Tree Preservation Order legislation (The Town and Country Planning (Tree Preservation Order and Trees in Conservation Areas) (Scotland) Amendment Regulations 2014).
- SSSIs and SSLIs are two environmental factors where the former focuses on areas which are designated for the special interest of its flora, fauna, geology or geomorphological features (The Register of Sites of Special Scientific Interest (Scotland) Regulations 2008); and the latter focuses on areas which are

designated due to its scenic or landscape quality, natural or cultural heritage features, cultural associations and other perceptual facets such as tranquillity and size.

- World Heritage Sites are of international significance and planning authorities are obligated to protect and preserve the site's OUV if a development proposal has the potential to affect it. UNESCO has provided guidelines defining OUV as a metric used to signify exceptional cultural/natural importance that must be recognised globally for present and future generations (Gurira & Ngulube 2016).

Biodiversity is a policy aspect which includes the presence or potential presence of legally protected species of animals and plants. If any evidence suggests that such a species is present within the area of interest or may be affected by a proposed project development, confirmation is required to establish if there are protected species within the area. This allows a level of protection to be factored into the planning and design phase of project development afforded by several legislations (Wildlife and Natural Environment (Scotland) Act 2011, Habitats Regulations 1994, Protection of Badgers Act 1992, Wildlife and Countryside Act 1981). This helps to avoid negative impacts such as ground disturbance, habitat destruction, removal of access to grassland foraging and nesting.

The visual impact aspect is recurring in terms of the location of residential communities and is normally contained within a vector data model. To avoid situations of inconvenience such as clear visibility or noise nuisance, a minimum distance may be required (Ali *et al* 2019). A distinction can be made if there is suitable screening such as trees or where the introduction of a RET would not significantly alter the character of the landscape. Visual impact is commonly based on public opinions particularly the viewpoints from local residents (Azizi *et al* 2014).

2.4.2 Methods and weightings

From the site selection tools examined in Section 2.3 and those summarised in Table 2.1, the MCDM/AHP method is commonly used for extrapolating and weighting information with fewer tools exploiting the Weighted Overlay Analysis and Boolean Overlay Analysis methods. These weightings are used to identify and prioritise aspects which are considered more significant than others. Although there is no standard process for weighting the examined aspects, the assignment of relative weightings is normally determined by researchers following consultation with key investors, partners and policymakers (Günen 2021).

The values for the weightings assigned to each aspect tend to vary amongst existing site selection tools and are normally presented as decimal values or percentages totalling 1.0 or 100% respectively. However, it is not uncommon for researchers to devise scenarios where all aspects are equally weighted (Watson & Hudson 2015, Majumdar & Pasqualetti 2019, Giamalaki & Tsoutsos 2019, Al Garni & Awasthi 2017). This equal weighted approach is the simplest decision-making method for avoiding risk and can lead to a greater understanding of the importance of weighting each aspect depending on the given scenario.

Scenarios can be designed to focus on specific aspects to encourage RET deployment such as location and proximity to existing transportation links and transmission line networks to boost economic gains (Günen 2021); or the environment to highlight areas which do not require substantial ecological protection (Giamalaki & Tsoutsos 2019). It is shown in Table 2.1 that each site selection tool may not consider certain aspects used in other tools.

2.4.3 Scope

The scope, or area of interest, examined within the site selection tools tend to focus on large regions or provinces. Often buffer zones are used to remove areas where development is unfeasible such as those in close proximity to environmentally protected areas or residential communities etc., but can also be used for identifying ideal route selection when included in a proximity analysis (Sivakumar *et al* 2021). As the scope within the examined site selection tools covers large areas of land, it is common for the information used to not consist of an intricate breakdown of factors for localised areas. A comprehensive list of factors for each aspect could provide detailed, high-resolution maps of site suitability for local areas including towns and cities. This is a research gap which is addressed in the next section.

2.5 Research gaps

At the time of project commencement, few prior works were identified that mapped opportunities for renewable energy systems deployment as a function of the various policy issues considered by UK local authority planners <u>and</u> the technical constraints considered by local utility providers (Watson & Hudson 2015, Palmer *et al* 2019). This project addresses the first research gap of developing a new evaluation method that combines policy and technical considerations relating to energy supply within the planning process by obtaining detailed, high-quality policy and technical aspect information via significant collaboration with the local authority (GCC) and utility provider (SPEN). Cooperating directly with policymakers from a local planning authority and energy experts from a local utility provider can provide prospects for discussing and receiving first-hand feedback on proposed evaluation methods. This method of working directly with specialists was missing in most of the examined site selection tools although it has been exploited in other projects and considered valuable (Song *et al* 2021, Ruiz *et al* 2020, Candelise & Westacott 2017).

The second research gap addressed is investigating opportunities within an urban setting as the site selection tools examined were primarily utilised on large regions of land. With opportunities to move strategic power into cities, to bring energy supply closer to local demand, allows for other policy aspect information to be introduced such as those related to city developmental plans to highlight areas of economic opportunity; or technical aspects including grid substation congestion to highlight areas where capacity of the circuits is capable in the absorption of new energy generation.

Therefore, to tackle these research gaps effectively, a novel method is implemented which brings together comprehensive and detailed policy and technical aspect information into a single composite opportunity map. This will be achieved by hosting a series of workshops with GCC and SPEN to discuss and collect all policy and technical information available for the city. Three systems will be introduced: a grid system to create a spatial relationship between all policy and technical information; a scoring system to differentiate between factors supporting, curtailing or remaining neutral in PVPS deployment; and a weighting system to determine the importance of each policy and technical aspect via use of the MCDM/AHP and the Weighted Overlay Analysis methods. This will all be encapsulated in a new interactive GIS tool able to accommodate different aspect information and allow users to change input parameters including enabling/disabling certain aspects due to specific scenarios or altering the weightings. Any change in parameters would update the final opportunity map in real-time.

The next section examines further the importance of recurring aspects and any additional aspects which may be significant in an urban environment.

2.6 Generic aspects for RET deployment

The location of deployment is heavily dependent on a variety of aspects which includes the environment, developmental planning, proximity to the nearest grid connection point etc. which must be considered as they could not only hinder the deployment of the chosen technology but also decrease its productivity. When evaluating the suitability of a site, two different sets of aspects and their breakdown of factors must be considered by potential developers: policy which facilitate or restrict the likelihood of receiving planning permission to build at the chosen site; and technical which conveys the advantages or limitations imposed by the location on the achievable power level.

Table 2.4 contains the recurring aspects identified from site selection tools examined in Section 2.4.1 with their associated factors included and grouped accordingly. These aspects are scrutinised further to highlight their significance. As the focus is on urban environments, additional aspects are studied which may play important roles in determining RET deployment.

Table 2.4. Recurring aspects identified from existing site selection tools.

Policy aspect	Factors	Description
Biodiversity	Creature habitats	Wildlife and plant information related to protection and conservation of special areas.
Environmental	Conservation areas Historically important areas Listed buildings Local nature reserves Preservation of woodland SSLI SSSI World Heritage Sites	Ecological and policy information related to protection and conservation of certain areas
Visual impact	Social	Social information related to distance to and visibility from residential areas.

Technical aspect	Factors	Description
Proximity	Transport links Transmission lines Hydrological features	Distance information related to transport links, grid connection points, transmission lines and hydrological features.
Terrain	Slope Landcover Elevation	Topographical information related to slope, landcover and elevation to identify terrain suitability and flood risk.
Weather	Solar Wind	Climate information related to solar irradiance and wind speed and direction.

2.6.1 Generic policy aspects

Based on reviewing various site selection tools, it was found that the most prominent policy aspect that affects national energy policy is the impact of energy sources on the environment. In Taiwan, for example, the environmental goal focuses on carbon emission reductions where the country aims to transition away from the use of fossil fuels due to their finite supply and perceived effect on the climate and landscape (Beccali et al 2003, Shen et al 2010). China has also declared environmental impact as a top priority when it considers energy development projects due to severe issues related to local air quality (Hu et al 2010). In Pakistan, a framework has been established to consider environmental parameters as part of their Long-range Energy Alternative Planning system, which is used to forecast supply and demand by assessing the validity of electricity generation scenarios in terms of their associated production costs and environmental emissions (Aized et al 2018). In the UK, one strategy is to encourage communities to build and own energy generation plant that satisfies the local energy demand (Tuohy et al 2015). This approach focuses on several key areas, most notably the environment (Mirzania et al 2019, Hvelplund 2006, Kiker et al 2005). It is significant that in all the aforementioned cases environmental policy plays a dominant role in assessing proposal suitability.

Another recurring policy aspect is biodiversity, where the utilisation of significant amounts of land for RETs can modify, fragment or destroy existing animal habitats (Gasparatos et al 2017). Any use of land will also need to consider the supporting infrastructure, such as access roads and equipment for maintaining the energy system, as the repercussions can create a chain reaction: frightening off wildlife, killing vegetation, lowering the mineral level of the soil, reducing available food sources for insects and animals and so forth (Pedroli et al 2013). Mauritius was used as a case study in a project that examined a procedure to determine site selection for wind turbines whilst preserving areas that enable biodiversity (Dhunny et al 2019). Mauritius (part of the Mascarene Islands), alongside Madagascar, is one of 35 global biodiversity hotspots and so the project was considered vital in helping to protect the indigenous biodiversity comprising a large variety of endemism (Mittermeier et al 2011). The EU has set up strict biodiversity regulations that are enforced by national authorities. So much so that the UK government, which was considering supporting the proposed Severn Barrage, would have had to convince the EU to relax its biodiversity guidelines (Jackson 2011). It can be difficult to ascertain habitats of protected species as these can drastically alter, by location and size, and so outpace any formal environmental designation. The following UK legislations involving protected species have authorised precise environmental surveys to be conducted on sites that are considered to contain protected habitats (Glasgow City Council 2001):

- Wildlife and Countryside Act 1981;
- Protection of Badgers Act 1992; and
- Habitat Regulations 1994.

The last regulation is intended to protect and support areas that are under threat, particularly those with existing animal habitats and vegetation (Stoms et al 2013). If a site contains a protected species, the planning application can be refused if no alternative mitigation measures are planned. Hence, it seems that the importance of the biodiversity policy aspect is on par with that of the environmental aspect.

Although natural constraints play a significant role in determining site suitability, a policy aspect which has not been covered to any great extent relates to the development and expansion of built-up urban areas such as towns and cities. Local authorities defer to a city development plan, which covers a variety of regulations in order to deliver comprehensive guidelines. These guidelines aim to provide opportunities for making investment-based decisions for both the public and private sectors assuming that the desired project has passed an environmental impact assessment. In China, city development plans are becoming more common whereby the focus is on economic growth through supporting the commercial, financial and service sectors, or outlining the relevant guidelines during the design phase of a renewable energy project (Fu & Zhang 2017). One such guideline is the strategic development framework used to inform spatial planning, development and delivery concerning future expansion and regeneration of a geographical area. This is achieved by identifying the connections and relationships within the local area to deliver a comprehensive guide for RET deployment. A similar framework is employed in Spain where the relationships between the business, education and commercial sectors play a role in supporting new RET projects (Terrados et al 2007, Ruiz-Romero et al 2013). This strategic framework can also be used by local authorities within the planning process to search for, and subsequently select, strategies that aid deployments. In the US, establishing relationships and opening communication channels between numerous local actors is encouraged for city development (Bayulgen 2020). Working collaboratively allows different interests to complement one another. But city development is not only fixated on the economic side, it also includes the residential sector where new housing land supply would be able to attract more people, and thus more labour, to an area. Although this would take up land that can otherwise be used for RET installations, it provides opportunities for other energy systems such as heat pumps and district heating as demonstrated in Kassel, Germany, as a means to tackle domestic energy demand (Schmidt et al 2017). Therefore, this city development aspect is noted in being significant for RET deployment in an urban setting and is added to the list of existing policy aspects for the new evaluation method.

When processing a planning application that involves deploying a RET within towns and cities and specifically near residential areas, the site itself must be surveyed and local people consulted to ensure that the project can be delivered with minimal intrusion. This approach is likely to be more helpful than asking for public opinion after a RET has been delivered (Swofford & Slattery 2010, Walker et al 2007). An example of such an approach is the Postal Code Rose policy set up by the government of The Netherlands, which introduced a subsidy for power generation from PV panels via local energy programmes (Kausika et al 2017). In 2008, the subsidy was set at €0.33/kWh with an approximate payback of 15 years. This policy became more lucrative after several years when additional benefits were added, such as grants to cover 15% of the investment cost for each system above 0.6 kWpeak and €650 per system. It was found that by having such local policies, the scheme became enticing and was particularly successful from a social point of view. It also provided insight from a marketing perspective in terms of engaging and convincing the local community to take up such offers (Graziano & Gillingham 2015). This strategy of reducing carbon emissions through social schemes results in the acceptance of RET at the community level. However, it is unlikely that all residents will be content with the introduction of a RET. Disregarding the positive energy benefits to the community, negativity may arise due to the visual impact resulting from alteration of the aesthetics of the surrounding area. This is primarily opinion-based relating to how people, especially local residents, perceive renewable technology being deployed in their vicinity and may create intractable opposition. On the other hand, it has been observed that the level of hostility would typically subside after a period of time if no more major obstacles are encountered (Van der Horst 2007). Hence, policies associated with a social perspective such as visual impact is considered important for evaluation.

While the above four policy aspects are generic in that they relate to most cities, other technology-specific policy aspects must also be addressed. One of these involves the economic aspect, particularly for RET deployments requiring financial subsidy due to high construction costs as, for example, reported in China and Algeria (Zhang et al 2019, Koussa et al 2009). In Belgium, additional economic considerations are included when utilising geothermal energy systems such as recoverable loans, heat premiums, tax rebates and an insurance system (Compernolle et al 2019). The advantage of a loan is that capital reimbursements can be reduced when the project does not earn enough. This policy instrument is a typical example of cost-sharing in which the risk of the geothermal development is also shared between the government and the private developer. With a heat premium, each MWh of geothermal heat produced returns a fixed premium to the developer. In the US, a federal tax rebate was available for investments in sustainable energy production and consumption (Grassi et al 2012). As the risks related to a geothermal project are high, insurance companies are unlikely to provide standard insurance services and therefore another insurance device is required. With financial information being an important part of project deployment within city policies, this aspect is added to the list of existing policy aspects for the new evaluation method.

Another policy aspect required in the case of PVPS is visual intrusion from glare caused by reflections, which may cause temporary loss of vision. Limited information is provided by the UK CAA in terms of PVPS deployments posing any real danger to aircraft and there is no quantitative benchmark to determine what levels of glare would be deemed acceptable (UK Civil Aviation Authority 2010). Research has been carried out, however, by aviation agencies from other countries such as America where flash blindness for a short period of 4-12 seconds can be caused by 7-11 W/m^2 reaching an observer's eye (US Federal Aviation Authority 2010). That said, while PVPS deployments are becoming more common in the vicinity of American airports, they have operated without any pilots reporting incidents of glare (Solar Trade Association 2011). A report from Germany also found that for solar concentrators, passers-by are unaffected by flash blindness at distances over 150 feet (Ho et al 2009). In the UK, it is considered unlikely to achieve an intensity of 7-11 W/m^2 in the case of PVPS although, at 2% reflectivity, this amounts to a maximum of 20 W/m^2 when in close proximity to the panels themselves (UK Civil Aviation Authority 2010). To err on the side of caution, the visual intrusion aspect is added to the list of existing policy aspects for the new evaluation method.

Table 2.5 lists the three additional policy aspects for inclusion within the new evaluation method.

Table 2.5. Additional policy aspects.

Aspect	Description
Developmental	Urban development information related to the location for commercial, housing, leisure or industrial development use.
Economic	Financial information related to gains, losses and risks involved.
Visual intrusion	Safety information related to glare that might constitute a safety risk to aircraft or vehicles.

Now that the pertinent policy aspects have been highlighted and additional aspects identified, the next section examines the recurring technical aspects and additional aspects that must be considered at each site when assessing the deployment potential of a RET.

2.6.2 Generic technical aspects

A RET concerned with electrical power production will likely be connected to the local network as established to delivering electricity to consumers (Al-Shetwi et al 2020, Komiyama & Fujii 2019). It is important that these connection points are not too far from the RET deployment site as transmission lines can be costly and incur energy loss (García et al 2019). Generally, the rule is that the greater the distance to the substations and the energy transmission lines, the greater the cost that will be created by requiring new transmission lines and new substations to support the infrastructure. This will cause the total investment costs to increase. If the distance to connection points are short, this can considerably lower the overall cost and provide an advantage in reducing energy loss (Colak *et al* 2020). In Scotland, SPEN publishes procedures for connecting energy generation from RET in an urban environment where a connection will be made to a primary or secondary substation via an 11 kV circuit (SP Energy Networks - Connection Opportunities 2015). Low power installations may be connected to the low voltage network. Hence, the financial cost and the location of a grid connection point must be determined for each proposed RET deployment site. Other considerations include the type and capacity of the renewable system, the requirement for ground works, substation reinforcement etc. Therefore, the grid connection distance is a significant technical aspect.

The electricity network is composed of substations connected to consumers ranging from dwellings to large corporate enterprises (Lee et al 2020). However, if the power flow exceeds the network capacity, this can lead to congestion and increased power loss (Tévar et al 2019). Therefore, even when the RET site has a nearby network connection point, connection may not be possible if the associated substation is heavily congested. This may require the National Grid to re-dispatch production in order to maintain the physical feasibility of the energy transmission which in turn can increase generation costs (Steinhäuser & Eisenack 2020). SPEN produces publicly accessible ‘heat maps’, which indicate the extent of each 11 kV circuit to incorporate distributed generation (Circuit Level) and the effect of such distributed generation on adjoining circuits (Primary Area Level) (SP Energy Networks - DG Heat Maps Overview 2015). Each circuit at each substation is rated between 1 (low risk) and 3 (high risk) for seven issues such as existing fault levels, risk of reverse power flow and rise in voltage within the network. On examination, the combined ratings for the 74 primary substations in or immediately adjacent to Glasgow fall between 8 and 12 with 10 being the most frequent rating. As substation congestion can affect voltage levels in an urban electric network, it is added to the list of existing technical aspects.

Deploying RET will also depend on the site terrain, particularly in relation to issues such as flooding potential, broken ground and access limitation. For example, for PVPS, the technology does not require deep foundations as the system can be held in place with ground anchors if necessary. However, heavily sloping or broken ground with limited access – such as a railway cutting – or a site liable to flooding will be more difficult to develop than an open flat piece of land. Terrain information can display the topography of the land and highlight areas where steeps slope occurs to avoid situations which may cause difficulties in access and foundation work as this can incur high financial costs (Cunden *et al* 2020). Landcover is an important factor where areas with poor vegetation coverage are preferable to avoid overgrowth and ground instability. In addition, areas with vegetation of low heights such as grasslands, shrublands or croplands are also considered suitable (Prieto-Amparán *et al* 2021). Elevation can not only be used to highlight areas susceptible to flooding if they are lowland and close to hydrological features such as rivers or dams, but also highlight areas in high altitudes which can be beneficial for specific RETs. For PVPS, high altitudes result in larger solar radiation for direct and global components of solar irradiance and fewer scattered or diffused radiation (Ghose *et al* 2020); for wind, higher altitudes results in more wind power however, there is normally a cut-off at 2,000 m above sea level due to reduced air density which can result in decreased wind power (Noorollahi *et al* 2016). Overcoming such barriers will affect the economic feasibility of the site and therefore terrain suitability is considered a significant technical aspect.

The above three generic technical aspects will apply to any given site. In addition, there are technical aspects that are technology-specific such as weather. This includes the nature of the local wind regime, which will dictate the power that can be extracted from wind turbines (Ansari et al 2019, Habib et al 1999, van Haaren & Fthenakis 2011). This aspect can be covered by available wind maps showing the wind resource both spatially and temporally (Kılıç 2019, Janke 2010). Reliable estimates of daily, seasonal and yearly variations in wind speed and the development of a detailed wind-resource assessment map both play important roles in accelerating the deployment of wind energy projects (Cunden *et al* 2020). Identifying potential sites that meet wind energy resource requirements is fundamental to the design and planning of wind projects coupled with other significant aspects such as terrain and proximity to the national high voltage transmission lines (Baseer *et al* 2017). In the case of PVPS deployment, many countries are taking advantage of opportunities to invest in solar technology due to falling prices as well as advancements in manufacturing processes and demand for solar energy (Majumdar & Pasqualetti 2019, Marques-Perez *et al* 2020). The siting of solar PV deployment, particularly in the form of solar farms, normally requires large areas which can incur high construction costs making it imperative for selecting the most ideal location for high efficiency and low investment costs (Choi *et al* 2019). Areas with high levels of GHI radiation, suitable terrain and good proximity to transport links and transmission lines would likely attract potential investors, especially considering solar PV farms can remain in the same location for a long period of time and would require simple road access for maintenance and repairs (Mirzania *et al* 2020). It can be seen that the weather aspect is an important technical aspect to include in the evaluation method.

Another technology-specific aspect, in the case of a PVPS deployment, is the solar irradiation exposure time. Where a PV array is partly shaded, this will cause a substantial drop in overall power output (Mendez et al 2003, Nwaigwe et al 2019, Singh 2013). Therefore, the efficiency of the output generated by PV panels depends on several influences such as the orientation of the panel, sky conditions and shading caused by surrounding obstructions, the most prominent being surrounding trees and high-rise buildings (Singh *et al* 2020). And so, it is critical to quantify the shading loss to predict the return investment before installing PVPS at a designated site. This vital assessment of shading caused by adjacent sky obstructions is included and added to the list of existing technical aspects for the new evaluation method.

Table 2.6 lists two additional technical aspects for inclusion within the new evaluation method. Due to the focus being on urban environments, it would be unlikely for wind turbine deployment to be given consent within densely populated towns or cities due to the size of land required and an appropriate proximity required from buildings and

Table 2.6. Additional technical aspects.

Aspect	Description
Overshading	Shade information related to site overshading from nearby buildings or tall structures.
Substation congestion	Grid network information related to the capacity of the circuits connected to a substation to absorb new energy generation.

residential areas. Therefore, PVPS technology is the chosen RET for assessing the new evaluation method as this is accepted in urban settings and has been utilised to supply local communities and integrated into buildings (Tiba *et al* 2010, Song *et al* 2019).

2.6.3 Summary

From literature review and examining existing site selection tools alongside additional RET deployment projects, several generic policy and technical aspects and their known common factors have been identified and summarised in Table 2.7.

Table 2.7. Summary of generic aspects found in literature review.

Policy aspect	Factors	Description
Biodiversity	Creature habitats	Wildlife and plant information related to protection and conservation of special areas.
Developmental	City development plan Housing land supply Strategic development framework	Urban development information related to the location for commercial, housing, leisure or industrial development use.
Economic	Financial subsidy	Financial information related to gains, losses and risks involved.
Environmental	Conservation areas Historically important areas Listed buildings Local nature reserves Preservation of woodland	Ecological and policy information related to protection and conservation of certain areas

	SSLI SSSI World Heritage Sites	
Visual impact	Social	Social information related to distance to and visibility from residential areas.
Visual intrusion	Glare	Safety information related to glare that might constitute a safety risk to aircraft or vehicles.
Technical aspect	**Factors**	**Description**
Overshading	Building/tree shadows	Shade information related to site overshading from buildings and trees.
Proximity	Transport links Transmission lines Hydrological features	Distance information related to transport links, grid connection points, transmission lines and hydrological features.
Substation congestion	Congestion	Grid network information related to the capacity of the circuits connected to a substation to absorb new energy generation.
Terrain	Slope Landcover Elevation	Topographical information related to slope, landcover and elevation to identify terrain suitability and flood risk.
Weather	Solar	Climate information related to solar.

With the policy and technical aspects identified, the next section explores PVPS technology in greater detail.

2.7 PVPS technology

Electricity is produced directly from sunlight by a photovoltaic cell, in which solar radiation falling on two different semiconductors in close contact generates an electrical voltage (Kazmerski 2006). An incident photon with sufficient energy will knock an electron out of its normal condition of being bound in the crystal structure of the cell; these free electrons can move across the junction between the two materials more easily in one direction than the other, giving one side a negative charge and therefore voltage relative to the other (Li *et al* 2015). The amount of energy generated by a PV cell depends on the amount of sunlight that falls on it, and this in turn depends on location: in the northern hemisphere, the more southerly the location (greater irradiance), the more energy a given PV cell can harvest (Rhodes *et al* 2014). As only some of the photons carry the required amount of energy, only a small fraction of the radiation can be turned into useful electricity, typically 4-25%, although this is an evolving area and cells with over 40% efficiency are under testing (NREL National Center for Photovoltaics 2020). Commercially available solar cells can be made of monocrystalline silicon grown from a seed crystal (efficient but expensive); polycrystalline silicon made from grains of the monocrystalline version (less efficient but cheaper); or a thin film of amorphous silicon (least efficient and cheapest) (Dhass *et al* 2020).

The voltage and current generated by an individual cell are small, so many of these are connected in series (to increase the voltage) and in parallel (to increase the current), to form a panel. Multiple panels are in turn connected in series and in parallel to form an array. An array needs to be held in place by a frame and fixed in place either by piled foundations or concrete weights on the legs. The PV array produces direct current which must be passed through an inverter to convert it into alternating current with a frequency of 50 Hz before it can be fed into the UK's National Grid (Drax Group 2017).

When considering a possible layout, it is important that where panels are connected, if any one becomes shaded, the whole array feeding that inverter will perform poorly. Overshading can arise not only from surrounding buildings and trees, but also from other parts of the PVPS itself if multiple arrays are lined up too closely behind one another. Therefore, determining the ideal inter-row spacing is necessary to ensure that optimally tilted arrays never cast a shadow over each other.

PVPS deployments have been realised at locations throughout the world as shown in Figure 2.1 for the case of Offingen in Germany (left of Figure 2.1) and Indiana in the United States (right of Figure 2.1).

Figure 2.1. PVPS as deployed in Germany (Photo by Andreas Gücklhorn on Unsplash) and in the United States (Photo by American Public Power Association on Unsplash).

PVPS is widely accessible to businesses and home owners with increasing efficiency allowing for reasonable energy generation and decreasing production costs (Ahmed *et al* 2009, Devabhaktuni *et al* 2013). However, what is required here is the ability to predict the power output for any given location for an area deployed with PVPS. Once a site area is known, consideration of PVPS layout gives rise to the panel area that can be deployed. This panel area can be processed by mathematical models to determine the hourly power output over a typical year.

The PVPS model employs equations related to solar geometry to determine the power output of a PV panel. The first calculation is for the declination angle of the Sun, *d*, between the equator and a line drawn from the centre of the Earth to the centre of the Sun (Cooper 1969):

$$d = 23.45\sin(280.1 + 0.9862y) \tag{2.9}$$

where *y* is the year day number (1-365).

The equation of time, *EoT*, corrects for the eccentricity of the Earth's orbit and the Earth's axial tilt (Milne 1921):

$$EoT = 9.87\, sin\,(1.978y - 160.22) - 7.53\, cos\,(0.989y - 80.11) - 1.5\, sin\,(0.989y - 80.11) \tag{2.10}$$

Local solar time, t_s, adjusts for the longitude of the site being considered (Kalogirou 2014):

$$t_s = GMT + L/15 + Eot/60 \tag{2.11}$$

where L is the longitude difference (from the local reference meridian).

The hour angle, θ_h, converts the local solar time to an equivalent angle relative to the local reference (Kalogirou 2014). The Sun moves 15° per hour, therefore each hour from solar noon corresponds to an angular motion of the Sun by 15°:

$$\theta_h = 15 * (12 - t_s) \tag{2.12}$$

The solar elevation, β_s, is the angular height of the Sun measured from the horizontal (Kalogirou 2014):

$$\beta_s = sin - 1(cosL * cosd * cos\theta_h + sinL * sind) \tag{2.13}$$

The solar azimuth, α_s, is the Sun's horizontal angle measured clockwise from North (in the northern hemisphere) (Kalogirou 2014):

$$\alpha_s = sin - 1(cosd * sin\theta_h / cos\beta_s) \tag{2.14}$$

The wall-solar azimuth, ω, is the difference between the surface azimuth and the solar azimuth (Kalogirou 2014):

$$\omega = \alpha_s - \alpha_f \tag{2.15}$$

where α_f is the surface azimuth.

The solar incidence angle, i_β, is the angle between the PV panel surface normal and the direct vector from the Sun (Duffie *et al* 1991):

$$i_\beta = cos - 1(sin\beta_s * cos(90 - \beta_f) + cos\beta_s * cos\omega * sin(90 - \beta_f) \tag{2.16}$$

where β_f is the panel inclination angle.

The solar irradiance of the PV panel comprises 3 components. The first is the direct component, $I_{d\beta}$, as given by the following equation (Lee *et al* 2012):

$$I_{d\beta} = I_{dh} cos\, i_\beta / sin\beta_s \tag{2.17}$$

where I_{dh} is the direct horizontal solar irradiance.

The second is the sky diffuse component, $I_{s\beta}$, applicable to a sky of anisotropic brightness distribution (Balafas *et al* 2010):

$$I_{s\beta} = I_{fh} * \{0.5[1 + cos(90 - \beta_f)]\} * \{1 + [1 - (I_{fh}^2/I_{Th}^2)]sin^3(0.5\,\beta_f)]\} * \{1 + [1 - (I_{fh}^2/I_{Th}^2)]cos2i_\beta sin^3(90 - \beta_s)\} \tag{2.18}$$

where I_{fh} is the diffuse horizontal irradiance and I_{Th} is the total (direct plus diffuse) horizontal irradiance.

The third component is the irradiance that reaches the panel after ground reflection, $I_{s\beta}$ (Kalogirou 2014):

$$I_{r\beta} = 0.5\{1 - cos(90 - \beta_f)](I_{Th})r_g \quad (2.19)$$

where r_g is the ground reflectance.

The total PV panel irradiance, I_{total}, is given as the summation of the three components, also known as GHI:

$$I_{total} = I_{d\beta} + I_{s\beta} + I_{r\beta} \quad (2.20)$$

The panel power output at a given time is calculated by the following equation (Dubey *et al* 2013):

$$Power = P_{STC}\left(\frac{I_{total}}{1000}\right)(1 - \beta\{T - 25\}) * p \quad (2.21)$$

where P_{STC} is the power output under Standard Test Conditions, β is an empirical coefficient, T the operating temperature (ºC), and p the number of panels.

A key issue when deploying PVPS is to maintain a minimum distance between rows of PV panels to avoid shading from neighbouring panels. As shown in Figure 2.2, this spacing is determined as a function of panel length, L, tilt angle, θ_t, and the Sun elevation angle, θ_e which is calculated by averaging the Sun elevation angle across the spring and autumn equinoxes and the summer and winter solstices. The inter-row spacing, D, is split into two parts: D_1, the horizontal projection of the inclined panel and D_2 which considers both the tilt angle and the solar altitude (Mohammed et al 2020).

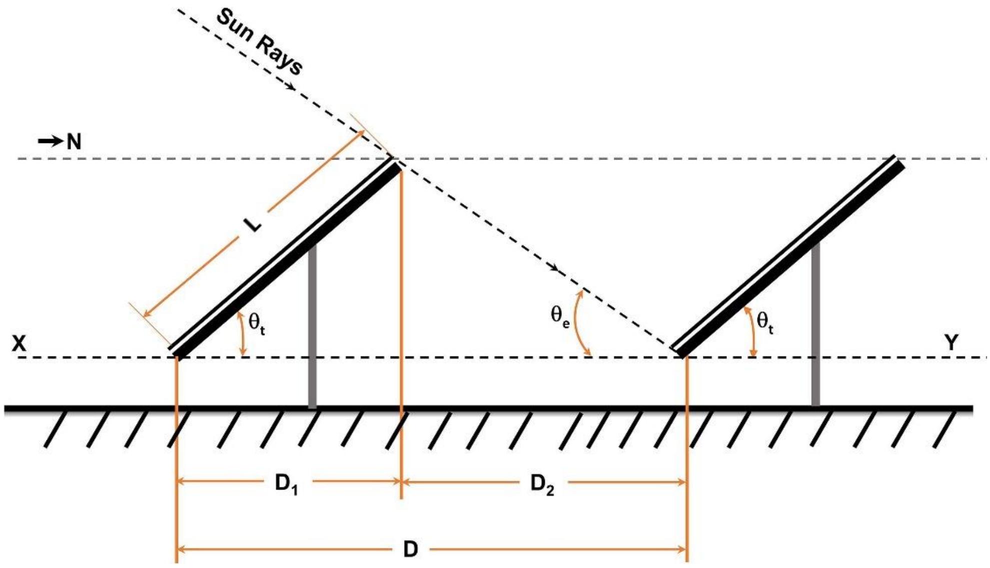


Figure 2.2. Inter-row spacing between panels (from Mohammed *et al* 2020).

The inter-row spacing is calculated from (Ravi *et al* 2016):

$$D = Lcos\theta_t + L\frac{sin\theta_t}{\tan\theta_e} \tag{2.22}$$

Chapter 3 – Methodology

3.1 Overview

In Chapter 2, it was shown that a number of existing site selection tools use common GIS methods coupled with weightings for generic policy and technical aspects to identify sites of suitability for RET deployment in typically large rural areas. This chapter introduces the workshops and consultations held with partners for PVPS deployment in an urban environment; the policy and technical information and their underlying factors obtained from these meetings. The design of the new evaluation method is described comprising of the grid, scoring and weighting systems and the translation of these into the high-level programming language Python encapsulated into the QGIS mapping software.

3.2 Workshops and consultations

A series of workshops were held at the University of Strathclyde attended by planning and utility personnel from the Land and Environmental Services department of GCC, energy experts from SPEN and members of ESRU. These were followed by further consultations with GCC and SPEN and held in their respective headquarters for additional information and data collection.

3.2.1 Introductory Workshop

The initial kick-off meeting involved several activities, the first of which showcased GIS technology and how it could be used to display information on a digital map. A prototype of a GIS tool was developed specifically for the workshop and demonstrated how publicly available information could be exploited. The prototype contained OS spatial data for the Shetland Islands in the Northern Isles of Scotland which included coasts, buildings and roads. Topographic information was also included displaying terrain details and contours with postcode boundaries overlaid to show the level of granularity the tool could provide. Each building possessed data such as council tax band, year of build, household size etc. which could be displayed and filtered and colours can be used to visually denote various categories for each type of information stored within the tool.

As the purpose of the first activity was to exemplify the use of a GIS-based tool imported with publicly available information, it was followed by the second activity where members from GCC and SPEN were invited to brainstorm with their departmental colleagues and note down the type of spatial information they held which could be used as input to the tool. As this was the first workshop in understanding what was required, a mixture of factors were deliberated with GCC focused on the policy factors and SPEN on the technical factors. Most of the factors deliberated were generic, some of which were shown previously in Table 2.7. It was agreed that for the following workshop, both GCC and SPEN would provide additional and full information of all factors from their data sources. GCC would also provide spatial information of the VDL sites which were the focus of PVPS deployment of which there are 766. The terms ‘aspects’ and ‘factors’ were also defined and allowed all the information factors to be collated and sorted into either a policy or technical aspect with a designation which captures the common characteristic (i.e. a factor directly related to the environment would be classed under the ‘Environmental’ aspect).

The third activity involved articulating the scoring criteria. There have been psychometric studies which concerned the range of scores and determining which situation a suitable certain number of scores be used (Nunnally & Bernstein, 1994). Some studies have suggested a 3-point scoring system was found to be sufficient when analysing subjective options and found that collapsing larger score ranges would not diminish the reliability or validity of the results (Preston & Colman 2000, Jacoby & Matell 1971). The range of scores was discussed in the workshop with references made to a GIS project which developed a decision support system to generate information on the most favoured location for wind turbine development using a 3-point scoring system (Clarke *et al* 1997). Other GIS projects have used larger ranges of scoring such as a 5-point system with classifications ‘Highly Suitable’, ‘Suitable’, ‘Moderately Suitable’, ‘Less Suitable’ and ‘Not Suitable’ (Saraswat *et al* 2021, Ajibade *et al* 2019, Giamalaki & Tsoutsos 2019); or a 10-point scoring system where extreme scores indicated highly suitable areas (Colak *et al* 2020, Baban & Parry 2001).

Although these projects with a scoring system 5 or greater were not specifically referenced in the workshop, the range of scores were discussed with an implication that having a larger pool of classifications can lead to a greater amount of subjective opinions and disagreements. An example was given illustrating whether the difference between a ‘Less Suitable’ site and a ‘Not Suitable’ site was large enough to constitute a separate classification if the same site was consented to have new build housing constructed. The same logic could be applied to other information such as the presence of creatures which are protected under legislation or a World Heritage Site. It was agreed that to maintain a degree of consistency and to aid in avoiding instances of discrepancies when processing information from diverse contacts and sources, a simple 3-point scoring system would be used with the possibility of the tool to support functionality to have a user-defined multi-point scoring system. The scoring system adheres to higher values indicating less suitable sites, these criteria are shown in Table 3.1. In some cases, a showstopper score is added where a factor underlying any policy aspect, particularly related to environmental, cannot be mitigated. It is also possible for a single factor to contain multiple scores, this would be a common situation in regards to proximity to specific features where a low score can be attributed to a specified distance and a high score can be attributed when this distance has been exceeded. It is relatively straightforward to change these categories for any city to reflect local requirements.

Table 3.1. Scoring criteria for policy and technical aspects.

Score	Policy aspect	Technical aspect
1	Possible	Favourable
2	Intermediate	Likely
3	Sensitive	Unlikely
4	Showstopper	-

The fourth activity involved discussions on the scoring methods to determine how the overall aspect score can be calculated from the scores of its associated factors. For example, the environmental aspect contains several factors of varying scores but it was unclear up to this point how the overall environmental score should be calculated. During this activity, the idea of importing all spatial information into the new GIS evaluation tool and breaking this information into a grid system was introduced. The grid system would allow the overall aspect score to be calculated as each grid cell would possess a unique ID allowing the user to determine which factors converge within any cell. The resolution of the grid would be determined during the development of the tool. Knowing the scores of overlapping factors allows the possibility to calculate the overall aspect score. The next step was to determine the scoring method required for computing the overall aspect score at each individual grid cell.

The first scoring method suggested and termed ‘stringent’ would impose pragmatic constraints by setting the overall aspect score as the highest underlying factor score. For example, a cell overlapped by several environmental factors would be scored the same as the factor with the highest score. The stringent method was considered for a much safer evaluation as it would highlight areas of great sensitivity. These areas could be avoided when applying for planning permission in order to greatly reduce the risk of rejection. Although the stringent method provides the most sensitive view of opportunity, it has the disadvantage of constricting more land if a single factor does not support RET deployment.

Another method was proposed which was intended to encourage development by setting the overall aspect score as the median value of the individual factor scores. This method was termed ‘lenient’ and although its evaluation was not as strict as the stringent method, some additional rules were introduced such as: any cell containing a showstopper factor will always be scored as such; any cell containing three or more scores of 2 (i.e. ‘Intermediate’ or ‘Likely’), will be scored a 3. Although the lenient method provides the most optimistic view of opportunity, it has the disadvantage of hiding individual aspects with high factor scores as would be exposed by the stringent method. The statistical median function was used in favour of the mean as the former has greater resistance and less sensitivity to extreme values which can drastically alter the final results (Jiang & Ma 2021, Viana-Fons *et al* 2020). For example, if a site is affected by four factors, three of which score 1 and the fourth scoring 3, the median value of these would be 1 but the average value would be 2 (when rounding). Therefore, it can be quite significant where sites might be overlapped by several factors which support RET deployment but one factor could mark the site at a higher score. However, the tool would support functionality to change between the use of the median and mean statistical functions when calculating the scores.

The fifth and final activity was defining the weighting system. With multiple factors affecting each of the policy and technical aspects, a critical feature of the tool would be to weight each aspect in a manner that reflects city policy with respect to the encouragement of local RET development. The weightings determine those policy or technical aspects that should be prioritised, allowing planners to encourage or limit RET deployments depending on circumstances. While individual weightings can be assigned any value, the sum of all policy aspect weightings must equal 1.0 as described in Section 2.4.2; likewise, the sum of all technical aspect weightings. The discussion of weightings would continue in the next series of workshops when more information would be collected and debated on how each aspect should be weighted.

The first workshop ended with members of GCC and SPEN informed of additional information required for the next workshop to discuss: all relevant factor information they hold and the aspects they should be assigned to; how each of the factors should be scored or the rules needed if multiple scores are necessary; and how the weightings should be applied to each aspect.

3.2.2 Subsequent workshops and consultations

Successive workshops and consultations allowed the collating of information brought by GCC and SPEN and involved discussions agreeing on the factors that belong to individual policy aspects that do, or should, underpin development control and the factors that belong to the individual technical aspects that constrain the achievable energy production at a given site. Once all the information was presented, each factor was debated, its score determined by their likelihood of supporting or curtailing RET, and the weighting determined for each aspect based on their assigned scale value from Table 2.2 due to their significance in relation to other aspects and in guidelines of receiving planning permission (Glasgow City Council 2019, Scottish Government 2014). However, it was agreed with the consulted GCC and SPEN specialists that alternative scenarios be investigated whereby all policy aspects and, separately, all technical aspects are equally weighted to perceive the results if all information was balanced and treated with equal importance.

Unlike Table 2.7 in Section 2.6.3 which tabulated generic aspect and factor information which could potentially apply to any city, some of the generic information and new information discussed in the workshops focus on Glasgow City and is shown in Table 3.2. Each aspect is further elaborated in the following subsections with the names and scores of all associated factors underlined for the reader’s convenience. The weightings for each aspect have been determined using the MCDM/AHP method which is discussed later in Section 3.3.2.3.

Table 3.2. The aspect factor scores for Glasgow City.

Policy aspect	Weighting	Rating	Score	Factor	Data source
Biodiversity	0.326	Possible	1	No species on the protected list believed to be present.	GCC (2019)
		Intermediate	2	UK protected species possibly resident which requires an environmental survey and mitigation measures.	
		Sensitive	3	European protected species possibly resident which requires an environmental survey and serious mitigation measures.	
Developmental	0.114	Possible	1	Master plan area; Strategic economic investment locations; Transformational regeneration areas.	GCC (2019)
		Intermediate	2	Community growth masterplan area; Economic policy areas; Green belt; Green network opportunity areas; Housing land supply; Industrial-business marketable land supply; Local development framework; Network of Centres; Strategic development framework; Strategic development framework - river.	
		Sensitive	3	Housing land supply with consented developments.	
Environmental	0.326	Possible	1	Green corridors; Local nature reserves.	GCC (2019)
		Intermediate	2	Conservation areas; Listed buildings; Ancient woodlands; Tree preservation orders; World Heritage site buffer zone.	
		Sensitive	3	Sites of special landscape importance; Gardens and designed landscapes; Scheduled ancient monuments; Sites of importance for nature conservation.	
		Showstopper	4	Sites of Special Scientific Interest; World Heritage site (Antonine Wall).	

Visual impact	0.148	Possible Intermediate	1 2	No residential areas overlook the site. Residential areas overlook the site.	Edina (2021)
Visual intrusion	0.086	Possible Intermediate Sensitive	1 2 3	All other areas. Between 1 and 5 km radius to the south of an airport or heliport or within 100 m of a motorway. Within a 1 km radius to the south of an airport or heliport or within 100 m of a motorway.	GCC (2019)
Technical aspect	**Weighting**	**Rating**	**Score**	**Factor**	**Data source**
Overshading	0.484	Favourable Unlikely	1 3	Falls outside the estimated annual shaded footprint. Falls within the estimated annual shaded footprint.	OS (2019)
Substation congestion	0.168	Favourable Likely Unlikely	1 2 3	Combined heat map score under 10. Combined heat map score equal to 10. Combined heat map score greater than 10.	SPEN (2020)
Substation connection distance	0.231	Favourable Likely Unlikely	1 2 3	Within 100 m of a substation connection line. Between 100 m and 200 m of a substation connection line. Further than 200 m from a substation connection line.	SPEN (2020)
Terrain	0.117	Favourable Likely Unlikely	1 2 3	Flat ground, no access issues or risk of flooding. Heavily sloping or broken ground; restricted access; unsafe buildings; medium risk of river or coastal flooding; high risk of surface water over large area. No direct access; site under water or with high risk of river or coastal flooding.	CEDA/SEPA (2019/2020)

3.2.2.1 Policy aspects for Glasgow City

The generic economics aspect was not included in the assessment as there were no financial information available for PVPS. Therefore, the remaining five policy aspects, each comprising several factors, affect whether a site is suitable for development: biodiversity, developmental, environmental, visual impact and visual intrusion. The definitions of a number of factors associated with these aspects are based on Glasgow City Council's City Development Plans (Glasgow City Council: IPG6 Green Belt & Green Network 2017, Glasgow City Council: SG 4 Network of Centres 2017), the Scottish Planning Policy (Scottish Government 2014), and UK legislation. These aspects are now considered in turn.

3.2.2.1.1 Biodiversity

For biodiversity, the <u>Creature Habitats</u> factor applies to all green sites such as parks, forestry and areas with flora and fauna which are likely to contain hotspots of the habitats. Information about species is held by the Land and Environmental Services department at GCC and is classed as confidential. As the new GIS evaluation tool is released publicly, no specific details of any species are held. Instead, the information highlights general areas where creature habitats are likely to be present but no precise locations are given to avoid risk of certain animals being hunted. Advice from the GCC Land and Environmental Services department is that some general issues with PVPS need to be considered in terms of biodiversity impact: the amount of ground disturbance for installation fixings such as poles or platforms; the size of the panels, which may cause habitat shading; and the density of panels, which will determine the shading extent and impact on access to grassland foraging and nesting.

It was decided that this factor should have multiple scores where a score of <u>1</u> is allocated to areas where no species on the protected list are believed to occur; a score of <u>2</u> is allocated to areas where UK protected species may possibly occur and would require an environmental survey and mitigation measures put in place; and a score of <u>3</u> is allocated to areas where European protected species may possibly occur. With the significance of this aspect considered high due to its importance in preserving biodiversity and protections set in legislation (Nature Conservation (Scotland) Act 2004), it was considered one of the most important aspects in terms of weightings.

3.2.2.1.2 Developmental

For city development, several factors relating to sustainable and economic growth are included. Most factors prioritise support to local areas through new housing, facilities, businesses and travel links.

Community Growth Masterplan is intended to address projected shortfalls in housing land over the next decade and beyond. It is considered a long-term approach to development planning which looks beyond current economic circumstances to provide a sustainable approach to meeting Glasgow's housing needs. It also recognises the need for more community facilities, both of a public and commercial nature such as schools, sport halls, gyms, transport links for buses etc. This factor was scored a 2 as land could be used for supporting growth on a community level in terms of new facilities and housing.

Economic Policy Areas applies to city and town centres as these are normally areas which can be developed to build a strong circular economy. In Glasgow, information from the Chamber of Commerce focuses its economic development efforts on key sectors: Digital Technology, Finance and Business Services, Low Carbon, Design and Advanced Manufacturing. This factor supports investment in new infrastructure to unlock the development potential of economically constrained locations and was scored a 2 for supporting growth on an economic level in terms of attracting new businesses.

Green Belt includes designations for land surrounding towns and cities but can also take other forms including buffers and corridors. Its purpose is to protect and enhance the quality, character and landscape setting and to give access to open space within and around settlements as part of the wider structure of green space. In addition, it aims to direct planned growth to the most appropriate locations and support regeneration. The area of Green Belt within Glasgow has been relatively limited in extent and its area shrunk further in recent years (by approximately 600 ha within the last decade) with the release of Green Belt land to meet the growing housing demand (Glasgow City Council 2017). This factor was scored a 2 to provide protection zones to surrounding natural areas and to avoid detrimental effects on the landscape due to PVSP deployment.

Green Network Opportunity Areas links together natural, semi natural and man-made open spaces (which may include leisure or recreational facilities) to create an interconnected network that provides multi-function benefits including opportunities for physical activity, increased accessibility within settlements and to the surrounding countryside, enhanced biodiversity, water management, active travel and the quality of the external environment. This factor was scored a 2 for improving travel links within and outwards of the local community.

Housing Land Supply – Consented contains areas where new housing is anticipated on those sites which have emerged from the Green Belt Review. This factor was scored a 3 as the land has been prioritised for housing construction.

Housing Land Supply – Potential contains areas identified by the Green Belt Review where housing could be developed. The council’s Housing Investment Team advises that a demand for housing for the years 2020-2025 is estimated to be around 18,358 according to Glasgow's City Development Plan (Glasgow City Council 2016). This factor was scored a 2 as the development plans have not been finalised and there could still be potential for other projects to take place.

Industrial-Business Marketable Land Supply contains areas to invest for industrial and economic growth to benefit the city’s businesses and residents by having a broad and more integrated economy with diverse business opportunities including in the social enterprises sector to create a more confident and competitive workforce in the city. Opportunities also include an improved supply of goods quality, sustainable housing, better access to information technology and an improved active travel and public transport network for business and residents. This factor was scored a 2 for supporting growth to nearby industry and businesses in terms of travel links and housing.

Local Development Framework aims to influence the location of development to create a ‘compact city’ which supports sustainable development. It will also help to ensure that the city is well-positioned to meet the challenges of a changing climate and economy and to build a resilient physical and social environment which helps attract and retain investment and promotes an improved quality of life at a neighbourhood level. This factor was scored a 2 for promoting local projects and encouraging collaboration between businesses and residents.

Master Plan Area provides the appropriate physical environments to: support strong communities; support a rich and pleasurable quality of life for inhabitants and visitors; connect people and places by providing ease of movement within; and through developments, create places of distinction and enduring quality. Master planning can help achieve these outcomes by providing a structured approach and framework to a wide range of complex issues. A major city deal in 2017 involved a £1.13 billion University of Glasgow campus expansion to develop the former Western Infirmary site and fund major infrastructure projects to drive innovation (Glasgow City Council 2017). This factor was scored a 1 for encouraging growth and expansion to improve the surrounding areas and boost the local economy.

Network of Centres ensures that all of Glasgow's residents and visitors have good access to a network of centres which are vibrant, multi-functional and sustainable destinations providing a range of goods and services. This is achieved by maintaining and strengthening the role of Glasgow City Centre as the key economic driver in the West of Scotland; supporting the role that Town Centres play as integrated transport hubs and encouraging travel by sustainable means to and between Centres. This factor was scored a 2 for promoting services to provide for local residents.

Strategic Development Framework – River contains areas where development proposals are likely to have an impact on the function or character of the River Clyde or its surroundings. Aspirations include flood management, access, sustainable travel, navigation and leisure. This factor was scored a 2 for promoting services along the river and measures would need to take place to ensure any development is not at risk of flooding or damage due to the close proximity.

Strategic Development Framework covers large areas of the City which span beyond neighbourhood level to help deliver sustainable economic growth, shape good quality places and enhance the quality of life in the Glasgow and the Clyde Valley city region. This factor was scored a 2 for encouraging relationships within the local area between the business, residential and commercial sectors.

Strategic Economic Investment Locations are areas identified as possessing an ability to offer low carbon economic growth and to support the Scottish Government's key sectors and Scottish Enterprise locational priorities. As strategic priorities, they best reflect the need for sustainable locations to address long-term drivers of change. This factor was scored a 1 for encouraging development of low carbon solutions.

Transformational Regeneration Areas highlight large-scale housing-led regeneration projects. The programme aims to provide new sustainable mixed tenure communities through the provision of new housing, community facilities, green space and, where appropriate, commercial units. This factor was scored a 1 for promoting projects aimed at regenerating areas through various means, one of which could involve RET deployment.

The developmental aspect focused on using the available land strategically to promote economic and social growth by various means such as creating or expanding the commercial enterprises, industrial infrastructure, or attracting tenants to new housing. All factors were scored to reflect the support of the local authority's ambition of developing areas via community schemes and, although this is not considered as significant as some of the other aspects such as biodiversity and environmental both of which have protections set in legislation, its weighting was considered of lesser importance.

3.2.2.1.3 Environmental

For environmental protection within the city, several factors are included. Some have previously been described in Section 2.4.1 and are briefly summarised. Most factors were scored above 1 to protect natural green areas and to preserve the surrounding landscape.

Conservation Areas are designated under the (Planning (Listed Buildings and Conservation Areas) (Scotland) Act 1997) as being of special architectural or historic interest and character of which it is desirable to preserve or enhance. This factor was scored a 2 for protecting areas with special architectural or historic importance.

Green Corridors are protection buffers and can include rivers, watercourses, canals, railway lines, motorway corridors and trunk roads. Whereas Green Belts tend to constrain urban areas and the availability of developable land, Green Corridors support development and ensure continued local access to green space services.

This factor was scored a 1 for promoting such development in areas which could be used for RET deployment.

Historic Gardens Designed Landscapes aims to ensure the appropriate protection, enhancement and management of Glasgow's heritage assets by providing clear guidance to applicants. The Council will protect, conserve and enhance the historic environment in line with Scottish Planning Policy/Scottish Historic Environment Policy for the benefit of our own and future generations. This factor was scored a 3 for preserving and protecting local heritage and as such, RET development is discouraged.

Listed Buildings are those designated by Historic Scotland which are of special interest, architecturally or historically and which satisfy set criteria from the (Planning (Listed Buildings and Conservation Areas) (Scotland) Act 1997) which are used to distinguish this significance. Over 1,800 structures within the city are listed by Historic Scotland to protect them for future generations (Glasgow City Council 2020). This factor was scored a 2 for conserving such buildings and awareness is required for RET proposals.

Local Nature Reserves are areas of at least locally important natural heritage, designated and managed by local authorities to provide people better opportunities to learn about and enjoy nature. This factor was scored a 1 for encouraging RET deployment to provide clean energy.

Old Wood are areas with ancient (of semi-natural origin) woodland or long-established (of plantation origin) woodland. This factor is used to identify and assess woodland areas of important nature conservation value, to increase the total extent of priority woodland habitat within the City and to promote woodlands for socio-economic and public amenity benefits. This factor was scored a 2 for advising RET proposals to be mindful of the protection of such woodlands.

Proposed Conservation Area is the designation of potentially new conservation areas which can provide improvements to homes including replacement windows, re-roofing, extensions and installation of satellite dishes. This factor was scored a 2 for focusing on upgrading existing homes in the local area.

Scheduled Ancient Monuments ensures the appropriate protection, enhancement and management of Glasgow's heritage assets (The Ancient Monuments and Archaeological Areas (Applications for Scheduled Monument Consent) (Scotland) Regulations 2011). The aim of scheduling is to preserve the country's most significant sites and monuments as far as possible in the form in which they have been inherited. This factor was scored a 3 for shielding sites and monuments from local projects and developments.

Sites of Importance for Nature Conservation is a non-statutory designation given to a locally important area of nature conservation interest and provides guidance on the natural environment including protected sites and species and the enhancement of biodiversity (Nature Conservation (Scotland) Act 2004). This factor was scored a 3 for ensuring protection for naturally sensitive areas.

SSLI are identified by a set criterion including scenic quality, landscape quality, natural heritage features, cultural heritage features, cultural associations and other perceptual value such as tranquillity and size. This factor was scored a 3 for ensuring protection for culturally sensitive areas and scenic landscapes.

SSSI are areas designated for the special interest of its flora, fauna, geology or geomorphological features (The Sites of Special Scientific Interest Regulations 2008). This factor was scored a 4 for safeguarding the longevity of rare and/or special natural features.

Tree Preservation Order are areas protected for preservation, planting and replacement of trees by the (The Town and Country Planning (Tree Preservation Order and Trees in Conservation Areas) (Scotland) Regulations 2010). This factor was scored a 2 for conserving areas for tree protection and regeneration.

World Heritage Site - Antonine Wall Buffer is the buffer zone to protect the immediate setting of the Antonine Wall and the adjacent environment which contributes to the character, significance and understanding. Definition of the buffer zone has been based on visibility to and from the site and analysis of the land use setting including urban areas. This factor was scored a 2 for ensuring project development stays within a certain proximity to the Antonine Wall.

World Heritage Site - Antonine Wall highlights the Frontiers of the Roman Empire and provides advice for developers, decision makers and the general public for consideration in the assessment of planning applications affecting the Antonine Wall and its setting. This factor was scored a 4 for safeguarding a historical artefact.

For any kind of application which utilise land use, an environmental assessment must be conducted by GCC and would need to conform with the City's development planning regulations (Glasgow City Council 2019). Therefore, emphasis was given to the environmental policy aspect as this concentrated on protecting the local natural landscapes and aimed to prevent as much damage to the immediate surroundings as possible. This aspect played the key role in determining site suitability as they may include legally protected preservation areas and would require greater attention when determining site location. The significance of this aspect is considered high with protections set in legislation and was therefore, assigned equal weighting with Biodiversity.

3.2.2.1.4 Visual impact

For visual impact, the Social factor is influenced by subjective judgement based on the proximity of residential properties to a given site of a PVPS which can populate a large area. However, they do not possess great height and in an urban environment, they are unlikely to significantly impact on the quality of view especially as there are often a natural barrier of tall trees between sites and communities.

Community information containing building height and elevation are considered with longer visibility from tall buildings or rising ground. A buffer around communities, which are unprotected by natural screening such as trees, was created with a radial distance of 500 m as used by previous studies (Castillo *et al* 2016, Watson & Hudson 2015, Uyan 2013). Multiple scores were assigned to this factor where a score of 1 was allocated to areas where no residential areas overlook the site; and a score of 2 was allocated to areas where residential areas did overlook the site. With community opinions taken into account of local energy solutions, this aspect was weighted to be less important than Biodiversity and Environmental but more important than Developmental.

3.2.2.1.5 Visual intrusion

Existing regulations require CAA to be consulted for major solar PV developments within 24 km of an officially safeguarded aerodrome such as Glasgow Airport, although the aerodrome may choose to reduce this distance to 5 km. Glasgow's Aerodrome Traffic Zone also covers a radius of just less than 5 km. A report from STA stated that glare from solar panels has not been an issue within airports with local PVPS deployments. As PV panels are designed to absorb light, their reflectivity is considerably lower than that of other objects commonly visible on and around aerodromes such as building facades, metal roofs and bodies of water. Additionally, prior to landing, the nose of a commercial aircraft is tilted slightly upwards making it less likely that reflections from panels would enter the cockpit no matter the orientation of the PV array. For motorways, there may also be a slight risk of glare but no incidents have been reported of drivers involved in accidents with glare being the primary cause.

Buffer zones of variable distances were created around the airport, heliport and motorways and as a result, multiple scores were allocated. A score of 1 is assigned to all areas outside the buffer zones; a score of 2 is assigned to areas between 1 and 5 km radius to the south of an airport or heliport or within 100 m of a motorway; a score of 3 is assigned to areas within a 1 km radius semicircle to the south of an airport or heliport.

The southern direction is emphasised due to the orientation the PVPS system would be facing as it is in the northern hemisphere and should be facing towards the equator due to the higher concentration of solar radiation. A minimum distance of 100 m from motorways is advised to reduce risk of glare and improve safety of the PVPS system (Colak *et al* 2020, Majumdar & Pasqualetti 2019). This aspect is considered the least weighted due to such low risks of endangerment.

3.2.2.2 Technical aspects for Glasgow City

The generic weather aspect is not included in the assessment as the scope of this project is for Glasgow City and due to its relatively small size compared to large rural regions of land which is normally examined with site selection tools, the solar irradiance is assumed to be uniform across the city and is discussed further in Section 3.3.3. The proximity aspect which measured distances between potential sites to roads, hydrological features and substations was changed to only include substation connection distance reflected in the same aspect name; major roads and motorways are included in the Visual intrusion policy aspect; and hydrological features are included in the Terrain aspect. Therefore, the following four technical aspects affect whether a site is suitable for development: Overshading, Substation Congestion, Substation Connection Distance, and Terrain. These aspects are now considered in turn.

3.2.2.2.1 Overshading

This aspect is enabled via building height data included in the DSM from OS, which enables determination of an overshading footprint (Ordnance Survey - OS Terrain 2021). Four key dates were used to compute the footprint: the spring and autumn equinoxes; and the summer and winter solstices. Utilising GIS technology, building height data and hourly solar elevation angles for these seasonal dates were used to calculate building shadows based on trigonometric relations between the solar path, the ground level and any obstructing obstacles as shown in Figure 3.1.

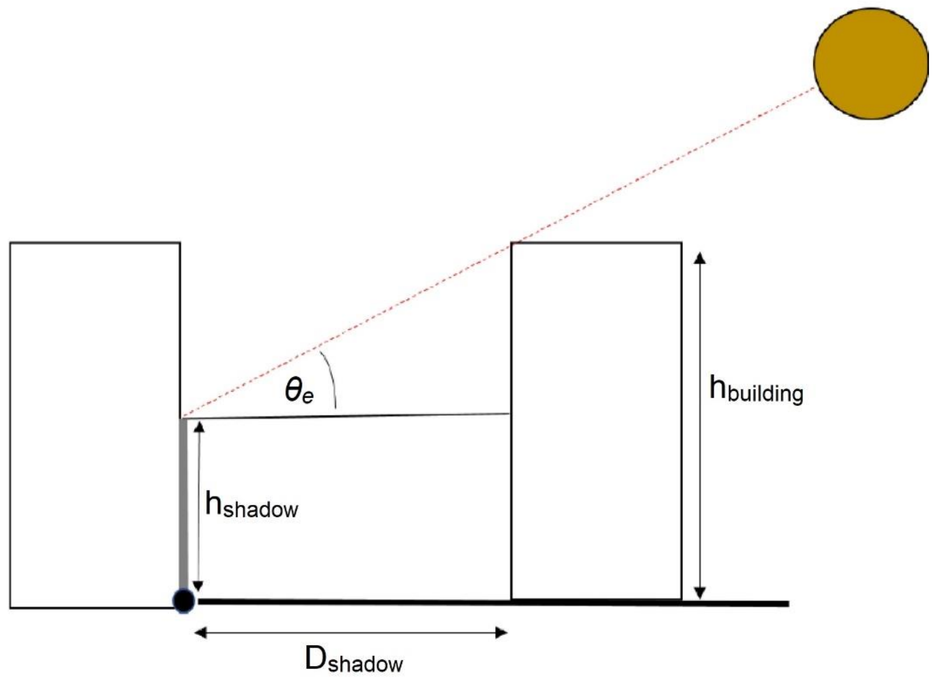


Figure 3.1. Building shadow geometry (from Vulkan *et al* 2018).

Due to the density of buildings within an urban environment, shadows cast by buildings can be obstructed by other buildings from which the shadow height, h_{shadow}, can be calculated (Vulkan *et al* 2018):

$$h_{shadow} = h_{building} - D_{shadow} * \tan(\theta_e) \quad (3.1)$$

where $h_{building}$ is the building height, D_{shadow} is the building shadow distance, and θ_e is the hourly Sun elevation angle.

If no obstacles are present, h_{shadow} becomes zero and the equation to calculate D_{shadow} reduces to:

$$D_{shadow} = \frac{h_{building}}{\tan(\theta_e)} \quad (3.2)$$

The building shadow distances were then superimposed to give a reasonable, composite annual overshading footprint. Using this data identifies the areas of land that will be overshaded but does not imply that all the area will be shaded all the time.

It was decided that this factor should have multiple scores where a score of 1 is allocated to areas which fall outside the estimated annual shaded footprint; and a score of 3 is allocated to areas which fall within the estimated annual shaded footprint. As the efficiency of a PVPS is crucially dependent on the amount of solar irradiance received, any overshading can drastically lower the power output and due to this reason, this aspect is highly weighted.

3.2.2.2.2 Substation congestion

A substation in a favourable proximity may not guarantee effective network connection if existing circuits are overloaded or if there are significant connections with the possibility of reverse current flow. This aspect is linked to the Substation Connection Distance as the situation may change over time as loads change and substations are upgraded. SPEN assesses congestion around primary substations from two perspectives: the ability of each 11 kV circuit to take distributed generation (Circuit level) and the impact of distributed generation on other circuits (Primary Area level) (SP Energy Networks - DG Heat Maps Overview 2015). The company publishes GIS-based Network Heat Maps, which score each circuit at each substation on a 3-point scale for each of seven issues including existing fault levels, risk of reverse power flow and rise in voltage within the network. However, the heat maps show no variation between the different circuits at any substation in the Glasgow area. The total score for any substation could therefore theoretically range from 7 (best) to 21 (worst). In practice all the scores for the 74 primary substations in or immediately adjacent to Glasgow fall between 8 and 12, with 10 being the most frequent score.

It was decided that this factor should have multiple scores where a score of 1 is allocated to areas where the combined heat map score is under 10; a score of 2 is allocated to areas where the combined heat map score is equal to 10; and a score of 3 is allocated to areas where the combined heat map score is greater than 10. As the level of congestion could improve over time with upgrades to the substation infrastructure, this aspect was considered of lesser importance in weightings.

3.2.2.2.3 Substation connection distance

An urban PVPS could be connected to the grid directly to a primary or secondary substation in addition to a connection point on an 11 kV circuit. Generally, the location and cost of a grid connection must be determined for each project and for the type of RET as multiple considerations are needed to be taken into account such as the capacity and type of equipment proposed for the installation as well as on the layout of nearby 11 kV circuits and secondary substations. SPEN operates 74 primary substations within the city and in the immediate surroundings, each substation enclosed around 11 kV circuits feeding a number of secondary substations. The density of the circuits tends to increase the closer to a substation which in turn increases the probability of there being a suitable connection point. A criterion based on the straight-line distance to the nearest 11 kV circuit provides a sufficient indication of the relative suitability of different sites. However, this is not the actual distance covered by a connection cable as it would normally be routed along roadsides. Although calculating the real distance through the streets to the nearest accessible circuit is a viable analysis via GIS technology, this was not implemented for this project as a feasibility study would be required to determine the ideal route for installing connection cables considering the logistics involved such as traffic redirection and the impact to local commercial businesses.

Therefore, it was decided that this factor should have multiple scores where a score of 1 is allocated to areas within 100 m of a substation connection line; a score of 2 is allocated to areas between 100 m and 200 m of a substation connection line; and a score of 3 is allocated to areas further than 200 m from a substation connection line. The connection distance aspect highlights sites of suitability in terms of how close a proximity they are to the nearest substation connection point. This was to prevent unnecessary amounts of excavation of ground or fields which could impact the traffic, local communities and the surrounding environment. This aspect was considered second in technical priority.

3.2.2.2.4 Terrain

Most urban land will not present problems for PVPS deployment in terms of accessibility as transport links tend to have wide coverage although, in some rare occasions, there may be sites that have been built with no direct road access. As PVPS do not require deep foundations, its panels can be held in place with gravity anchors if necessary which minimises any negative environmental impact. However, deploying this type of RET would be more difficult on sites vulnerable to flooding, steep slopes or sites with limited access. The terrain information was generated via a qualitative judgement based on data provided by CEDA and SEPA in the form of a DTM and flood map respectively (Centre of Environmental Data Analysis 2021, Scottish Environment Protection Agency 2021).

It was decided that this factor should have multiple scores where a score of 1 is allocated to areas with flat ground, no access issues or risk of flooding; a score of 2 is allocated to areas with steep slopes or broken ground, restricted access and greater risk of flooding or accumulating surface water over large areas; and a score of 3 is allocated to areas with no direct access or with a high risk of river or coastal flooding. As PVPS does not require deep foundations, does not have a significant impact on the environment, and mitigation plans can be implemented to avoid flooding, terrain was considered the least important of all technical aspects.

3.3 GOMap tool development

City-level information, comprising the policy and technical aspects, their underlying factors and scores as elaborated in the previous section are encapsulated in a GIS evaluation tool named GOMap, which is built on the open source QGIS software and supported by the scripting language Python. This section considers the required GIS grid resolution, describes the implementation of the scoring and weighting processing scheme, and elaborates on the PVPS model as embedded in GOMap.

3.3.1 QGIS

GOMap is built upon QGIS, a free open source GIS software where its performance can be extended with a wide range of external plugins or by modifying the source code directly. Various plugins have been developed specifically for QGIS to serve environmental purposes such as evapotranspiration prediction and near surface air temperature mapping (Ellsäßer *et al* 2020, Touati *et al* 2020). The core functionality of GOMap is written in Python version (3.7) while the GUI is developed using Qt designer. GOMap is compatible with QGIS version (3.16) and all its functionalities can be run on a standard QGIS for desktop without requirements of any additional python libraries package.

3.3.2 Python scripting

To facilitate all the information discussed and collected during the workshop and consultation sessions, Python is used to integrate the GOMap tool with QGIS. The main functionality of GOMap includes three systems: the grid system; the scoring system; and the weighting system. With these systems translated into Python and implemented, external Python scripts are used to import spatial information including automatic adjustment to the local coordinate reference system used to accurately represent objects on a two-dimensional projected map. The following sections gives details on these systems and scripts.

3.3.2.1 Grid system

There can be multiple factors active at any given location and corresponding to some geographical resolution set by the local authority. A spatial representation system with variable dimensional capability is implemented whereby a grid covers the entire city at the required resolution. The agreed scores for each aspect factor are assigned to each grid cell via an independent GIS shapefile. As each cell possesses a unique ID number, it is possible to determine which factors converge within any cell. Figure 3.2 shows two grid resolutions applied to a portion of a city. Each cell needs to have a score associated with the active factors as described previously. In this example, the actual site being processed is marked in light brown. Here, a resolution issue arises because the site is only partly covered by cells.

For example, in the left image, only 2 out of 8 cells (25%) mostly cover the site: the coverage of cells 21 and 78 are 85% and 98% respectively. If a part of the cell covers the site, this requires a mechanism to decide how much of a factor that is

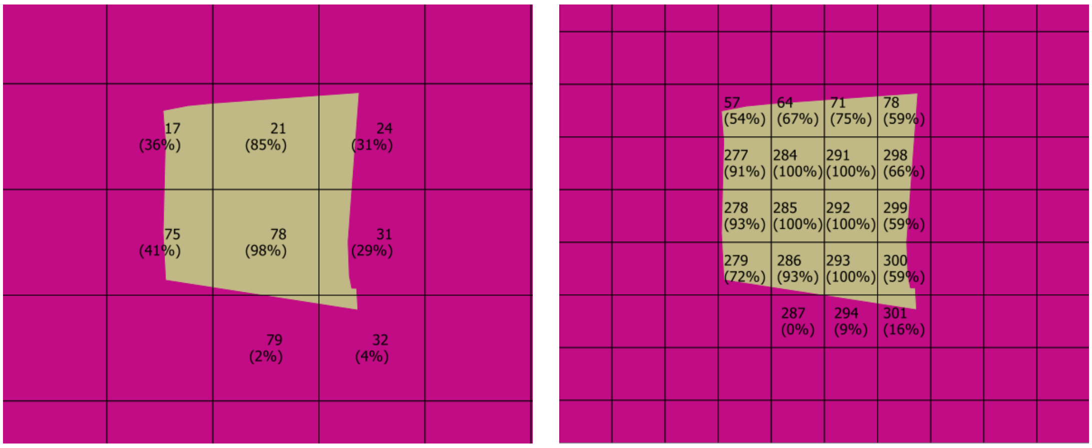


Figure 3.2. Varying grid resolutions: coarse (left); fine (right). The images show the cell ID and the extent to which cell covers the site.

active for a cell should be associated with the site. A rule is therefore introduced whereby if the site occupies 50% or more of the cell then it is assumed that the cell's active factors are associated with the site. The accuracy of this rule can be improved by adopting a higher gridding resolution as shown in the right image where 16 out of 19 cells (84%) pass the overlap rule and can then therefore inherit the cell's properties.

The question then is what resolution is best to ensure that typical city sites can be processed to an acceptable accuracy?

A systematic study based on area analysis was undertaken using spatial information of the VDL sites. Similar to the method shown in Figure 3.2, multiple grid resolutions were generated and the convergence of VDL sites investigated in terms of: the area coverage of the cell; the total number of cells generated; and the difference of the area covered by the cells compared to the original area of the VDL sites.

The findings are reported in Table 3.3. The total original area of all VDL sites was calculated to be 1168.8 ha. Beginning with a coarse grid resolution of 100 m x 100 m which comprised of 18,308 cells would cover 762.1 ha (65.2%) of the original area.

The missing areas are largely due to the coarse cells overlapping parts of the curvatures of VDL site boundaries which fail the 50% coverage rule described previously. To reduce this error margin, increasing the resolution by 4 times to 50 m x 50 m would consist of a grid with 71,688 cells, cover 956.4 ha (81.8%) and shows

Table 3.3. Determining ideal grid resolution from VDL coverage and number of grid cells generated by varying grid resolutions.

Grid resolution (m)	Area (ha)	No. of grid cells	Difference to original area (%)
Original area	1168.8	-	-
1 x 1	1168.6	176 million	99.9
10 x 10	1121.7	1.76 million	96.0
50 x 50	956.4	71,688	81.8
100 x 100	762.1	18,308	65.2

how incrementing the resolution can significantly improve land coverage due to the finer grid cells overlapping more of the VDL sites than its boundaries.

Increasing the resolution further to 10 m x 10 m results in 1.76 million and covers the majority of VDL sites at 1121.7 ha (96.0%). With higher resolutions and finer grid cells, the area coverage by the grid cells reaches closer to the original area of the VDL sites. However, additional grid cells would need to be generated which can drastically degrade performance in GOMap and not provide significantly new or useful information. This can be seen by setting the resolution to 1 m x 1 m which is comprised of 176 million grid cells covering almost the entirety of VDL sites at 1168.6 ha (99.9%). This is 100 times greater than the resolution at 10 m x 10 m with an unnecessarily large number of grid cells but only provides an additional 45.6 ha (3.9%) of VDL coverage. This additional information does not justify the vast number of grid cells necessary. Therefore, it was concluded that a 10 m x 10 m grid is a suitable default for the examination of a city which, for Glasgow, at this scale would comprise 1.76 million cells. Setting this high resolution provides relevant city information and going beyond this would not yield any further significant information.

3.3.2.2 Scoring system

With the grid resolution determined, the scoring mechanism can be applied for each cell that overlaps a site. The scoring system was defined from consultations with local authority planners and utility specialists through workshops and planning documents as described in Section 3.2. An example is given in Table 3.4 where a cell has several active policy factors.

Table 3.4. Example policy aspects factors affecting a cell.

Aspect	Factor	Factor score	Aspect score
Biodiversity	Creature habitats	1	1
Developmental	Green belt	2	2
	Network of centres	2	
	Strategic economic investment locations	1	
	Transformational regeneration areas	1	
Environmental	Conservation areas	2	3
	Historic gardens designed landscapes	3	
	Scheduled ancient monuments	3	
Visual impact	Social	2	2

Here, the policy aspect score is the median score of the active underlying factors. For example, the environmental aspect comprises three factor scores (2, 3, 3) with a median value of 3; whereas the developmental aspect comprises four factor scores (1, 1, 2, 2) with a median score of 2. By default, GOMap automatically rounds the scores up for the more pessimistic value to acknowledge the constraints involved. This can be changed to round the scores down for a more optimistic value: this was not done in the work reported here, however, the option is available as from a decision maker's perspective, providing alternative rounding mechanisms can provide better view of the potential solutions depending on attitudes. For example, a decision maker with a low risk-taking attitude may weigh negative outcomes more highly; conversely, a decision maker with a high risk-taking attitude may be more likely to weigh positive outcomes more highly (Firozjaei *et al* 2019, Al-Yahyai *et al* 2012). The overall policy score is then determined as the median value of the active aspect scores, here 2. The same process is repeated for the technical aspects to arrive at an overall technical score.

Factor and score information were imported into GOMap and contained in its own GIS map layer representing the geographical data as a visual representation of the hierarchy as shown in Table 3.5 which contains all policy and technical aspects, their associated factors and the scores of each factor used in the output. Each layer can be independently enabled/disabled depending on the given scenario. Multiple scores can be stored within a GOMap layer as can be seen by some factors.

Table 3.5. Policy and technical factors and scores.

Policy aspect	Factor	Factor score
Biodiversity	Creature habitats	1, 2, 3
Developmental	Community growth masterplan area	2
	Economic policy areas	2
	Green belt	2
	Green network opportunity areas	2
	Housing land supply – consented	3
	Housing land supply – potential	2
	Industrial-business marketable land supply	2
	Local development framework	2
	Master plan area	1
	Network of centres	2
	Strategic development framework – river	2
	Strategic development framework	2
	Strategic economic investment locations	1
	Transformational regeneration areas	1
Environmental	Conservation areas	2
	Green corridors	1
	Historic gardens designed landscapes	3
	Listed buildings	2
	Local nature reserves	1
	Old wood	2
	Proposed conservation area	2
	Scheduled ancient monuments	3
	Sites of importance for nature conservation	3

	Sites of special landscape importance	3
	Sites of special scientific interest	4
	Tree Preservation Order	2
	World heritage site – Antonine Wall buffer	2
	World heritage site – Antonine Wall	4
Visual impact	Social	1, 2
Visual intrusion	Airport, helipad and motorway	1, 2
	Helipad inner radius	3
Technical aspect	**Factor**	**Factor score**
Overshading	Building shadows	1, 3
Substation congestion	Congestion	1, 2, 3
Substation connection distance	Connection distance	1, 2, 3
Terrain	Terrain suitability	1, 2, 3

3.3.2.3 Weighted system

Weightings governed which policy or technical aspects should be prioritised when being evaluated by the tool to give a realistic screening of the available resource. This could be used by planners to encourage or mitigate deployment of projects depending on the circumstance. The MCDM/AHP method is used to determine the weightings of each policy and technical aspect. Using the scale system for pairwise comparison as shown earlier in Table 2.2, each aspect is given a scale in relation to its importance over the other aspects as discussed during the workshops with GCC and SPEN. For similar reasons to the scoring system in regards to simplicity, scale values up to 3 were used to identify aspects which are of equal or greater importance in relation to other aspects with the inverse of these scales used to identify aspects which are of lesser importance in relation to other aspects.

For the policy aspects, the pairwise comparison matrix and the calculation of weightings are shown in Tables 3.6 and 3.7 respectively. The calculations to

Table 3.6. Pairwise comparison matrix of the evaluation criteria for policy aspects.

Aspects	Biodiversity	Developmental	Environmental	Visual impact	Visual intrusion
Biodiversity	1.000	3.000	1.000	3.000	3.000
Developmental	0.333	1.000	0.333	0.500	2.000
Environmental	1.000	3.000	1.000	3.000	3.000
Visual impact	0.333	2.000	0.333	1.000	2.000
Visual intrusion	0.333	0.500	0.333	0.500	1.000
Σ	3.000	9.500	3.000	8.000	11.000

Table 3.7. Weighting by pairwise comparison for policy aspects.

Aspects	Biodiversity	Developmental	Environmental	Visual impact	Visual intrusion	Weighting
Biodiversity	0.333	0.316	0.333	0.375	0.273	0.326
Developmental	0.111	0.105	0.111	0.063	0.182	0.114
Environmental	0.333	0.316	0.333	0.375	0.273	0.326
Visual impact	0.111	0.211	0.111	0.125	0.182	0.148
Visual intrusion	0.111	0.053	0.111	0.063	0.091	0.086
Σ	1.000	1.000	1.000	1.000	1.000	1.000

determine the CR is shown in APPENDIX II.1: Table A2.1. For the technical aspects, the pairwise comparison matrix and the calculation of weightings are shown in Tables 3.8 and 3.9 respectively with the calculations to determine the CR shown in APPENDIX II.1: Table A2.2.

Once the weightings have been determined, the Weighted Overlay Analysis method is used to calculate the final opportunity map from the sum of multiplying the scores of each aspect by its weight for each grid cell using Equation 2.8. The GIS tool would use a modified version of the standard Weighted Overlay Analysis method by having similar logic performed on information based in vector format as opposed to raster which it was originally designed for. The weighting system is designed to run concurrently with the grid and scoring systems to generate the final opportunity map. This allows for a single opportunity map to be updated in real-time as any policy and technical information can be independently switched on/off and the final scores recalculated. Two methods of weightings are available:

- Non-equal – All policy and technical aspects weightings are determined using the MCDM/AHP method to set the order of importance based on city planning policies and expert knowledge. Table 3.10 shows an example of how the final score is reached using the Weighted Overlay Analysis method where the sum of the weighted scores is given as the final score of a grid cell. Using the example shown, the final policy and technical scores are 1 and 1 respectively.
- Equal –All policy and all technical aspects are treated with equal importance and are given equal weightings. Table 3.11 shows an example of how the final score is reached using the Weighted Overlay Analysis method for the same grid cell as the non-equal method. Here the final policy and technical scores are shown to be 2 and 2 respectively. It can be seen that the final opportunity map can be significantly different depending on whether non-equal or equal weightings are used.

Table 3.8. Pairwise comparison matrix of the evaluation criteria for technical aspects.

Aspects	Overshading	Substation congestion	Substation connection distance	Terrain
Overshading	1.000	3.000	3.000	3.000
Substation congestion	0.333	1.000	0.500	2.000
Substation connection distance	0.333	2.000	1.000	2.000
Terrain	0.333	0.500	0.500	1.000
Σ	2.000	6.500	5.000	8.000

Table 3.9. Weighting by pairwise comparison for technical aspects.

Aspects	Overshading	Substation congestion	Substation connection distance	Terrain	Weighting
Overshading	0.500	0.462	0.600	0.375	0.484
Substation congestion	0.167	0.154	0.100	0.250	0.168
Substation connection distance	0.167	0.308	0.200	0.250	0.231
Terrain	0.167	0.077	0.100	0.125	0.117
Σ	1.000	1.000	1.000	1.000	1.000

Table 3.10. Example of final score with weighting application.

Policy aspect	Score	Weighting	Weighted score	Final score
Biodiversity	1	0.326	0.326	1
Developmental	2	0.114	0.228	
Environmental	1	0.326	0.326	
Visual impact	2	0.148	0.296	
Visual intrusion	3	0.086	0.258	
Technical aspect	**Score**	**Weighting**	**Weighted score**	**Final score**
Overshading	1	0.484	0.484	1
Substation congestion	1	0.168	0.168	
Substation connection distance	2	0.231	0.462	
Terrain	2	0.117	0.234	

Table 3.11. Example of final score with equal weighting application.

Policy aspect	Score	Weighting	Weighted score	Final score
Biodiversity	1	0.200	0.200	2
Developmental	2	0.200	0.400	
Environmental	1	0.200	0.200	
Visual impact	2	0.200	0.400	
Visual intrusion	3	0.200	0.600	
Technical aspect	**Score**	**Weighting**	**Weighted score**	**Final score**
Overshading	1	0.250	0.250	2
Substation congestion	1	0.250	0.250	
Substation connection distance	2	0.250	0.500	
Terrain	2	0.250	0.500	

3.3.2.4 Shapefile conversion

The shapefile conversion script is a standalone executable file containing Pythonic logic for the grid and score systems described earlier and applies grid representation and scores to all spatial information entered. Executing the script outside of GOMap allows the spatial information to be processed and imported into the tool in a streamlined, efficient procedure, although the script can be performed during the running of GOMap. The weighting system only applies during the running of GOMap and is not used in the standalone script as it determines the final opportunity map.

Before running the shapefile conversion script, spatial information is placed in the *Shapefile conversion* directory as shown in Figure 3.3. When running the script, user input is required for several parameters from the command prompt as shown in Figure 3.4. The user is prompted to enter information including:

- How the shapefiles are to be used (i.e. scope or as a policy/technical aspect);
- If the scope is selected, the cell size is entered (e.g. entering *10* would create grid cells with a length and width of 10 m), and the percentage value of the cell overlap rule;
- If policy or technical are selected, the name of the aspect is required (i.e. Environmental) and the cell size.

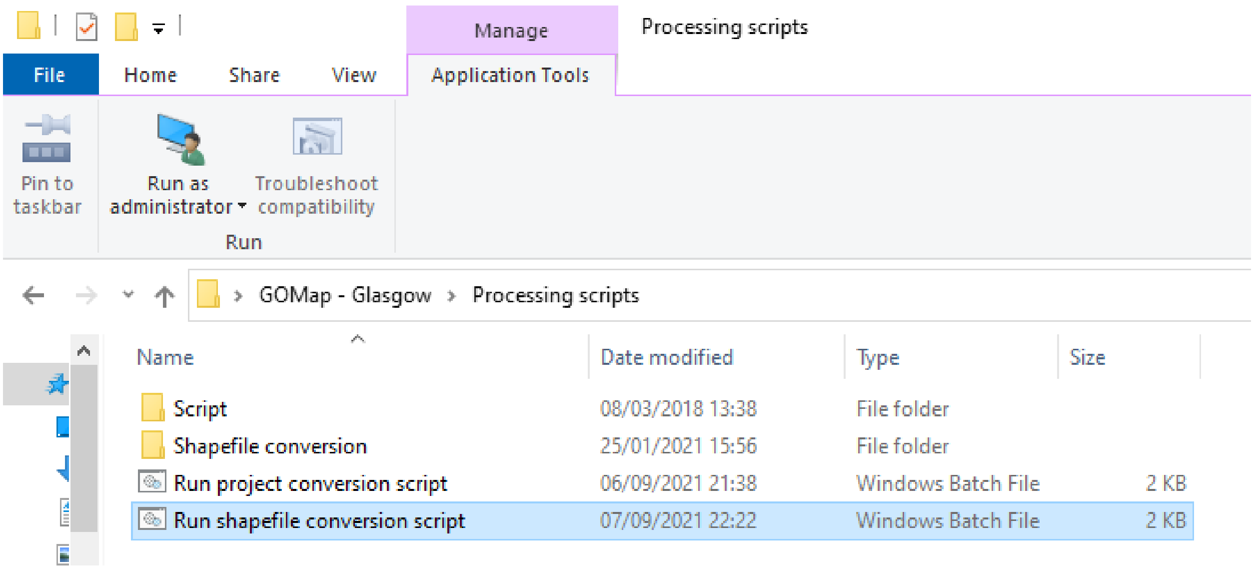


Figure 3.3. GOMap Scripts directory.

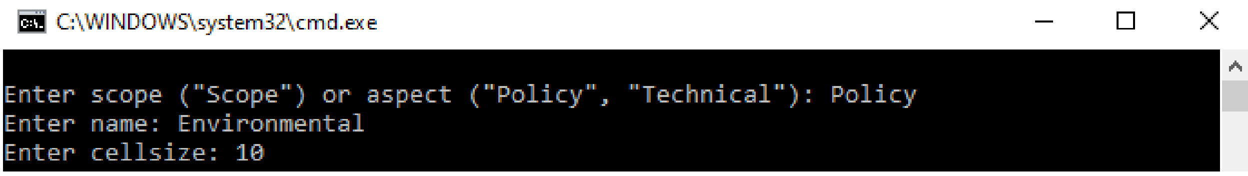


Figure 3.4. Shapefile conversion script being executed.

Different types of shapefiles are processed using various GIS operations accordingly:

- Line shapefiles are first converted to polygons using a *Buffer* operation. A data attribute named ‘Width’ measured in meters is used to represent power lines, roads, motorways etc. as polygons. The result is converted into the grid representation;
- Point shapefiles use a *Nearest Distance* operation which calculates the distance from each point of the layer to each grid cell of the city. A data attribute named ‘Name’ is used to identify the source location from which the distance is calculated;
- Polygon shapefiles are simply converted into the grid representation.

All input files are automatically moved to the *Original data* folder inside the main GOMap directory as shown in Figure 3.5 and contained within their own aspect folder. The hierarchy is similar to that of the *Aspects* folder inside the main GOMap directory as shown in Figure 3.6. All output files (the processed input files) have the same filename as their input counterpart and are added to the *Aspects* folder. The *Additional information* folder contains any spatial or textual information which can be overlaid on the final opportunity map to provide supplementary context. The *Scope* folder contains shapefiles used to show opportunities within particular areas of interest. The *About* text file provides information concerning the GIS project including hyperlinks which can be edited and viewed within the tool. The *GOMap* file is an executable QGIS file used to load the project created with the GOMap tool.

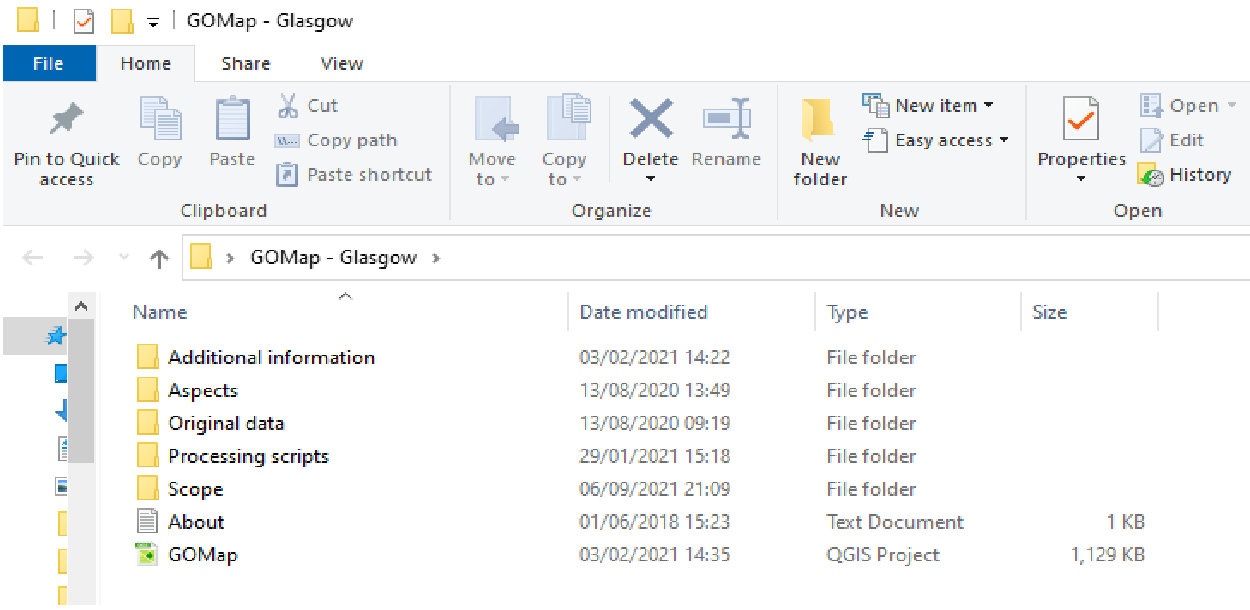


Figure 3.5. GOMap directory.

Figures 3.7 and 3.8 show the interface once the script has reached completion for both policy and technical information respectively. As mentioned earlier, the user is notified when the script is initialised and when it has completed processing each specific input folder.

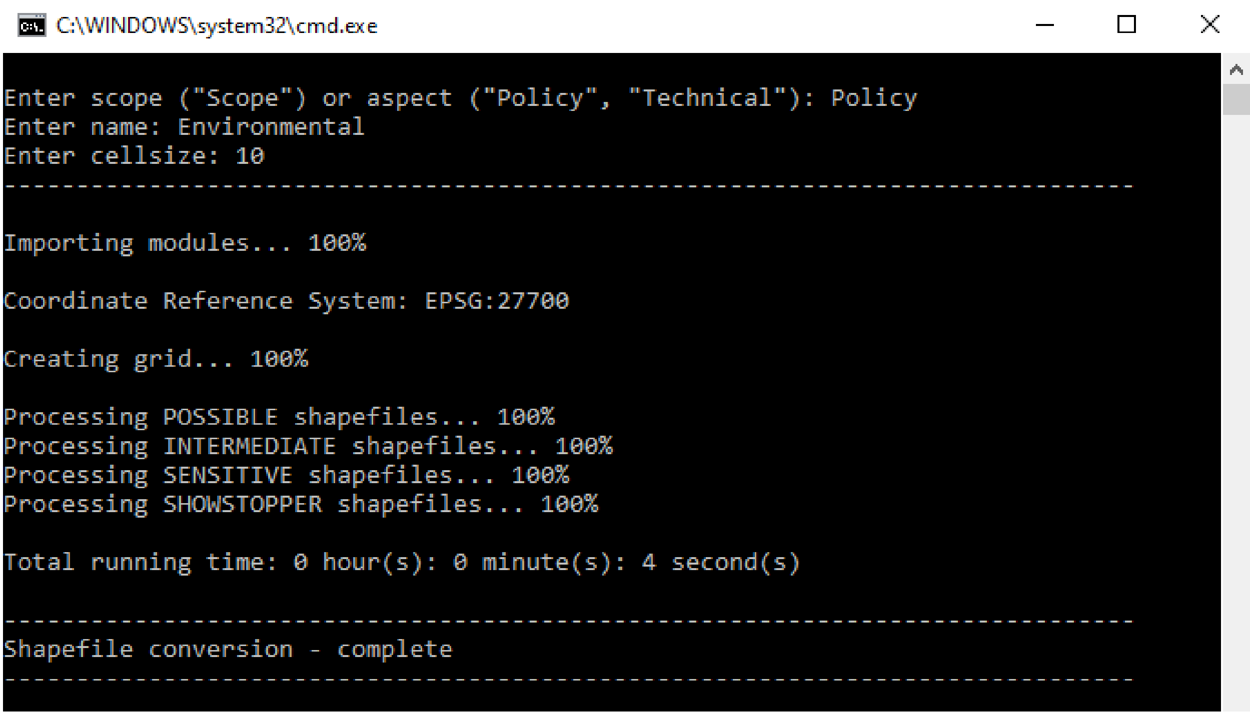


Figure 3.6. Policy shapefile conversion script completed.

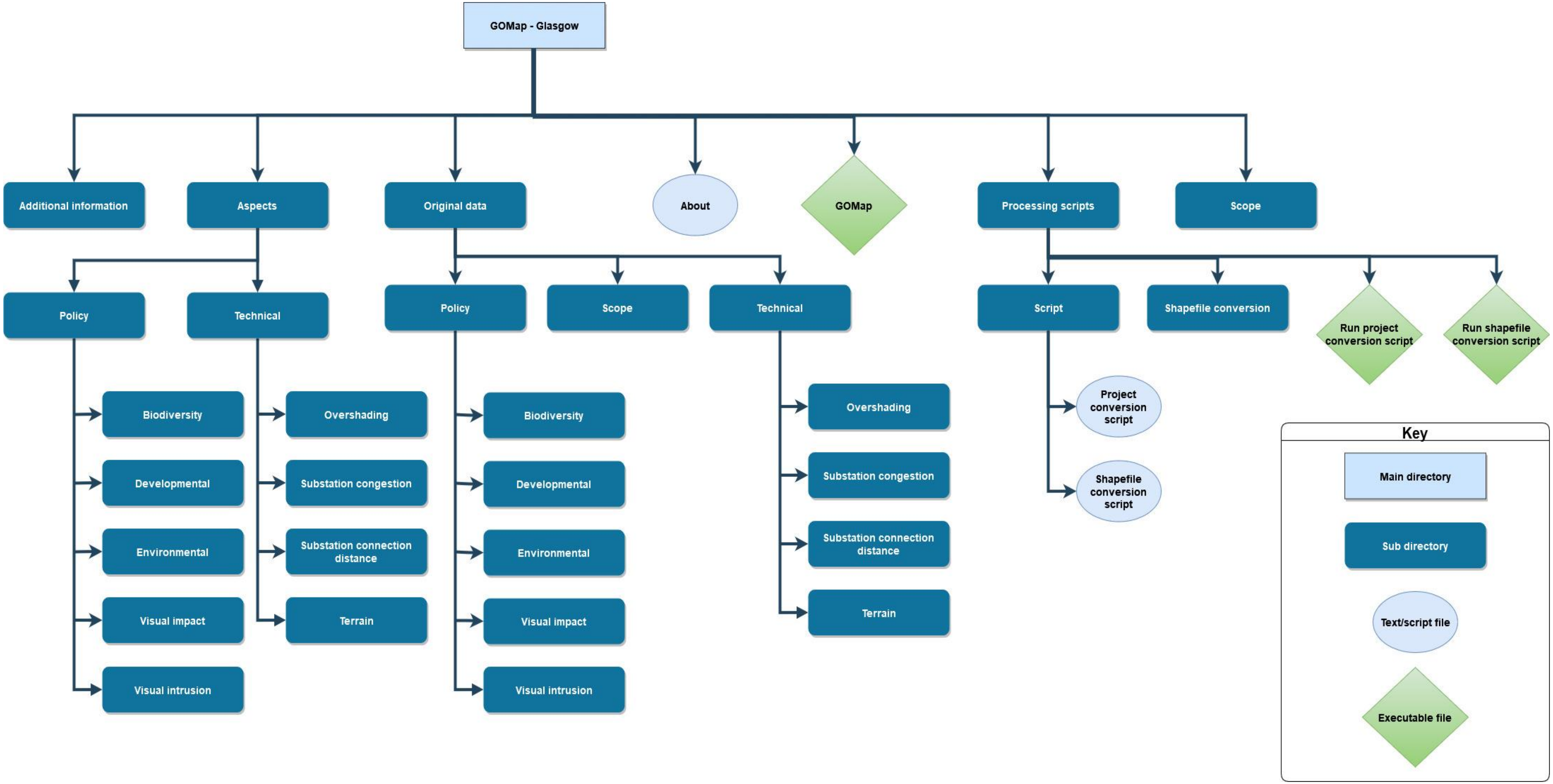


Figure 3.7. GOMap directory hierarchy.

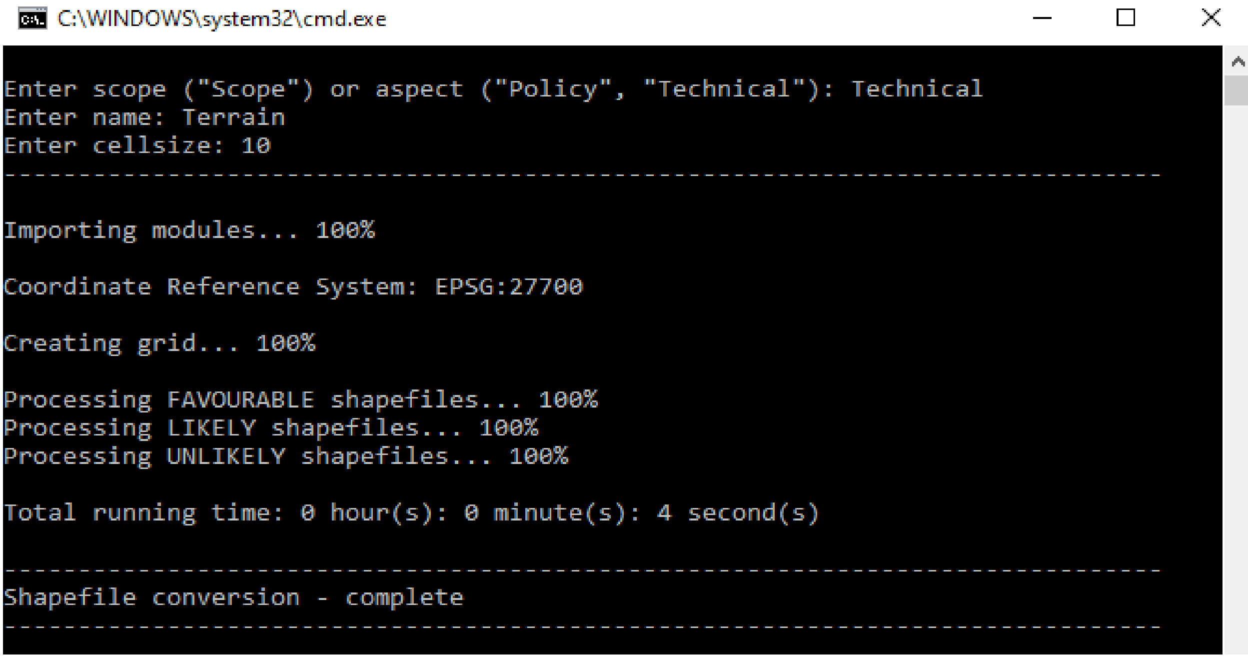


Figure 3.8. Technical shapefile conversion script completed.

3.3.2.5 Project conversion

The conversion of an existing project is achieved by executing another standalone executable file in a similar manner as the shapefile conversion script. The project conversion script takes the scores from existing shapefiles, rebuilds the original shapefiles at a user-defined grid resolution and then applies the same score to the newly converted shapefile. This allows the user to create the same GOMap projects at different resolutions.

For new projects, it is recommended to create it at low resolution as this decreases the amount of data to be processed and consequently improves performance speed. Once all spatial information including scores and weightings are confirmed, the project can be converted to higher resolution.

The script is executed in the *GOMap Processing scripts* directory as shown in Figure 3.9.

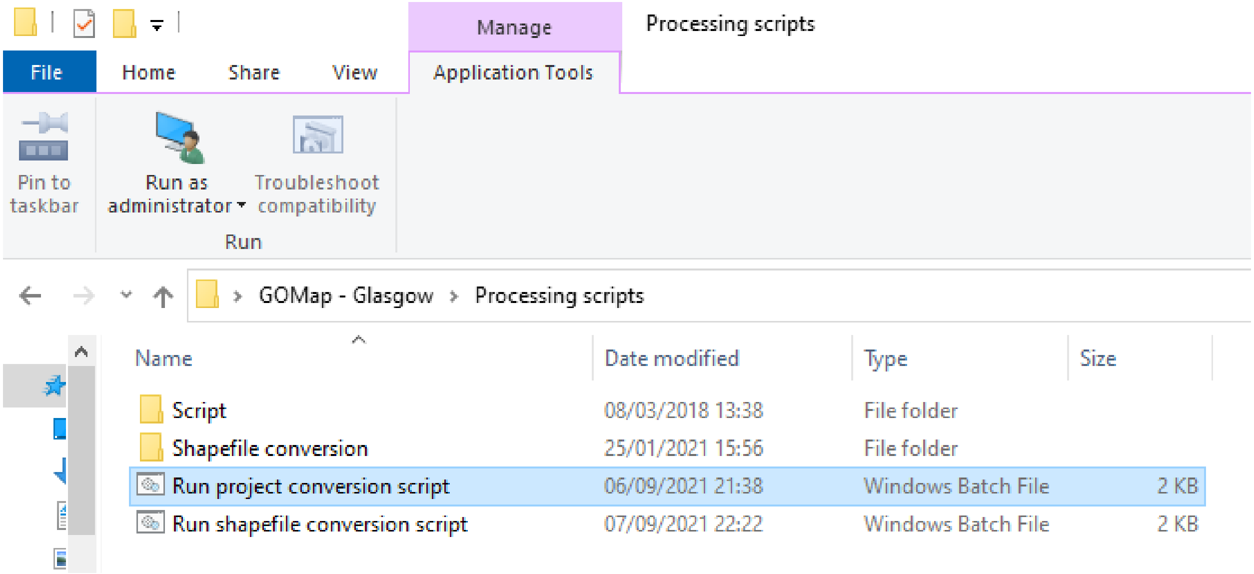


Figure 3.9. GOMap Processing scripts directory.

When running the project conversion script, the user is warned that all processed shapefiles will be converted. The script then prompts the user to enter a cell size as shown in Figure 3.10.

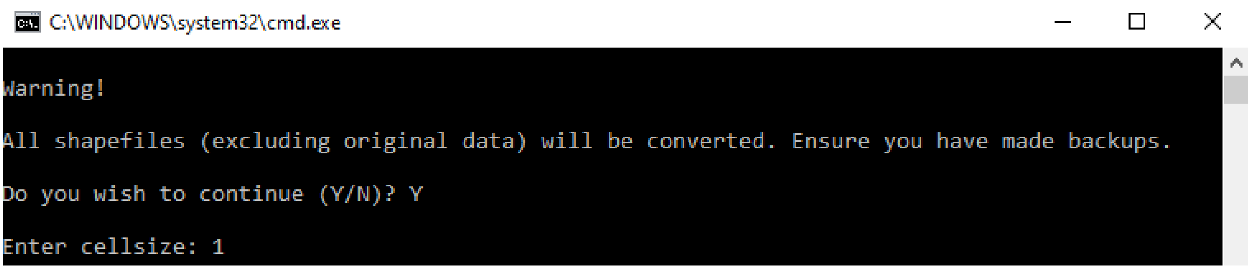


Figure 3.10. Project conversion script interface.

Once entered, the script processes the necessary shapefiles. Progress notifications are issued as shown in Figures 3.11 and 3.12.

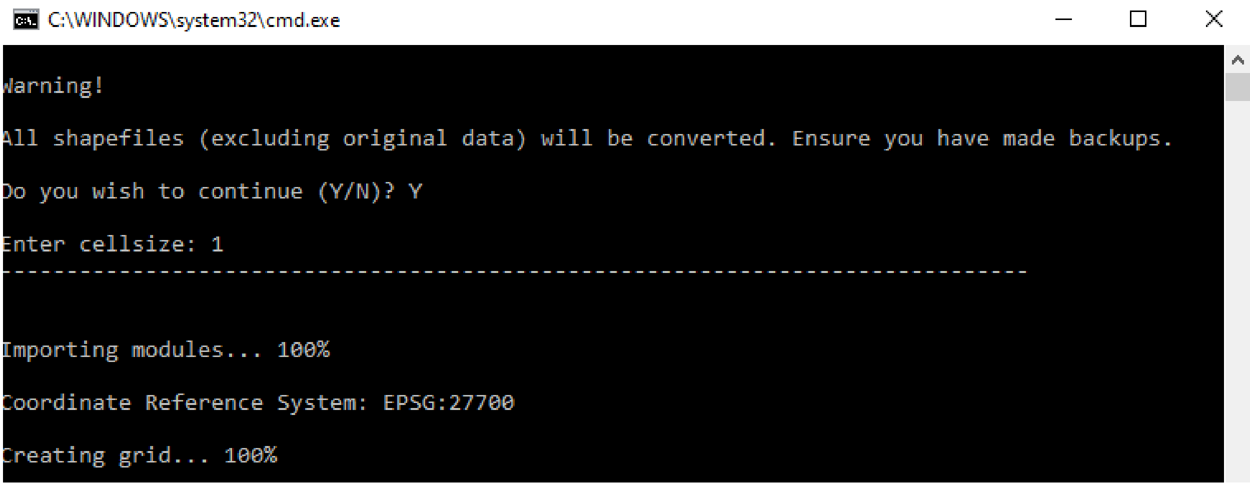


Figure 3.11. Project conversion script being executed.

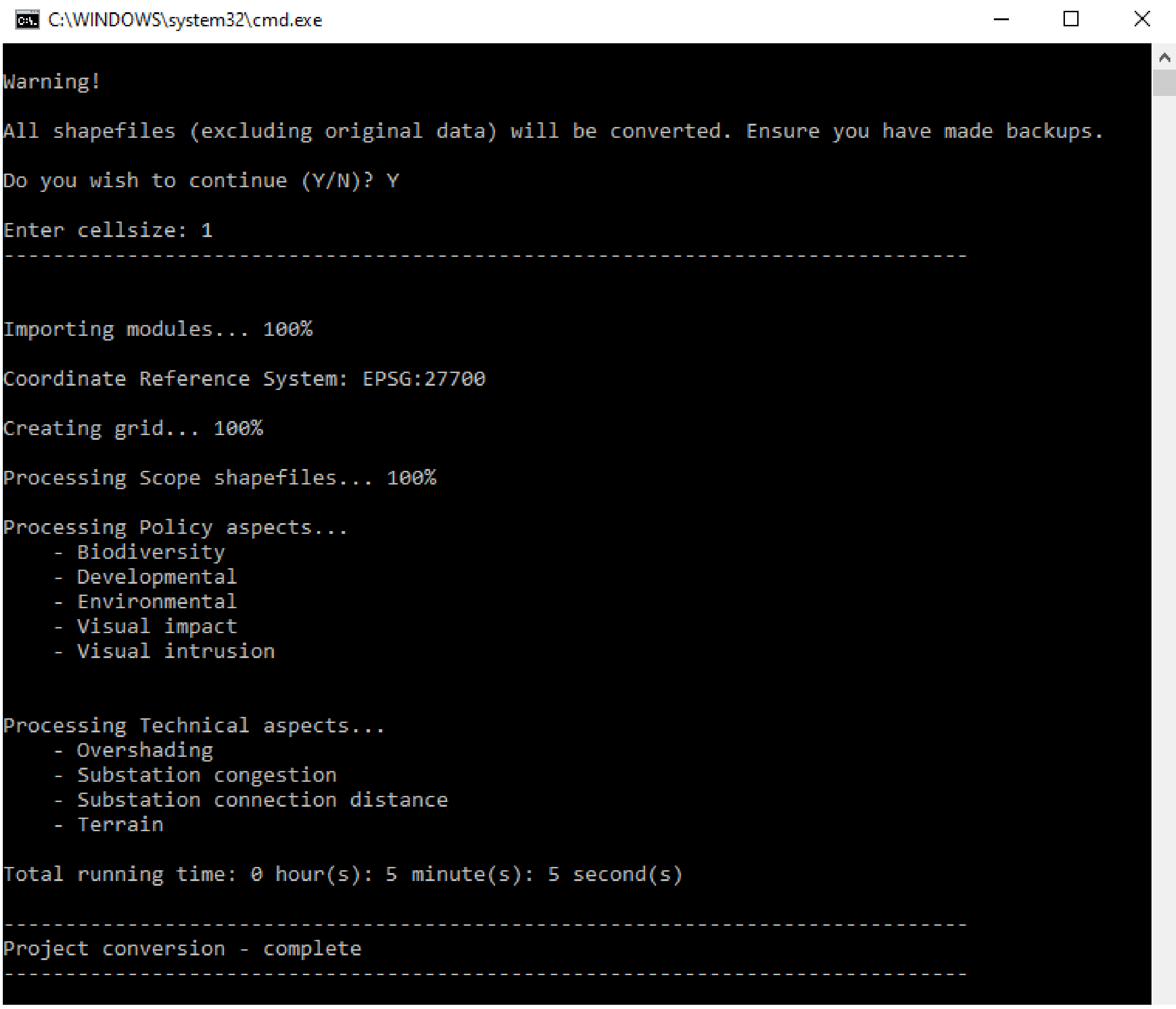


Figure 3.12. Project conversion script completed.

3.3.3 PVPS modelling and verification

The suitability of the PVPS model as embedded in GOMap was evaluated via an inter-model comparison with the commercial PVSyst tool (Westbrook & Collins 2013). PVSyst was chosen as it is extensively used within industry thus gaining credibility as a reliable estimation tool and used to verify if GOMap's PVPS model has been correctly configured by examining the outputs of both models. PVSyst allows users to estimate the energy yield given specific panel details and irradiance data. A fixed inclination plane was chosen as this provides a cheaper solution compared to PV tracking systems. Local hourly weather data, such as ambient temperature, direct normal solar radiation and diffuse horizontal solar radiation were obtained for Glasgow (Suncalc 2020, Solcast 2020) and introduced into the GOMap model. Assuming an initial panel azimuth of 180° (due south), Table 3.12 shows the results of the inter-model comparison for varying tilt angles which are illustrated graphically in Figure 3.13.

Table 3.12. GOMap and PVSyst annual energy output for varying tilt angles at panel azimuth of 180°.

Tilt angle (°)	GOMap model - annual energy output ($kWh/m^2.y$)	PVSyst model - annual energy output ($kWh/m^2.y$)
0	131.4	131.6
10	143.3	143.7
20	152.1	152.1
30	157.4	157.5
40	**159.2**	**158.9**
50	157.3	157.1
60	151.8	152.1
70	142.9	143.8
80	130.9	132.5
90	116.1	118.1

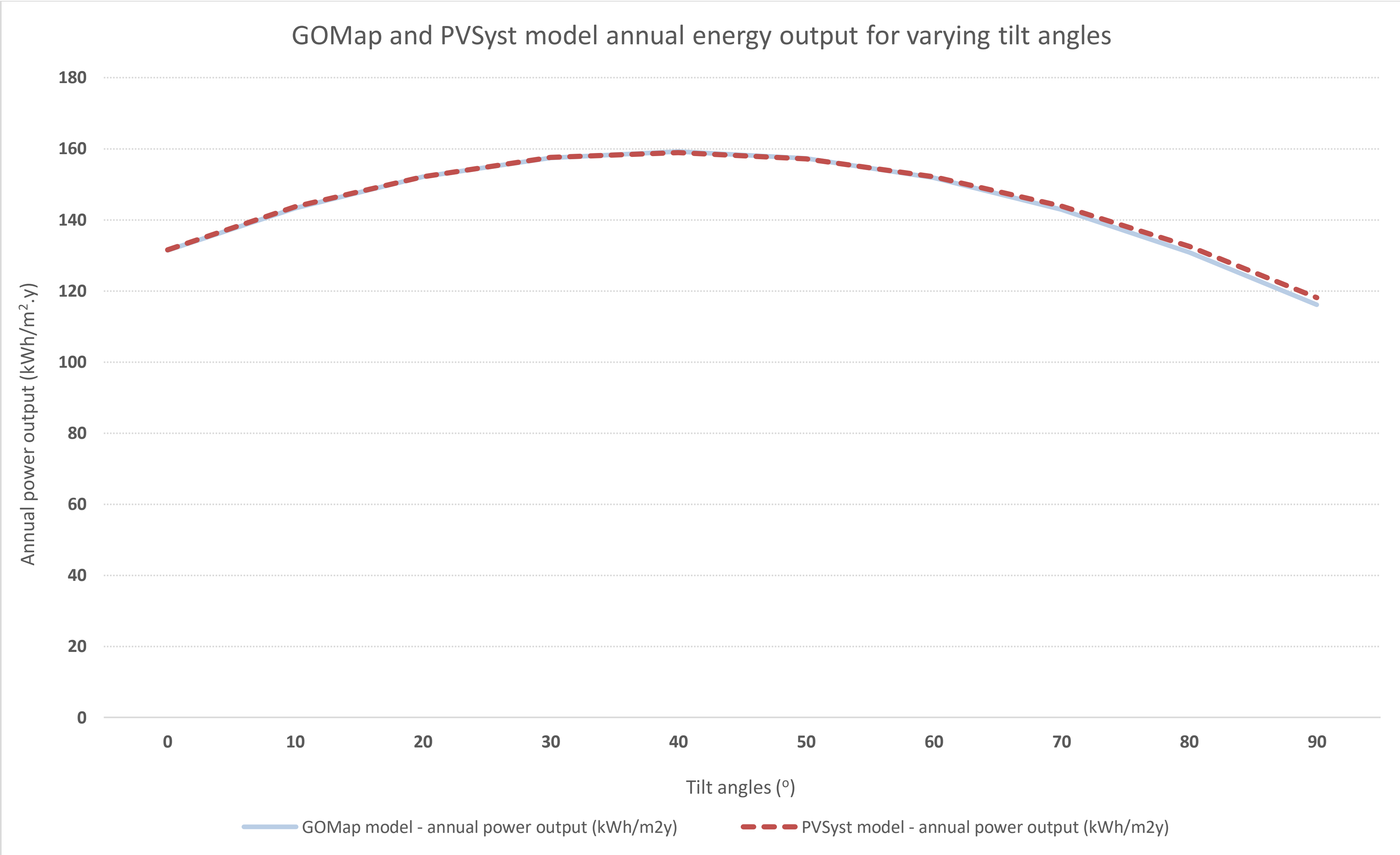


Figure 3.13. GOMap and PVSyst inter-model comparison.

The results of Table 3.12 show that for each tilt angle, the annual energy output from both models are in good agreement. For both GOMap and PVSyst, a horizontal panel (i.e. 0º tilt angle) would generate around 131 kWh/m^2.y rising to a maximum of around 159 kWh/m^2.y at 40º (highlighted in yellow) before decreasing again as the tilt angle increases further.

The result obtained from PVSyst was in close agreement with the result calculated by GOMap as summarised in Figures 3.14, 3.15 and 3.16. It should be noted that during this verification process, both models were tested using an alternative sky model (Hay & Davies 1980), which excludes horizon brightening. The GOMap model can optionally employ equations related to solar geometry distribution that correct for circumsolar and horizon brightening. When these are activated in GOMap, the maximum energy output rises slightly to 165 kWh/m^2.y. For the PVSyst tool, inserting the horizon brightening component required purchasing a licence. As this was not an option and considering the horizon brightening component adds only 3.7% of additional energy output, it was concluded that the GOMap model was acceptable.

Geographical Site		**Glasgow Airport**		Country	**United Kingdom**
Situation	Latitude	55.87° N		Longitude	-4.43° W
Time defined as	Legal Time	Time zone UT		Altitude	8 m
Collector Plane Orientation	Tilt	40°		Azimuth	0°

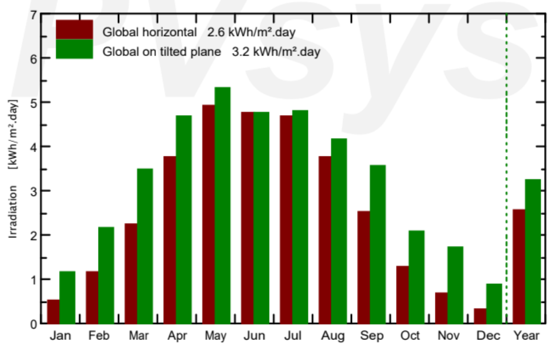
PV-field installation main features

Module type	Standard
Technology	Monocrystalline cells
Mounting method	Ground based
Back ventilation properties	Ventilated

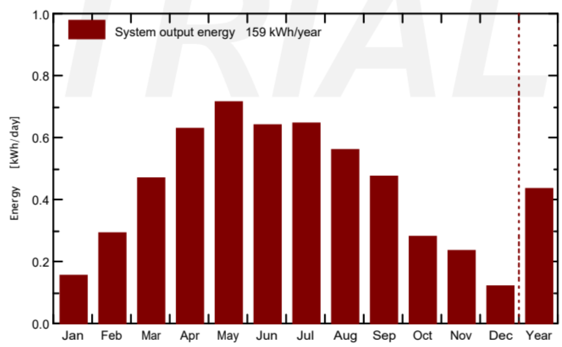
System characteristics and pre-sizing evaluation

PV-field nominal power (STC)	Pnom	0.1 kWp			
Collector area	Acoll	1 m²			
Annual energy yield	Eyear	0.16 MWh	Specific yield	994 kWh/kWp	
Economic gross evaluation	Investment	862 EUR	Energy price	0.43 EUR/kWh	

Meteo and incident energy



System output



	Gl. horiz. kWh/m².day	Coll. Plane kWh/m².day	System output kWh/day	System output kWh
Jan.	0.51	1.16	0.16	5
Feb.	1.18	2.17	0.29	8
Mar.	2.26	3.47	0.47	14
Apr.	3.78	4.67	0.63	19
May	4.95	5.32	0.72	22
June	4.77	4.77	0.64	19
July	4.67	4.81	0.65	20
Aug.	3.76	4.18	0.56	17
Sep.	2.54	3.55	0.48	14
Oct.	1.27	2.09	0.28	9
Nov.	0.69	1.74	0.23	7
Dec.	0.34	0.89	0.12	4
Year	2.57	3.24	0.44	159

Figure 3.14. PVSyst model results for PVPS in Glasgow without horizon brightening component.

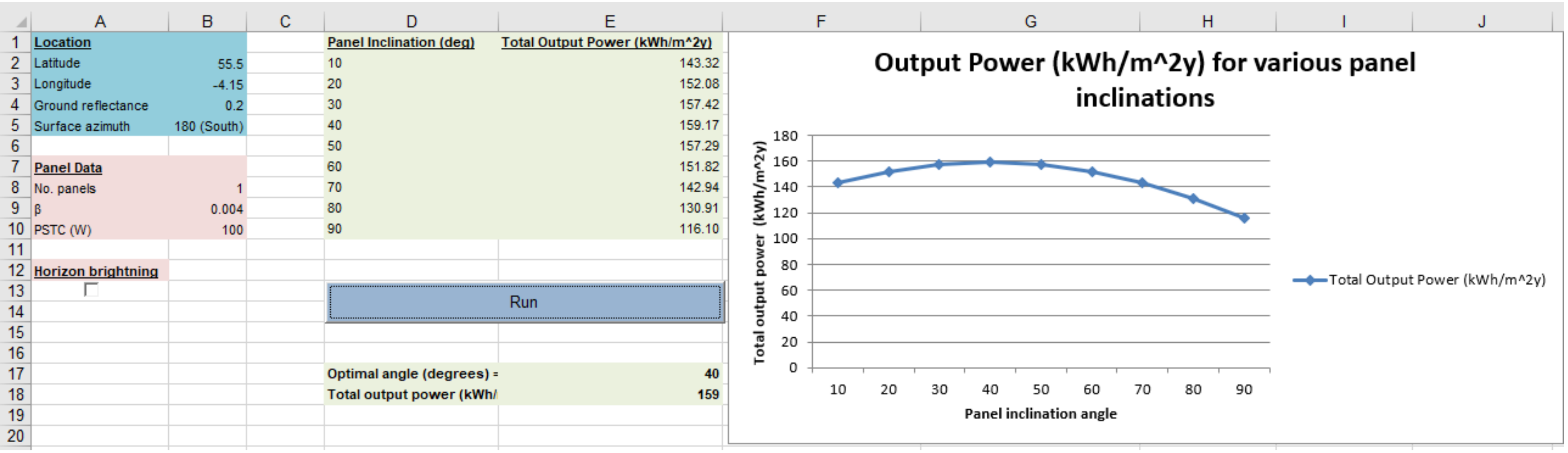


Figure 3.15. GOMap model results for PVPS in Glasgow without horizon brightening component.

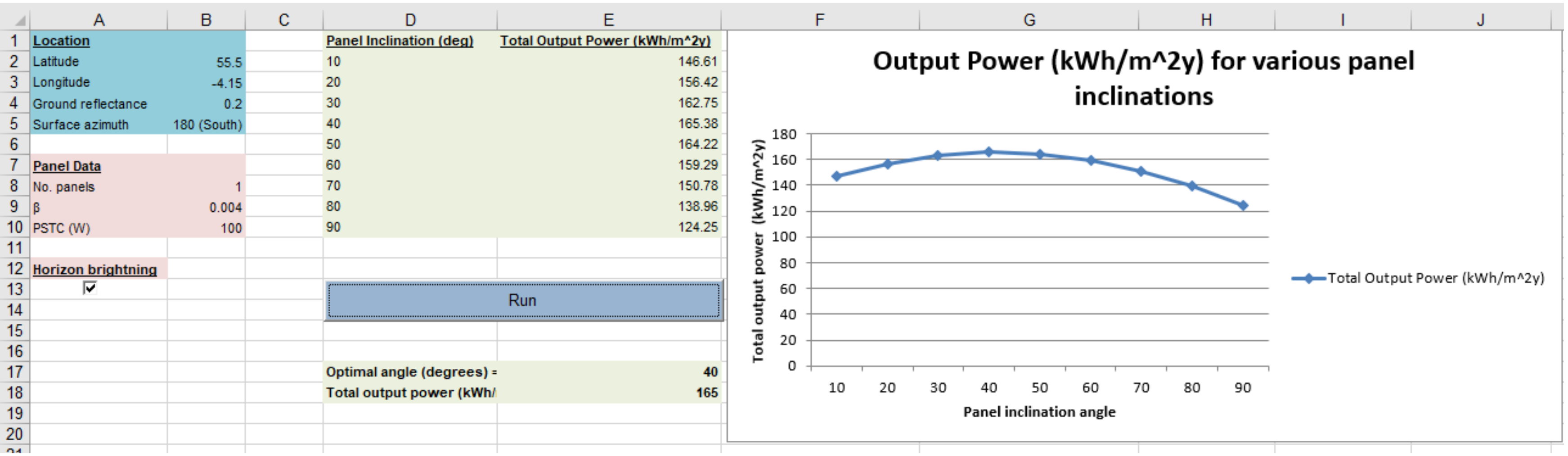


Figure 3.16. GOMap model results for PVPS in Glasgow with horizon brightening component.

3.3.3.1 Optimal parameters

With GOMap's PVPS model reporting accurate measurements verified by the commercial software PVSyst, a parametric study was conducted using the GOMap model for determining, in the Southerly direction, the optimal panel azimuth and tilt angle, and providing additional information including inter-row spacing and energy yield. The results of this study are shown in Table 3.13.

Table 3.13. Determining optimal tilt angle, inter-row spacing and energy yield for southern-facing panel azimuth.

Panel azimuth (º)	Optimal tilt angle (º)	Inter-row spacing (m)	Energy yield ($kWh/m^2.y$)
135	66	9.7	126.1
140	61	9.4	130.2
145	56	9.2	134.6
150	53	8.9	139.4
155	50	8.7	144.2
160	47	8.5	148.9
165	45	8.3	153.4
170	43	8.1	157.6
175	41	7.9	161.5
180	**40**	**7.8**	**164.8**
185	39	7.7	167.6
190	38	7.5	169.9
195	38	7.5	171.5
200	37	7.4	172.5
205	**37**	**7.4**	**172.8**
210	37	7.4	172.5
215	37	7.4	171.5
220	38	7.5	169.8
225	39	7.7	167.5

The results of Table 3.13 show that for the panel azimuth and tilt angle parameters used for verification with PVSyst (highlighted in yellow), it does not provide the highest energy yield. The energy yield continues to increase with incrementing azimuth angles which also decreases the inter-row spacing between panel rows. The azimuth angles when facing the south-westerly direction perform better in terms of higher energy yields and lower inter-row spacing compared to angles facing the south-easterly direction, this can be attributed to varying durations of exposure to short-wave and long-wave direct and diffuse solar radiation throughout the day taking into consideration clear or overcast skies (Vignola *et al* 2018). By this parametric study, the optimal parameters for Glasgow (highlighted in green) was determined:

- Panel azimuth = 205^o;
- Panel tilt angle = 37^o;
- Inter-row spacing = 7.4 m;
- Energy yield = 172.8 $kWh/m^2.y$.

In summary, the PVPS model as embedded within GOMap can take a site area as input and transform this to an hourly power output prediction for a PVPS installation over a year. This profile is then integrated to obtain the annual energy yield. A script was established to expand GOMap's functionality by generating polygon features on sites of interest designated as policy 'Possible' and technically 'Favourable' to represent the PVPS on the final opportunity map as shown in Figure 3.17. The purpose of the script is to determine the number of panels that can be physically installed on a given site to provide a more accurate energy yield estimate based on the site's geometry. The script interface as shown in Figure 3.18 allows the physical parameters of the PVPS model to be customised if these are known, otherwise the 'automatic' option calculates the optimal settings based on local coordinates and weather information on a site-by-site basis. Energy yield calculations can be summarised based on area such as Site ID, Wards or Postcodes and passed to the GUI described in the next subsection.

Figure 3.17. Overlaying PVPS polygons (blue) on a site of interest (green).

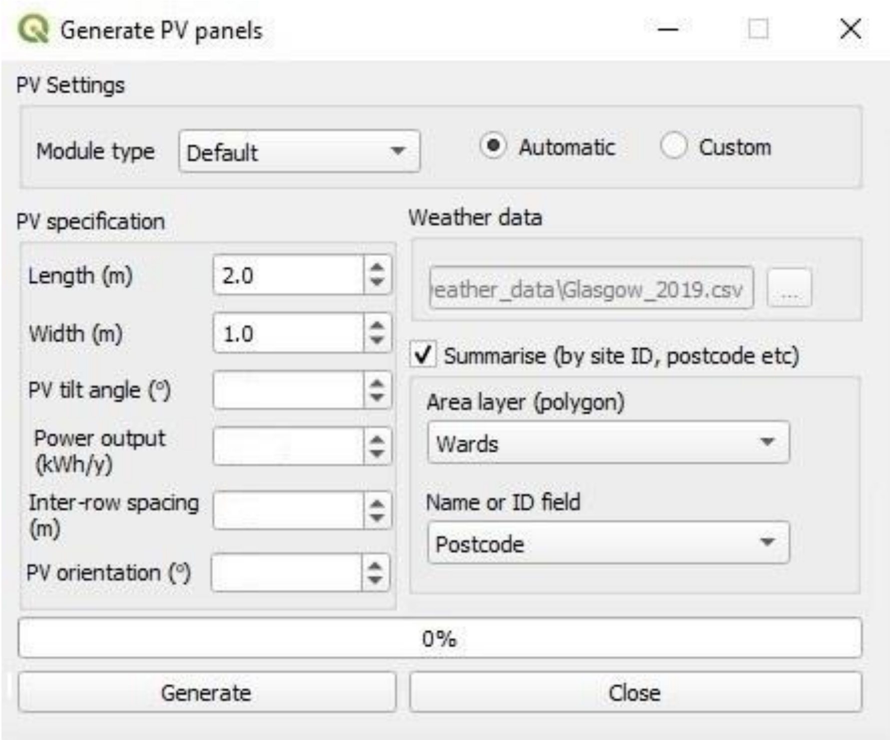


Figure 3.18. PVPS polygon generation interface.

3.3.4 GUI design

The final result – a policy and technical rating for each cell for an entire city or individual site – is displayed as an opportunity map highlighting areas suitable for RET deployment as shown in the example of Figure 3.19 where the areas depicting green show land that is both policy unconstrained and technically feasible. The focus selection panel contains all the layers loaded into GOMap (Figure 3.19, upper-left). The weightings for policy and technical aspects are shown and can be overridden (Figure 3.19, upper-right). It is possible to disable individual factors and/or apply aspect weightings to ascertain the impact on the RET deployment opportunity of adopting alternative planning policies or pursuing infrastructure development. The amount of available land is automatically passed to GOMap's in-built PVPS model which transforms this area into an equivalent annual energy yield (Figure 3.19, bottom-left).

The GOMap toolbar (Figure 3.19, upper-left) contains four interface buttons which possess the following functions:

- The 1st button starting from the left when set to ON enables the continuous update of the opportunity map and results for the acreage and energy yield whenever a change is made. When set to OFF disables the opportunity map and all underlying factors can be viewed individually.
- The 2nd button saves the current GOMap project.
- The 3rd button loads a description of the project which can be edited in the 'About.txt' file for each project and supports hyperlinks to external sources via the local internet browser.
- The 4th button contains a set of options and scripts including the PVPS model. Other scripts and models are described in the APPENDIX I.2.

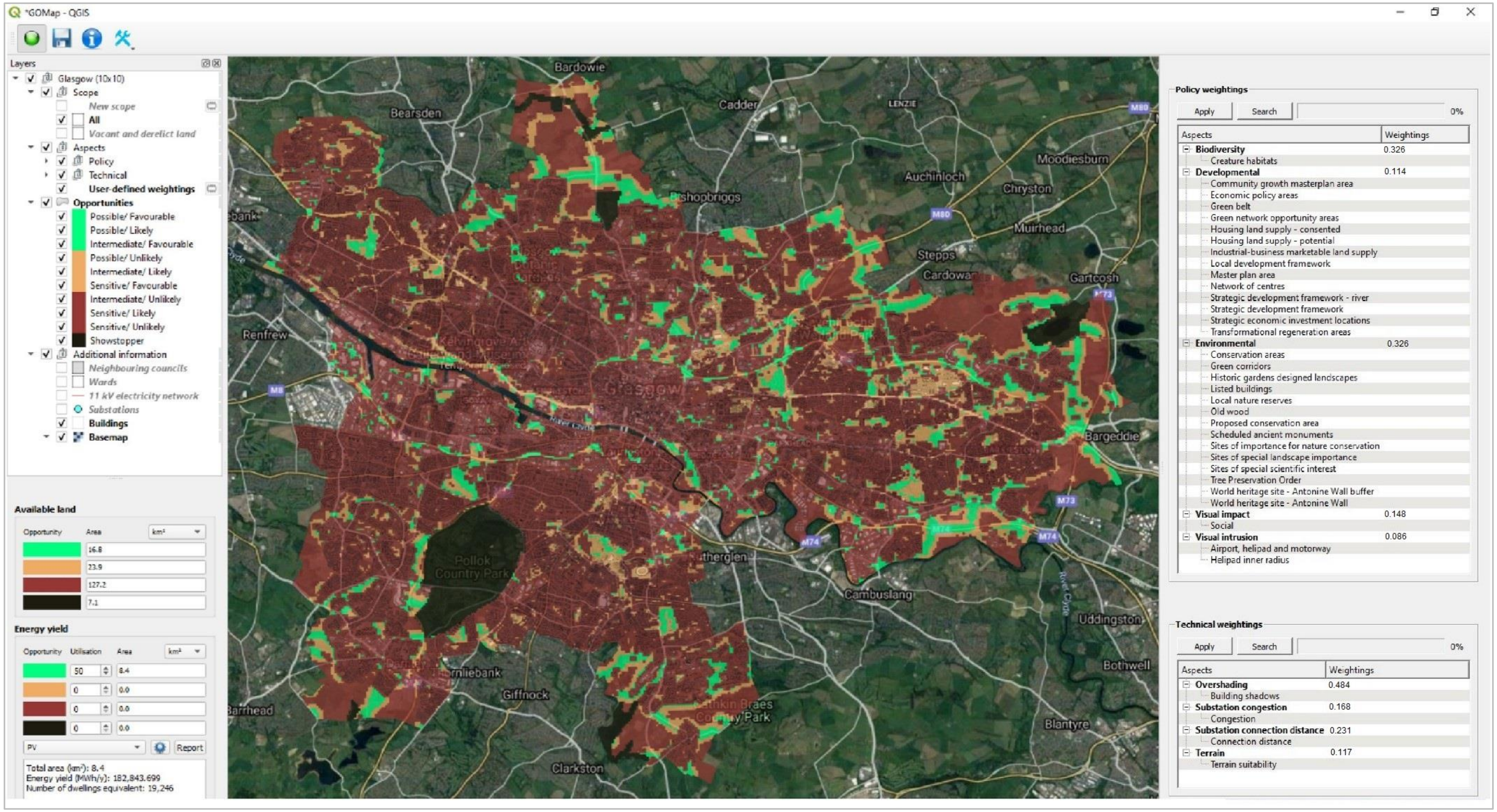


Figure 3.19. GOMap interface showing the opportunity map for Glasgow for the non-equal weighting scheme.

Chapter 4 – GOMap application

4.1 Overview

In Chapter 3, the process of collecting and collating information from workshops and consultations with partners was described. This information was used in the development of the GOMap tool in combination with PVPS modelling. This chapter introduces the workflow of the GOMap procedure beginning from raw information obtained from various sources to the processing stage involving conversion scripts and finally to the resulting opportunity map. The GOMap tool is then verified via two methods: first by an initial study to independently confirm the correct calculation of site overlapping cells; and secondly by following an ongoing planning application process.

4.2 Workflow

To create a GOMap project for a given city, a workflow is designed to allow a clean procedure of importing, processing and exporting accurate, high-resolution opportunity maps as shown in Figure 3.19. The workflow is illustrated in Figure 4.1 with the steps described as follows:

1. Organising all obtained information by their specific type and placing these in the GOMap's accompanying project template directory. All policy aspect information must be decomposed into factors within the Policy factor directory containing the shapefiles. The same procedure is repeated to the technical aspect information. All shapefiles related to the geographical sites or areas of interest must be added to the Scope directory. Any other optional information can be added to the Additional information directory which can include shapefiles, rasters or text files.
2. Excluding the Additional information directory, the policy aspect, technical aspect and scope directories are sequentially imported into the Shapefile Conversion Script. Executing the script loads the command prompt allowing the user to input information required to set the scripts parameters. These include: the names of the policy and technical aspects; grid resolution of the map; the grid cell overlap rule; and factor scores.
3. The script moves the original policy, technical and scope shapefiles to a safe, untouched directory whilst copying and applying the grid systems to copies of

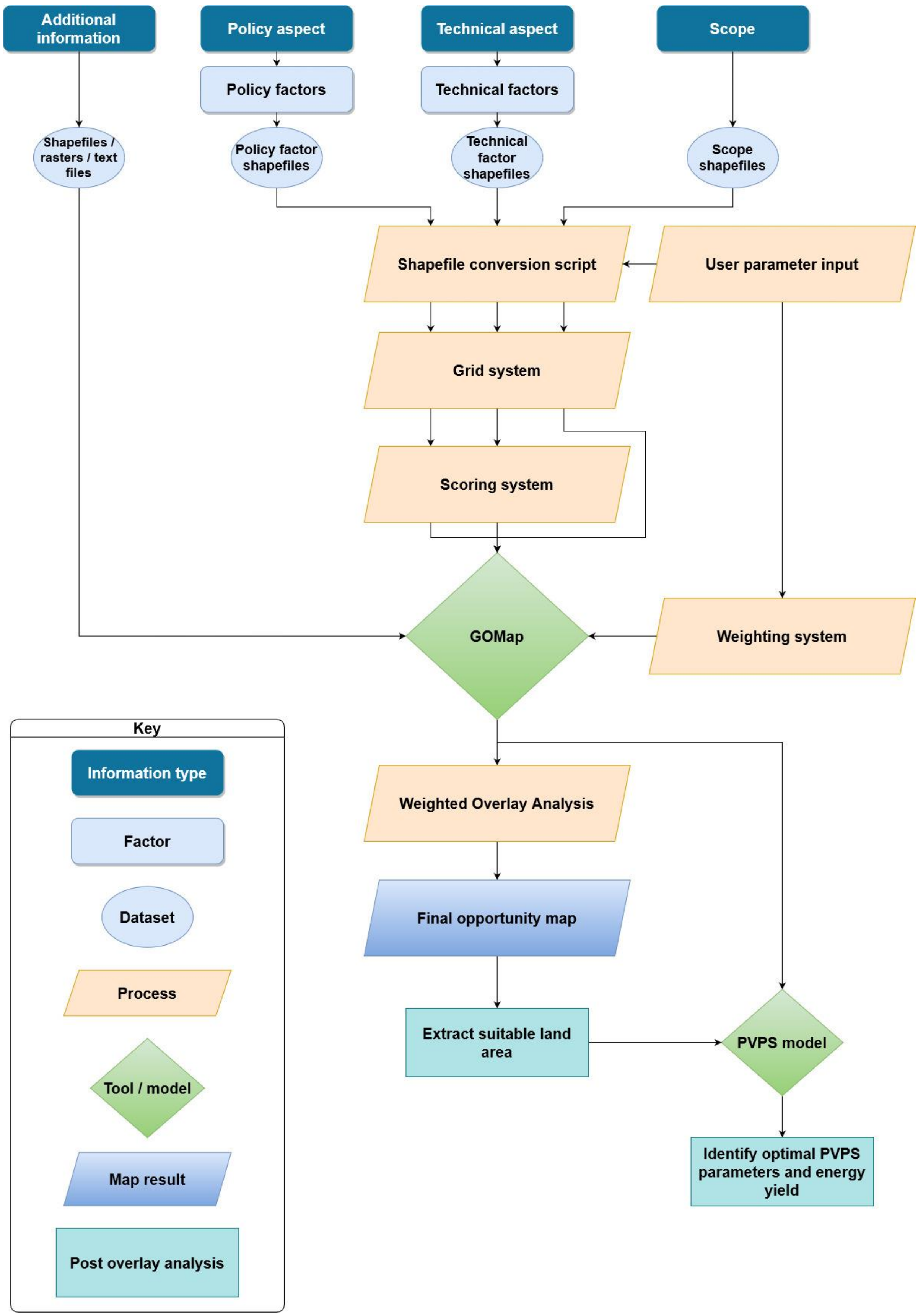


Figure 4.1. GOMap schema.

the imported shapefiles. The scoring system is only applied to the policy and technical shapefiles. The Additional information directory is ignored by the script.

4. Once the script has completed the import process, it automatically executes the GOMap project file which loads the QGIS software and enables the GOMap tool (the tool is otherwise disabled if no GOMap project file is loaded). The tool will load all shapefiles in the directories processed by the conversion script and all contextual files within the Additional information directory.
5. With the tool populated with all available information, the weighting system can be applied. The weightings are entered for both active policy and technical aspects and used as input parameters for GOMap's Weighted Overlay Analysis. Once applied, the final opportunity map will be generated.
6. Suitable land area or sites can be extracted and passed to the PVPS model to identify optimal parameters for PVPS deployment. Local coordinates and weather information are used to compute optimum panel azimuth, tilt angle, inter-row spacing and energy yield. All results are reported to the user.

4.3 Verification

Before applying GOMap to an actual city (here Glasgow), it was necessary to verify the tool's predictions. This was achieved via two methods: first, by an initial study to independently confirm the correct calculation of site overlapping cells; second, by following an ongoing planning application process.

4.3.1 Data analysis

The first method involved extracting the data for each grid cell within an opportunity map and importing these to an open source database management system, Apache OpenOffice (OpenOffice 2016). All grid cells were then processed and aspect scores determined via a separate implementation of the aforementioned workflow. These scores were then compared to those calculated by GOMap and coding adjustments implemented until no discrepancies were found.

4.3.2 Case-study

The second method involved comparing a number of GOMap outputs with the results of an independent assessment undertaken by a spatial planning manager within the Development Plan Group at GCC. The use of expert verification adds credibility to GOMap's analytical capabilities and with expert guidance reduces uncertainties in the final output particularly when the expert was actively involved in decision-making policies for energy schemes; this strategy has been adopted in other GIS-based studies in designing site selection tools (Dolui & Sarkar 2021, Saraswat *et al* 2021, Watson & Hudson 2015).

This independent assessment took the form of the ‘Housing Proposal H113, Summerston Project’ as part of the Proposed Glasgow City Development Plan Examination Report (Glasgow City Council 2016). The proposal for Summerston, located in north Glasgow within a larger area identified through the City-wide Green Belt Review (Glasgow City Council 2012), considered amongst other issues, the extent of any capacity for additional housing in relation to the shortfall in private sector housing land supply. Preliminary examination of the proposed project suggested that development should not commence until a feasibility study was conducted to examine whether there is any potential for additional housing, considering concern over land release covering such a large area as well as biodiversity impact, environmental impact, risk of flooding and impact upon drainage capacity. The spatial planning manager within the Development Plan Group at GCC applied GOMap to Summerston and reported that the results of GOMap’s opportunity map reflected the agreed outcomes for various issues from the Proposed Glasgow City Development Plan Examination Report which demonstrated that there were parts of Summerston that were policy and technically constrained.

However, it was noted that certain policy and technical factors were not included in GOMap’s assessment but were included in some of the outcomes of the preliminary examination such as: communication and community engagement; public transport links; noise protection areas; traffic management; air pollution and risk of deterioration in air quality, either directly, indirectly, or cumulatively; and sustainable transport modes such as walking and cycling routes. The spatial information for these factors were unavailable at the time. It was also reported by the spatial planning manager that although GOMap did not contain certain policy and technical factors described in the Proposed Glasgow City Development Plan Examination Report, it did provide additional insight into the effects other factors had on site suitability that were not covered by Examination Report.

4.3.2.1 Green Belt Review

The Green Belt Review, which objectively assesses the Green Belt's purpose and environmental capacity, and establishes whether boundary alterations are needed or where land could be removed for development, was commented on by SNH, who identified a number of issues within the site including greater surface water flood risk and adverse impacts on landscape character and visual amenities within a site designated SSLI. There was also risk of interrupting or removing key views, which may impact on prominent landscape attributes such as the loss of the valley enclosure role of the Blackhill slopes. There was also concern as to how the proposal could affect an existing canal classified as a Scheduled Ancient Monument within the marshland. Many objectors were concerned with the Green Belt's continuous erosion between Glasgow and the neighbouring authorities, which provides a valuable landscape buffer between the built-up area and the countryside. Objectors stated that moving forward with the housing project would compromise the character of the Green Belt and the recreational use of the countryside as well as negatively impacting the local distinctiveness, water courses and access requirements, resulting in an increased risk of pollution. The project was regarded as being unsustainable, reducing the quality of life for the local residents with no assessment planned for the impact the loss of green belt would have on the community, and reducing the level of access to the natural landscape, both of which was considered contrary to the policies enacted by GCC and the Scottish Government. The final comment identified that the site was constrained by transmission lines which would affect the logistics of project deployment. Based on these comments, SNH concluded that the Green Belt designation should be retained. The proposal was also considered contrary to the Scottish Planning Policy, which supports the protection of (and access to) open space within and around towns and cities.

The relevant policy and technical aspects and factors which directly affect the issues highlighted by the Green Belt Review were identified through visual inspection and discussion, and enabled within GOMap. These included the biodiversity aspect due to its relevance in the overall environmental capacity of the area; the developmental aspect consisting only of Green Belt and the Housing Land Supply factors; all environmental factors excluding the World Heritage Site factors; the Substation

Connection Distance aspect; and the Terrain aspect. The GOMap output is shown in Figure 4.2 where most of the area is designated as being constrained particularly in the central region and heavily constrained in the eastern region. A small amount of land is shown to be made available in the north western boundaries of Summerston.

The planning authority's response to the Green Belt Review was that it accepted the need for a thorough investigation to address the significant issues that could arise during project development through a comprehensive feasibility study and would consider whether there is any capacity for new development of housing within the proposed sites and if such a capacity exists, there will be a need for the developer to integrate the development plans with the wider green network in compliance with the planning policy.

4.3.2.2 Feasibility Study

A Feasibility Study was planned whereby consultations with East Dunbartonshire Council, situated north of Summerston, objected to the proposed development plan and commented that it was inappropriate for development as releasing any Green Belt land for development would compromise the principle of maintaining a compact city region. The feasibility study, if conducted fully, could determine the extent of the Green Belt release. However, it was objected that the status of the site was unclear in the City Development Plan with East Dunbartonshire Council maintaining its previous position that regardless of the outcome of the feasibility study, the concerned site should not be released from the Green Belt. Other objectors also pointed out the lack of clarity for both the local residents and investors between the proposal for a feasibility study and the proposal for housing development.

Conversely, SNH supported the feasibility study but considered that there may be limited housing potential within the site and, therefore, a landscape capacity assessment (an analysis of the capacity an area has for employment and housing development without significant effects on its character) may be necessary within the study in order to comply with the Scottish Planning Policy. SNH recommended that until the feasibility study was completed, the proposed project should be temporarily halted, otherwise its inclusion could create confusion and uncertainty.

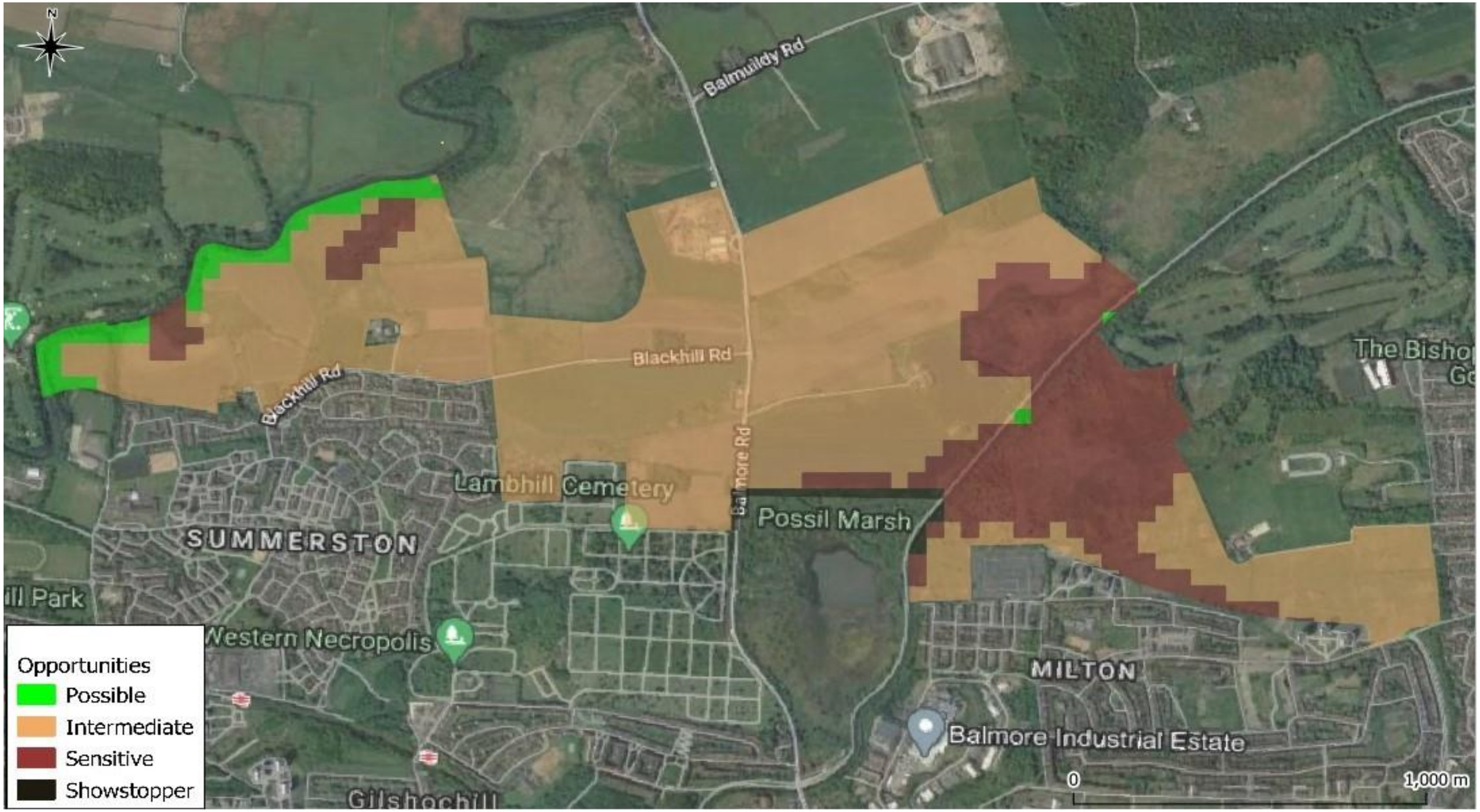


Figure 4.2. GOMap output of the green belt review where most of the area is constrained and with only a small amount of land available in the north-western portion of the target area.

The relevant policy and technical aspects and factors which directly affect the issues highlighted by the Feasibility Study were enabled within GOMap. These included the biodiversity aspect due to its relevance in the environment; all developmental factors; all environmental factors excluding the World Heritage Site factors; and the Terrain aspect. The GOMap output is shown in Figure 4.3 where the entire area is designated as being constrained and further investigation is necessary. The planning authority's response to the Feasibility Study was that it agreed such a study was necessary to identify sites vulnerable to issues and sites which are deemed suitable for project development.

Preliminary examination on sites such as those in the east of Balmore Road indicated that there were major environmental and hydrological issues that would have had to be considered for development and, as a result, these sites should not have been included as part of potential new housing land supply unless otherwise deemed possible by the feasibility study. The response also commented that the identification of such sites from the study coupled with a landscape capacity assessment can provide information and clarity to investors, developers and the local community in terms of the potential for housing in the location.

4.3.2.3 Strategic Development Plan

The Strategic Development Plan describes the strategy for the Housing Land Supply aimed at tackling the greater demand for new housing in Glasgow. The Strategic Development Plan concluded that no further green belt release would be required. However, objectors noticed that this contradicted a statement in the Green Belt Review, which stated that releasing the land was required to tackle the short to medium term housing land shortage, which was caused by conditions in the housing market. It was commented that the housing market should remain either static or improve from 2011 onwards. A Scale of Land Release Review that accommodates the development plan suggested that additional scrutiny and consultation with the local community be required and formal notice be given to the local community at the early stages of the pre-application consultation process to include the consideration of public investment opportunities such as transport and community facilities. The submission of a pre-application can occur if the feasibility site identifies a site which has sufficient land to develop more than 50 houses as this would be considered a major development.

Figure 4.3. GOMap output of the feasibility study where the entire area is constrained and further investigation is indicated as being necessary.

Due to its focus on investment opportunities for local community development in terms of housing and improved transport and community facilities, only the developmental aspect and all of its factors were included and enabled within GOMap. The output for new housing potential is shown in Figure 4.4 where large parts of the area could be used for new residential plots particularly in the central and western portions of Summerston. The planning authority's response to the Strategic Development Plan cited evidence from the private sector housing completions where it was shown that the housing market downturn from 2008 has continued and led to the increasing gap between the existing housing supply and housing demand. The feasibility study conducted for Summerston would aid in the consideration of determining if there is potential within the area to develop new housing which would contribute to the housing shortfall.

4.3.2.4 Biodiversity and Natural Environment

The Biodiversity and Natural Environment issues from the potential housing project was considered significant with objectors noting the contradiction with the Glasgow Local Biodiversity Action Plan (Glasgow City Council 2001), which was designed to prevent the separation or destruction of species. The area of interest is part of the River Kelvin Green Corridor and is a habitat for various protected species such as the tree sparrow noted for being particularly scarce and is protected by legislation (Wildlife and Countryside Act 1981). The area also provides shelter to other protected birds and mammals (some of which are known to be in decline) and to a variety of plants. It was mentioned that large scale development of existing agricultural land in the northern portion of Summerston would be detrimental to the green space environment, which is of benefit to the local community. Possil Marsh, an important natural resource designated SSSI, would be considered at risk of being vulnerable to polluted runoff. The City Development Plan considered the wildlife and fauna within the reserve of key importance which should be conserved. Although SNH agreed that a feasibility study should take place (whilst specifying the agreement was not the equivalent of an endorsement); they also observed that development of the site would have adverse impacts on landscape character and visual amenities particularly as the site was within a SSLI.

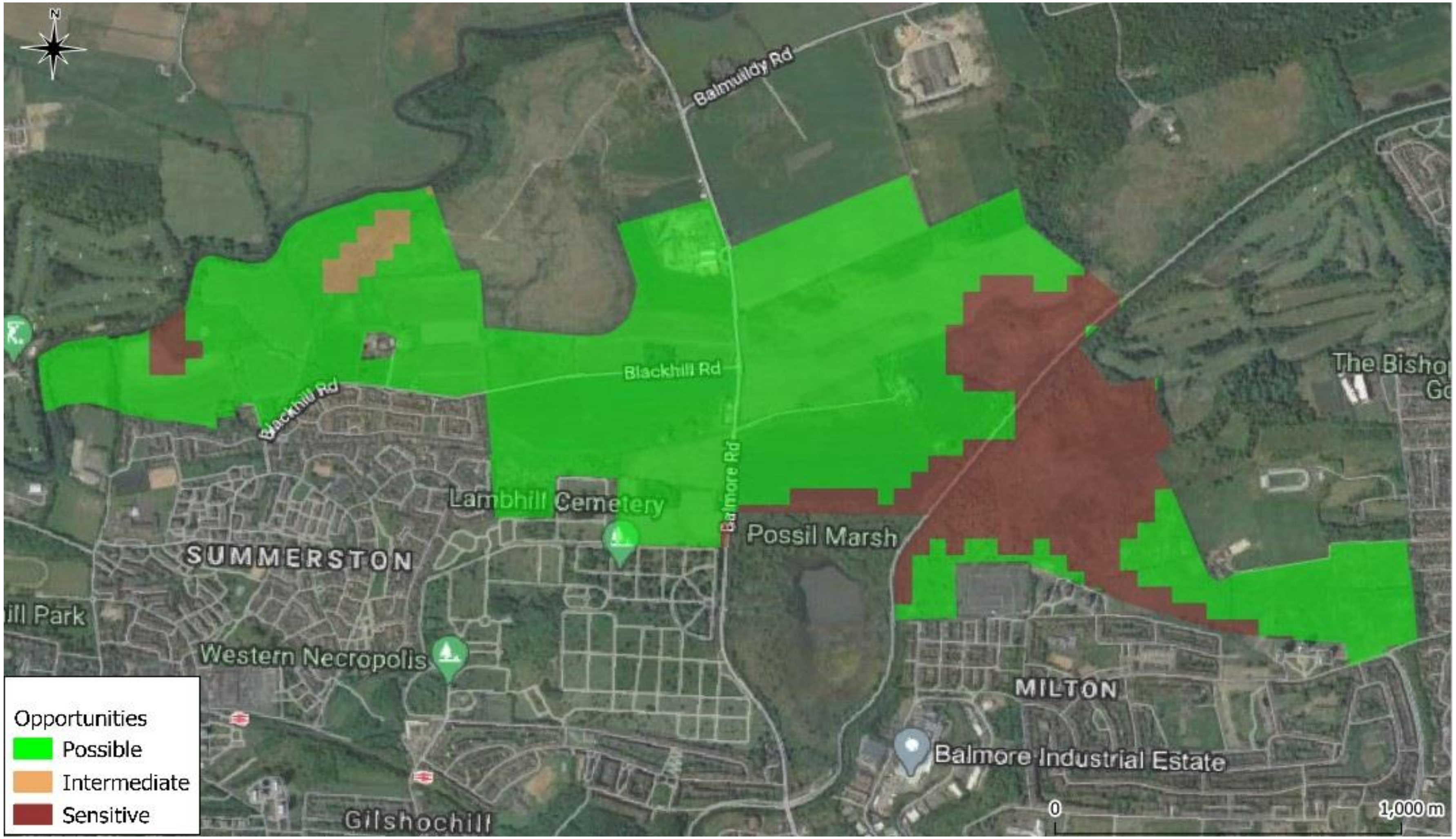


Figure 4.4. GOMap output of the Strategic Development Plan where large areas of land in the central and western regions show signs of encouraging development.

Due to its focus on preserving and protecting the local wildlife and countryside, the biodiversity aspect; all environmental factors excluding the World Heritage Site factors; and the terrain aspect were included and enabled within GOMap. The output shown in Figure 4.5 displays the potential biodiversity and environmental impacts on the land. Although the majority of the central region is constrained, a fairly large portion of land on the eastern side is considered safe from ecological damage but this is split by heavily constrained land in between. The planning authority's response to the Biodiversity and Natural Environment issues was that a major aim of the feasibility study was to comprehensively assess the potential for housing development taking into consideration the various environmental, biodiversity, hydrological and infrastructural issues that may impact the chosen site. All information recorded in the study would be fully considered before reaching a conclusion.

4.3.2.5 Antonine Wall

It was mentioned that the Antonine Wall, a UNESCO World Heritage site, was considered at risk of potential damage from the proposed development. The planning authority commented that the sites identified in the proposed housing development plans did not fall within the protected buffer zone surrounding this historical wall.

Within GOMap and enabling only two environmental factors, World heritage site – Antonine Wall buffer and World heritage site – Antonine Wall, the output shown in Figure 4.6 clearly shows that almost the entire area of Summerston lies outside the protected buffer zone (shown in red) of the World heritage site (shown as black). Only a marginal portion of the northern boundary can be seen as being constrained but the majority of Summerston lies well outside the buffer zone and as a result is suitable for development.

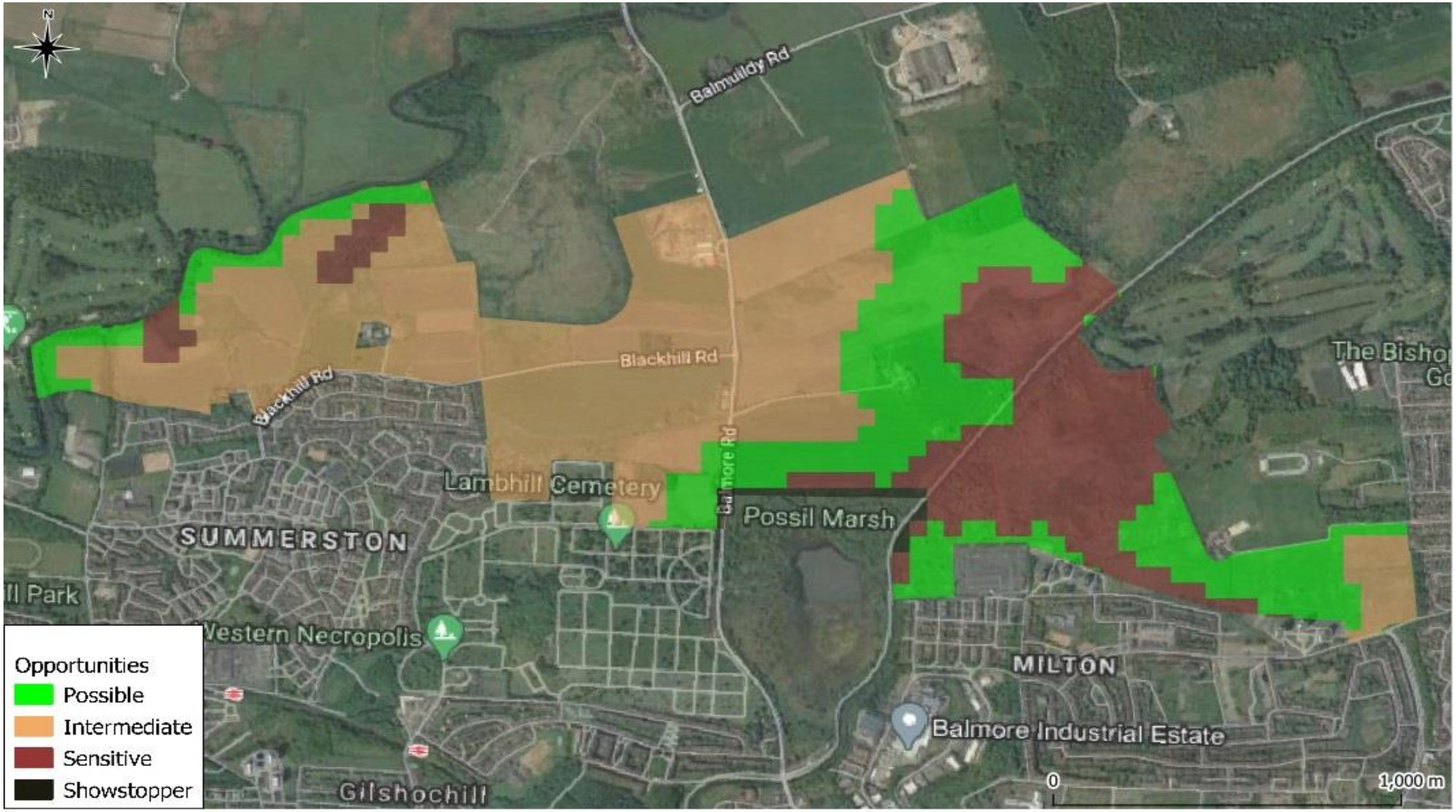


Figure 4.5. GOMap output of the Biodiversity and Natural Environment impacts where the central region is constrained and some parts are considered ideal in the eastern parts.

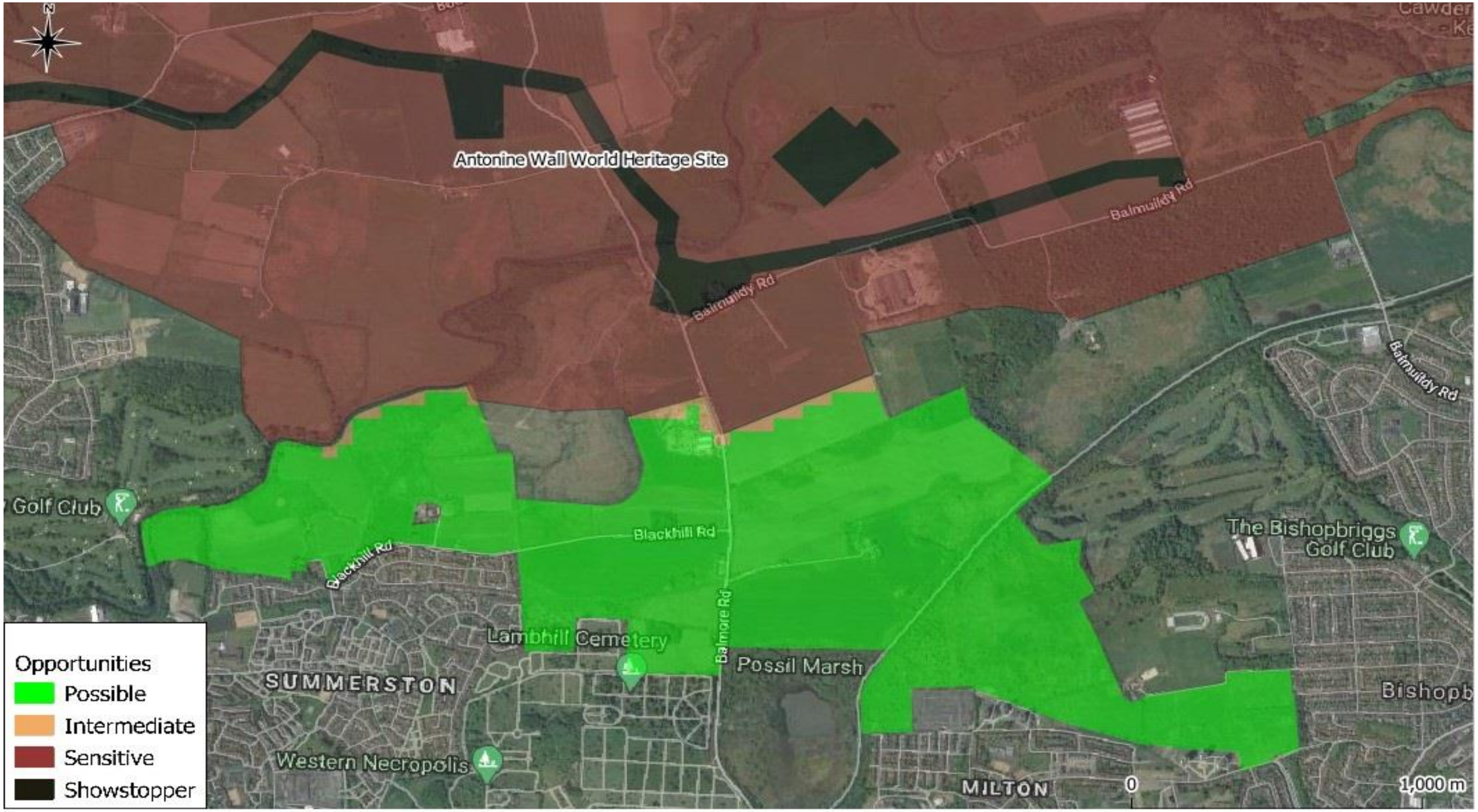


Figure 4.6. GOMap output of the Antonine Wall where most of Summerston is considered suitable for development as it lies outside the protected buffer zone.

4.3.2.6 Flood risk

Flooding and drainage were a major concern, particularly for the area around Caldercuilt Farm north of Summerston. SEPA advised against re-designating the land before a flood risk assessment was conducted. Due to inadequate drainage infrastructure, flooding from rainfall was an issue faced by both residential and non-domestic areas such as Lambhill Cemetery located close to Possil Marsh. It was noted that development of the project, which would involve ground surface hardstanding, would only increase the risk of flooding from surface water runoff.

However, enabling the terrain aspect only within GOMap, it was reported that the majority of the area (particularly the central and western regions of Summerston) was considered safe from flooding with data provided by SEPA as shown in Figure 4.7. There were some issues in the eastern areas where a large plot of land was heavily constrained and at risk. The planning authority's response to the flooding and drainage issues noted that these would be within the remits of the feasibility study and commented that all project development would require an effective drainage system to be implement.

4.3.2.7 Discussion of results

In the context of the research objectives outlined in Section 1.4 and research gaps outlined in Section 2.5, GOMap has demonstrated the ability to identify land that is constrained and unconstrained based on policy and technical information gathered directly from the local government authority, from the local utility provider and from publicly available sources. The real-time outputs from the interactive opportunity maps were generated via a grid system to create a spatial relationship between all policy and technical information, a factor scoring system to differentiate between factors supporting, curtailing or remaining neutral in project deployment, and a weighting system to prioritise or equalise the significance of each policy and technical aspect. This process was encapsulated in a novel GIS-based tool for use in city-scale sustainable development action planning.

For verification, GOMap was used to produce outputs from scenarios and conditions designed to examine the 'Housing Proposal H113, Summerston project'. It was confirmed by the spatial planning manager within the Development Plan Group at GCC that although the review board relied on plans and site visits, GOMap could have been used to highlight areas which require immediate attention particularly in

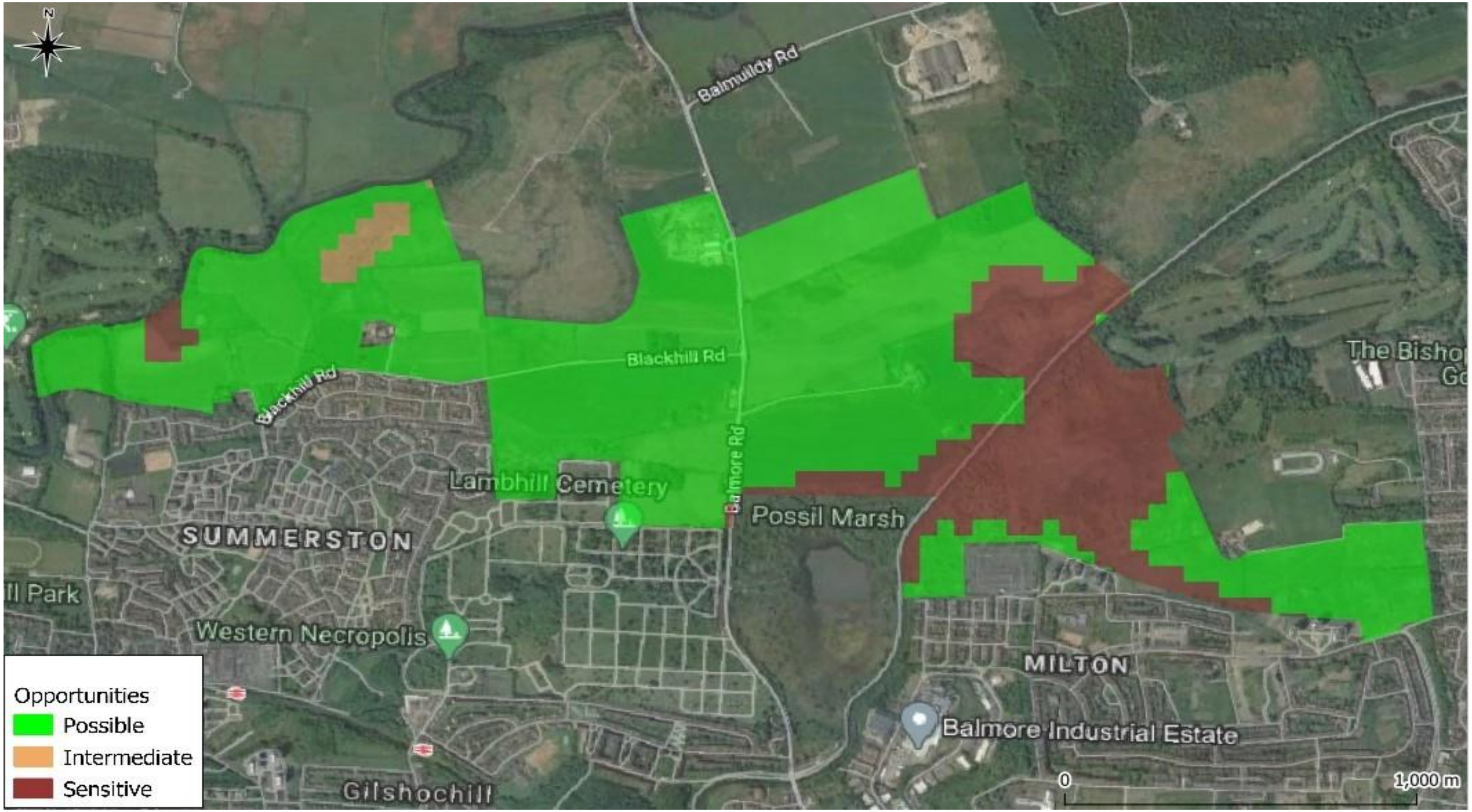


Figure 4.7. GOMap output of the flooding and drainage impacts where the central and western portions of the area are considered safe while a large portion in the east is heavily constrained.

cases of flood risk or deliver more immediate confirmations or otherwise in terms of spatial awareness such as the extent of buffer zones.

With GOMap verified, it is now ready to assess the RET deployment potential for an actual city and provide a justifiable contribution to wider academic knowledge as described in the next chapter.

Chapter 5 – Potential of PVPS in Glasgow City

5.1 Overview

In Chapter 4, the GOMap workflow and verification methods were explored. The verification method included a case-study for Summerston and compared outputs produced by GOMap, by enabling/disabling relevant policy and technical information, with the outcomes of the Proposed Glasgow City Development Plan Examination Report. This verification method was conducted by an expert confirming that GOMap's output agreed with the outcomes of the report on several issues. This chapter now explores applying the GOMap tool to the city of Glasgow to appraise the land available for PVPS deployment.

5.2 Context

Glasgow city was chosen principally because resources existed to extract the required information due to its selection as a UK Future City Demonstrator by Innovate UK (Energy Efficiency Demonstrator 2017). Glasgow is situated at 55.5^{o} N, 4.15^{o} W and comprises of 115 Wards as shown in Figure 5.1.

The focus of the study was dictated by GCC's interest in developing sites designated VDL, of which there are 766 and amounts to a total land area of 1,168.9 ha. Further, a major issue in Glasgow is the level of fuel poverty, defined as households who spend more than 10% of their annual income on fuel (Scottish Government: Scottish Fuel Poverty 2002). Glasgow contains approximately 310,000 dwellings (National Records of Scotland 2018) of which around 123,000 (41%) are socially owned and, of these, 37,000 (30%) have no wall insulation and are in the 'hard-to-heat' category. The level of fuel poverty is expected to increase when energy prices increase in future (Scottish Government 2020). Currently, the average heating energy demand of a dwelling across Glasgow is 13,000 kWh/y and the City's overall domestic heating requirement is around 4,100 GWh (Scotland Energy Database 2020). The average heat energy demand of a dwelling in each of Glasgow's Wards was investigated by collecting additional heat demand data from the online Scotland Heat Map GIS resource in the form of a raster file at a resolution of 50 m and covers all buildings across Scotland (Scottish Government 2019). This is imported into GOMap and converted to a 10 m x 10 m resolution overlapping Glasgow as shown in Figure 5.2. To obtain heat demand for dwellings only, the heat map is overlaid with the

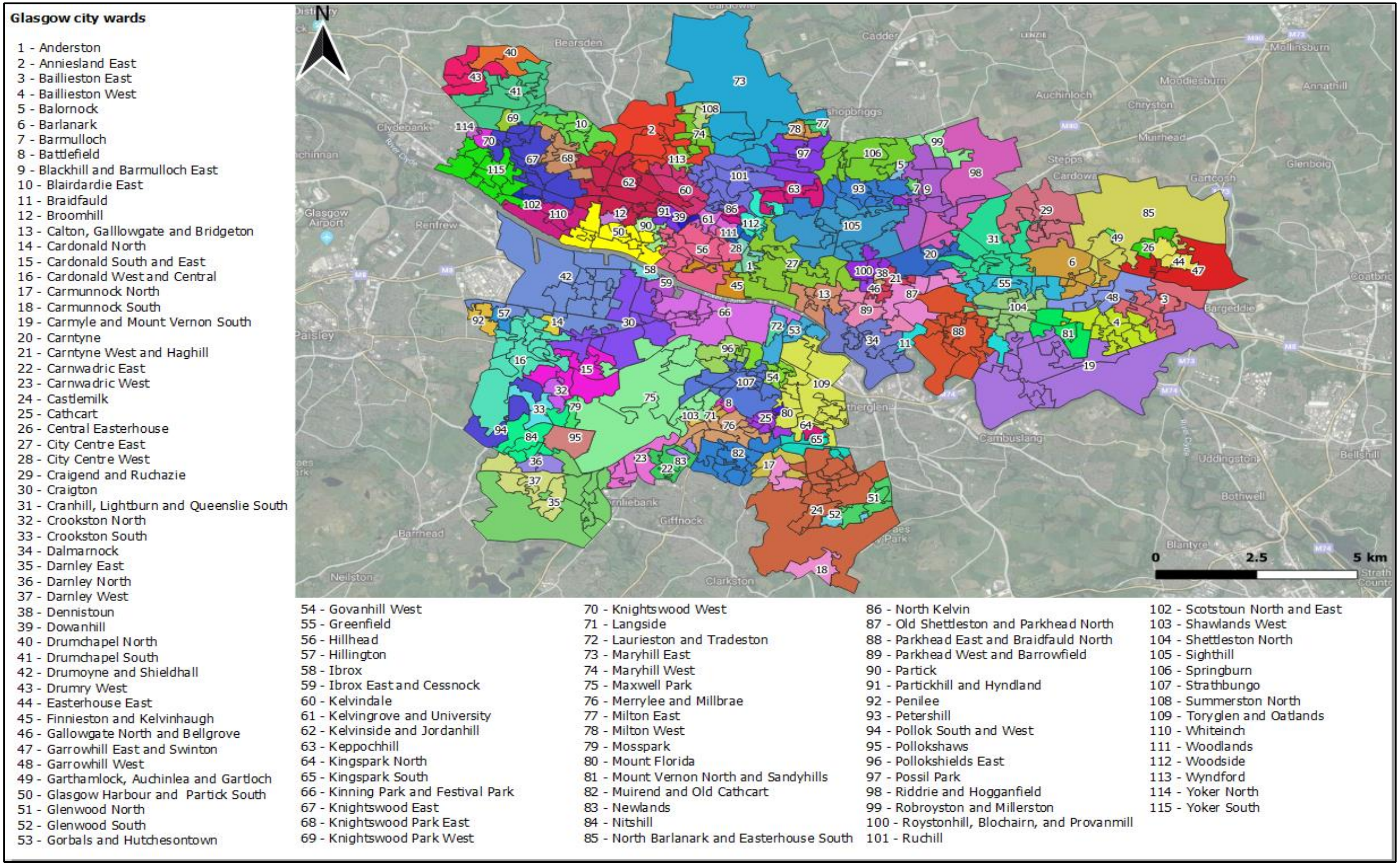


Figure 5.1. Wards in Glasgow City.

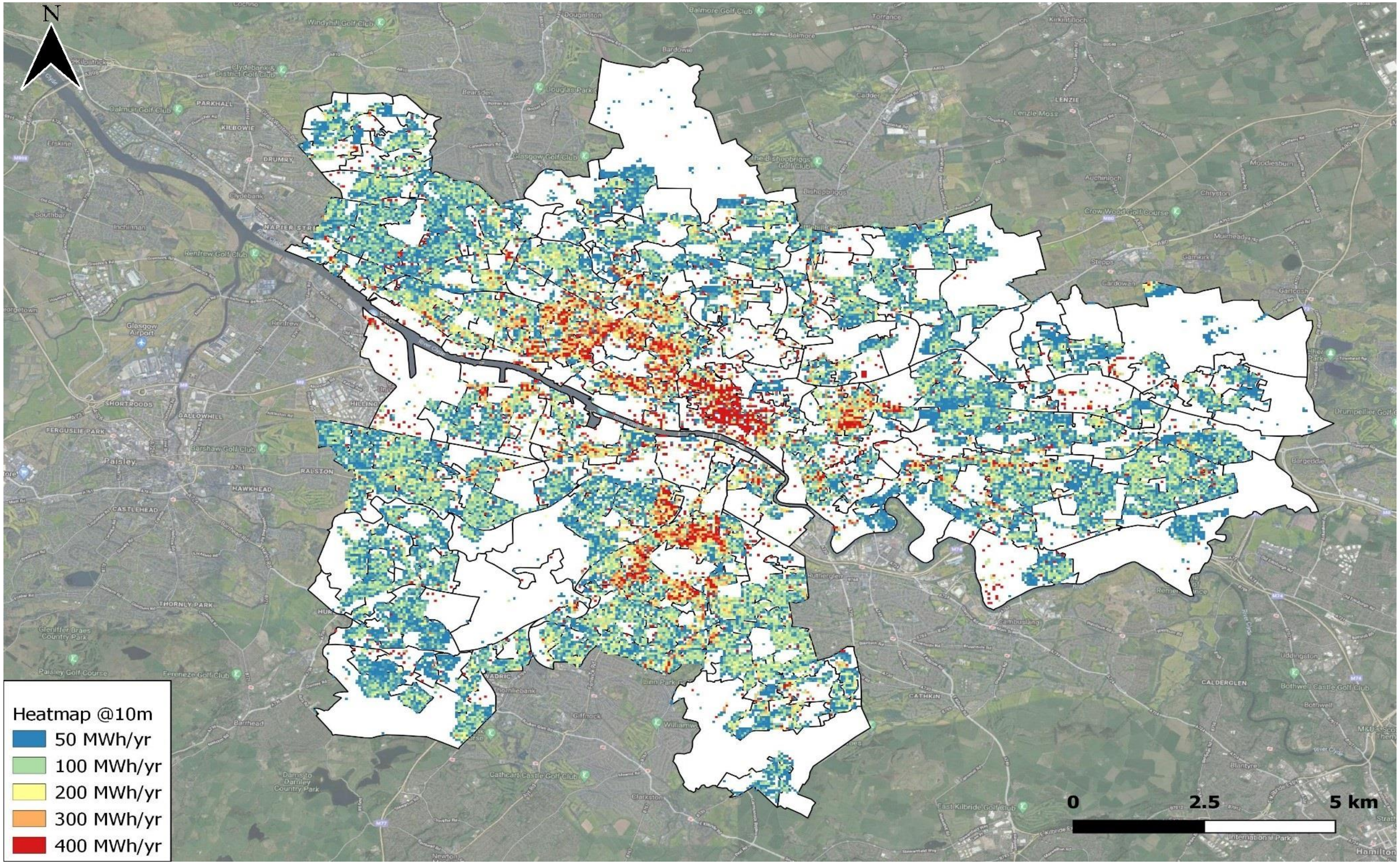


Figure 5.2. Glasgow heat map at 10 m resolution overlapping Wards.

dwelling shapefile obtained from Edina and all overlapping areas are extracted to avoid acquiring heat demand for non-dwellings such as commercial or industrial buildings. A statistical analysis is performed in conjunction with Glasgow Wards data to provide the total heat demand per Ward. This was further refined by using data from an AddressBase (Ordnance Survey - AddressBase, 2020), a dataset provided by OS containing the number of inhabited dwellings for each Ward, and calculating the average heat demand per dwelling per Ward. All Ward statistics are shown in APPENDIX II.2: Table A2.18.

As part of the Scottish Government's Energy Strategy (Scottish Government 2017), there is a commitment to electrify home heating. For the work reported here, PVPS is the RET considered in the GOMap evaluation as this was of immediate interest to GCC, who have previously installed PV systems at a number of primary schools (Campbell & Kennedy 2017) and were examining car park PV canopies as part of an EC Horizon 2020 research project (Ruggedised-Glasgow 2019).

PVPS technology has been extensively utilised elsewhere to supply local communities (Tiba *et al* 2010), alongside small-scale PV systems integrated into buildings (Song *et al* 2019) or installed at car parks to support EV charging (Fazelpour *et al* 2014).

GOMap was configured with the necessary policy and technical information and applied to explore future development scenarios of interest to GCC as follows.

5.3 Scenario outline

Several scenarios are examined for future development with input parameters summarised in Table 5.1.

- **Scenario 1** is the base case scenario in which all policy and technical aspects are enabled in the context of sites with the VDL designation.
- **Scenario 2** investigates the future intention of community education programs and the disregarding of glare from PVPS by relaxing (or disabling) pertinent policy social- and glare-related aspects in the context of sites with the VDL designation.

Table 5.1. Scenario information.

Scenario	Scope	Relaxed policy aspect	Relaxed technical aspect	Weighting method	Description
Scenario 1	VDL	None	None	Non-equal and equal	Base case scenario with all policy and technical aspects active.
Scenario 2	VDL	Visual impact Visual intrusion	None	Non-equal and equal	Assuming community-based education programs are provided and glare is disregarded from PVPS due to low-risk.
Scenario 3	VDL	None	Substation congestion Substation connection distance	Non-equal and equal	Assuming future upgrades to electric and substation network improving energy resources and minimising congestion.
Scenario 4	City	None	None	Non-equal	Identification of new suitable sites not categorised as VDL and could potentially be utilised for PVPS deployment.
Scenario 5	Multi-story car parks	Biodiversity Developmental Environmental	Terrain	Non-equal	Exploring the deployment of PV canopies on multi-story car park roofs for charging EVs.
Scenario 6	VDL	Visual intrusion	Overshading	Non-equal	Identification of new unconstrained sites for new build homes to tackle Glasgow's homeless issue.

- **Scenario 3** investigates the future intention of electricity infrastructure investment by relaxing pertinent technical substation-related aspects in the context of sites with the VDL designation.
- **Scenario 4** investigates the base case scenario with all policy and technical aspects active in the context of a new potential site within the city in areas not previously designated VDL.
- **Scenario 5** investigates the deployment of PV arrays on the canopies of multi-story car park for the charging of EVs by relaxing the policy and technical aspects which would have negligible impact on the assessment.
- **Scenario 6** investigates the alternative use of VDL sites for house building to tackle the homeless issue.

For each of scenarios 1 through 3, potential PVPS deployment is explored on sites designated VDL with results obtained from non-equal and equal weightings, the latter of which is in regards to GCC's interest. These results are compared to highlight any substantial differences between the use of the two weighting methods. Certain policy and technical aspects are relaxed to explore the effects disabling these aspects can have on available land and determine if more land is released or constrained for development when assumptions are made. In terms of policy aspects: the biodiversity and environmental aspects are often considered the most significant due to preserving and protecting natural sites; followed by visual impact related to the proximity to nearby settlements; then developmental and economic growth of towns/cities; and finally, visual intrusion from glare which is measured as low-risk. In terms of technical aspects: the overshading aspect is found to be the most significant particularly as it determines the energy output potential of a PVPS; followed by substation connection distance due to the logistics involved in installing connection cables to existing grid network lines; then the substation congestion aspect which determines if new energy can be injected into the grid network without risk of voltage overload; and finally, the terrain where areas of broken ground or those vulnerable to floods can be mitigated by flood management. The weightings for all aspects have been calculated using the MCDM/AHP method with the base case scenario shown in Section 3.3.2.3. Weightings and their corresponding CR for other scenarios are shown in APPENDIX II.1.

For each of scenarios 1 through 5, a land utilisation factor (or *packing factor*) is set and defined as the ratio of the total PVPS array area to the total land area occupied by the PVPS (ur Rehman *et al* 2020, Scurlock 2014). In some studies, a typical fixed-tilt PVPS was found to have a land utilisation factor between 47 – 51% (Araki *et al* 2017, Martín-Chivelet 2016, Horner & Clark 2013). In this study, the land utilisation factor (a user-defined parameter in GOMap) is set to 50% to fall within the range identified in the mentioned studies. This is required to ensure there is adequate space to deploy and maintain the PVPS installation. For Scenario 6, the land utilisation factor is set to 100% as this scenario focuses on new build housing which considers the average number of dwellings in Glasgow per hectare (National Records of Scotland 2018).

All Wards with potential sites are listed with the Ward possessing the highest energy output potential examined in greater detail. This includes identifying all individual sites within the Ward. Due to the amount of available land given by each site, not all sites are commercially viable for exploitation, therefore only the top 3 sites containing the largest amount of unconstrained area are scrutinised in the analysis. The top 3 sites depicted in the figures show areas of green which are suitable for PVPS deployment and categorised as policy 'Possible' and technically 'Favourable'; and areas of red which are unsuitable for PVPS deployment and designated as any other policy and technical categorisation. The policy and technical factors mentioned will include its score in parenthesis for the reader's convenience; the factors where scores are not mentioned can be assumed to possess multiple scores as shown previously in Table 3.5 of Section 3.3.2.2. Aspects which have no influence on the Wards or Sites will not be mentioned. A summary of each aspects influence on each Ward is tabulated in APPENDIX II.3: Table A2.19.

To calculate the PVPS energy generation, the area of unconstrained land is imported to GOMap's in-built PVPS model where the potential energy yield is calculated as a function of hourly solar geometry and weather information as described in Section 3.3.3. The output energy generation is used to calculate the number of dwellings equivalent in each Ward and the percentage ratio against all inhabited dwellings, these are calculated by using the statistics tabulated in APPENDIX II.2: Table A2.18.

5.4 Scenario 1: All factors and aspects active (base case)

Scenario 1 is the base case scenario in which all policy and technical aspects are enabled in the context of sites with the VDL designation.

5.4.1 Non-equal weightings

Scenario 1 assesses the available VDL when all policy and technical aspects are active with weightings shown in Table 5.2.

Table 5.2. Scenario 1 with non-equal weightings.

Policy aspect	Weightings
Biodiversity	0.326
Developmental	0.114
Environmental	0.326
Visual impact	0.148
Visual intrusion	0.086
Technical aspect	**Weightings**
Overshading	0.484
Substation congestion	0.168
Substation connection distance	0.231
Terrain	0.117

The outputs of the assessment revealed that there is 327.1 ha of unconstrained VDL sites available across the city available for PVPS deployment. This amount of land available can generate an energy yield of 136,474 MWh/y, the equivalent of supplying around 12,714 dwellings with heat energy.

It is found that there is a total of 361 out of 766 sites (47%), which are located in 63 out of 115 Wards (55%). The results of this scenario for only those Wards containing areas of opportunity are listed in Table 5.3 in descending order in terms of energy yield. Further information such as combined site area, the output energy, the number of dwellings that can be supplied, and the ratio of dwellings supplied with the total number of inhabited dwellings within the ward is also included.

Table 5.3. Scenario 1 – energy yield from non-equally weighted unconstrained VDL sites.

Ward	Site area (ha)	Output Energy (MWh/y)	No. of dwellings equivalent	Dwelling coverage within Ward (%)
Carmyle and Mount Vernon South	29.0	12,079	829	13.3
Darnley East	23.0	9,748	899	19.8
North Barlanark and Easterhouse South	20.1	8,406	930	48.2
Petershill	16.5	6,864	623	15.5
Garrowhill East and Swinton	15.2	6,395	733	64.1
Blackhill and Barmulloch East	14.2	5,962	372	11.9
Sighthill	12.8	5,333	722	13.2
Riddrie and Hogganfield	12.1	5,029	445	21.3
Maryhill East	11.0	4,620	457	14.1
Drumoyne and Shieldhall	10.4	4,322	437	5.1
Dalmarnock	8.8	3,631	320	6.3
Garrowhill West	8.3	3,486	266	16.6
Cranhill, Lightburn and Queenslie South	7.5	3,128	205	5.3
Barlanark	7.5	3,117	336	14.2
Keppochhill	6.6	2,760	53	2.7
Toryglen and Oatlands	6.6	2,755	272	3.5
Pollokshaws	6.5	2,722	445	67.3
Easterhouse East	5.7	2,387	255	33.5
Glasgow Harbour and Partick South	5.2	2,178	39	0.5
Parkhead East and Braidfauld North	5.2	2,171	261	3.4
Anniesland East	5.3	2,154	216	4.8
Craigend and Ruchazie	5.1	2,146	232	7.6
Glenwood North	5.0	2,112	186	9.8
Castlemilk	4.8	1,998	90	1.2
Ruchill	4.8	1,990	195	2.6
Drumchapel South	4.7	1,958	184	3.7
Kinning Park and Festival Park	4.6	1,935	307	5.1
Central Easterhouse	4.6	1,891	39	7.2

Old Shettleston and Parkhead North	4.4	1,825	182	7.5
Craigton	4.1	1,674	129	2.7
Yoker South	3.6	1,487	136	2.6
Woodside	3.1	1,312	92	3.7
Nitshill	3.1	1,289	101	4.2
Parkhead West and Barrowfield	2.9	1,218	43	2.1
Gorbals and Hutchesontown	2.9	1,170	130	4.0
Ibrox East and Cessnock	2.6	1,102	98	7.0
Possil Park	2.5	1,067	88	3.4
Baillieston East	2.5	1,031	66	2.3
Calton, Galllowgate and Bridgeton	2.5	1,024	298	5.1
Baillieston West	2.4	1,007	56	1.6
Drumchapel North	2.3	972	105	16.7
Finnieston and Kelvinhaugh	2.1	873	151	4.7
Hillhead	1.6	648	68	0.9
Drumry West	1.5	605	48	2.7
Wyndford	1.5	597	40	13.8
Carnwadric West	1.3	534	63	2.4
Braidfauld	1.2	478	46	2.8
Milton West	1.1	465	39	4.2
Springburn	1.2	462	42	1.3
Kelvindale	0.8	327	20	0.6
Milton East	0.7	309	41	7.1
Govanhill West	0.7	292	35	0.8
Roystonhill, Blochairn, and Provanmill	0.6	266	29	1.3
Kelvinside and Jordanhill	0.6	228	14	0.2
Carntyne	0.6	228	12	0.5
Greenfield	0.5	203	17	0.6
Maryhill West	0.5	198	31	1.5
City Centre East	0.3	122	123	1.4
Maxwell Park	0.2	92	5	0.1
Laurieston and Tradeston	0.2	77	15	2.2
Cardonald South and East	0.02	8	1	0.02
Darnley West	0.01	3	0.3	0.01
Mosspark	0.01	2	0.2	0.05
Total	**327.1**	**136,474**	**12,714**	**-**

The Ward with the highest energy yield is Carmyle and Mount Vernon South. With the weightings applied, this Ward comprises 29.0 ha of unconstrained land with a potential to generate 12,079 MWh/y. With an average dwelling heat demand of 14.6 MWh/y, the energy generated is equivalent to the heating requirement of up to 829 dwellings and covers 13.3% of dwellings within the Ward.

Carmyle and Mount Vernon South is situated on the east side of Glasgow as shown in Figure 5.3 and contains 14 VDL sites, the majority of which lie in the west of the Ward.

From a policy perspective, the biodiversity aspect which is one of two aspects with the highest policy weighting of 0.326 and has significant effect on not only discounting woodland areas within the Ward due to the possibility of existing creature habitats but also promoting areas where no biodiversity issues arise. The developmental aspect which, although it is given a low weighting of 0.114, has significant impact on industrial areas located on the west side as other policy aspects have little presence within the industrial areas. These developmental factors include 'Green network opportunity areas' (2), 'Network of centres' (2) and 'Strategic development framework – river' (2), all of which affects the VDL within the Ward in terms of their presence due to the large Clydesmill Industrial Estate located on the west side. Like biodiversity, the environmental aspect is given a high weighting of 0.326 with the 'Green corridors' (1) factor promoting areas of land adjacent to the River Clyde at the northeast and southwest parts of the Ward. Consequently, with high weightings, areas covered by the factor 'Sites of importance for nature conservation' (3) are immediately discounted. Two additional environmental factors 'Old wood' (2) and 'Tree Preservation Order' (2) focuses on the east and south areas of the Ward due to the proximity of nearby forestry. Although the visual impact has a weighting of 0.148, it does not affect any of the VDL sites as these are out of bounds from communities. A low weighting of 0.086 assigned to the visual intrusion aspect discounts small parts of the VDL unaffected by other policy aspects and based in the east and central parts of the Ward due to the M73 and M74 motorways respectively.

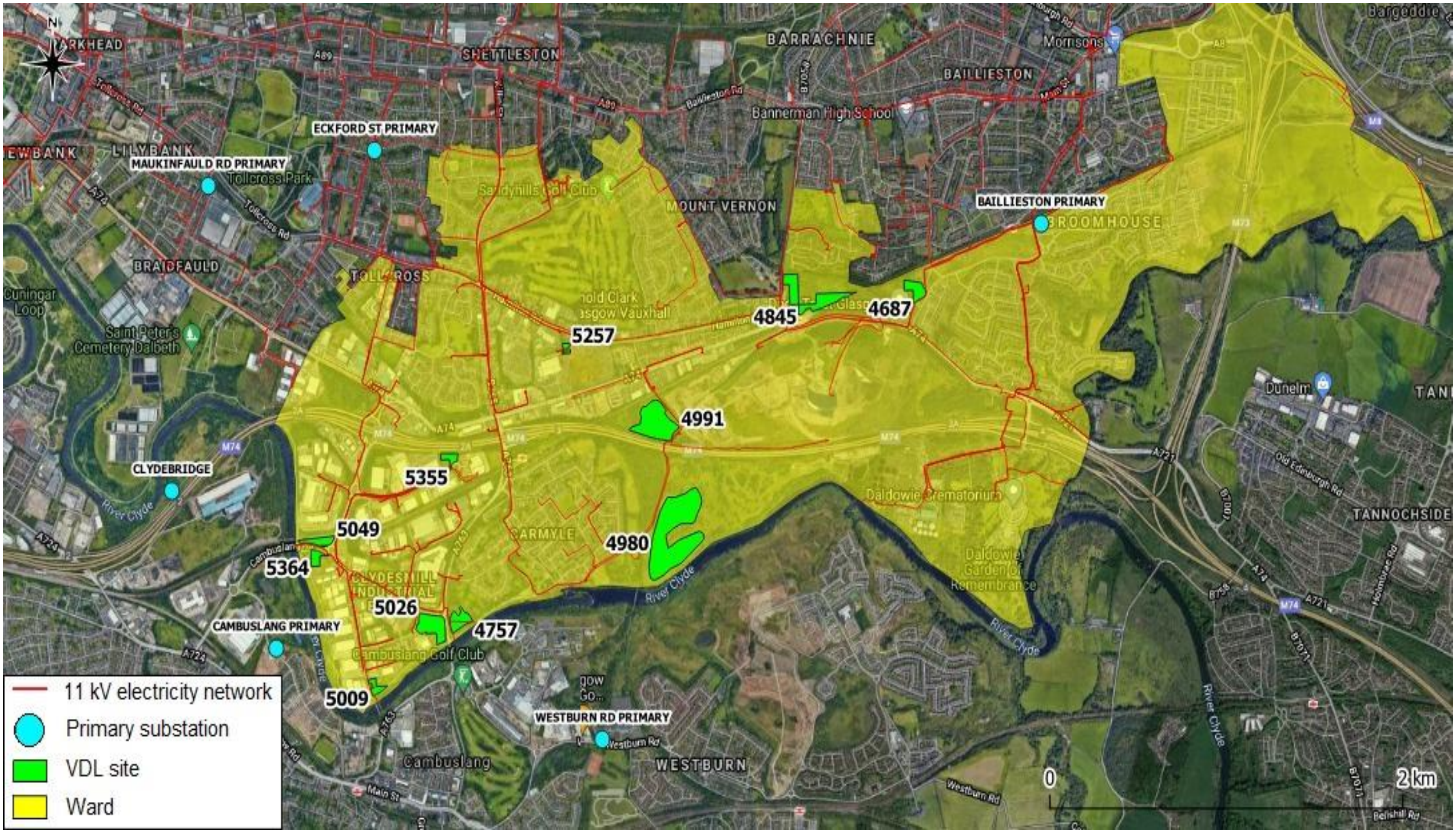


Figure 5.3. The Carmyle and Mount Vernon South Ward.

From a technical perspective, the overshading aspect is given the highest weighting of 0.484 and although it affects large areas of land due to industrial buildings, the majority of VDL are in open areas, particularly in the central region. The substation congestion aspect with regards to the substation connection distance aspect is considered favourable as the Ward lies in the outskirts of the City and contains high coverage of grid connection lines, both aspects possess weightings of 0.168 and 0.231 respectively. There are some issues with possible flooding in terms of terrain suitability due to the south and east parts of the Ward lying adjacent to the banks of the River Clyde. Although the terrain aspect is assigned the lowest weighting of 0.117, premeditated mitigation plans can be implemented to avoid major problems.

5.4.1.1 VDL site analysis

From a deeper analysis with GOMap, this Ward has shown that 14 out of 27 sites (52%) are categorised as being suitable. Details of these sites are listed in Table 5.4 in descending order in terms of the energy yield and the top three sites are shown in Figure 5.4.

Table 5.4. Sites of opportunity in Carmyle and Mount Vernon South.

Site No.	Address	Area (ha)	Output energy (MWh/y)	No. of dwellings equivalent
4980	East of Kenmuir Road	7.4	3,143	216
4991	East of Showmens	6.3	2,644	182
4757	West of 40 Gardenside Place	3.3	1,368	94
4845	South of Greentree Drive	2.2	906	62
5300	South of 69 River Road	2.0	833	57
5187	London Road	1.7	703	48
4735	South of 85 Hamilton Road	1.7	702	48
5026	Clydesmill Drive	1.6	673	46
4687	Daldowie Road	0.8	325	22
5049	Cambuslang Road	0.6	232	16
5364	South of Cambuslang	0.5	184	13

	Road			
5009	Cambuslang Road	0.4	154	11
5355	Fullarton Drive	0.4	147	10
5257	East of 76 Hamilton Road	0.2	66	5
Total	**-**	**29.0**	**12,079**	**829**

5.4.1.1.1 Site 4980

The largest of these sites is Site 4980 as shown in Figure 5.4 (upper) which covers of 7.4 ha of unconstrained land and is situated on the east side of the Carmyle community and sandwiched between the M74 motorway and the River Clyde.

While this is a good-sized area largely devoid of trees, there are several interconnecting roads and paths. In terms of the policy aspects, the biodiversity aspect classifies parts of the Site with trees as intermediate due to the risk of potentially damaging creature habitats. Two environmental factors are present: ‘Green corridors’ (1), which supports development in the southwest part of the Site; however, the factor ‘Sites of importance for nature conservation’ (3) runs along the banks of the River Clyde at the base of the Site, which may discourage land development. The visual intrusion aspect travels along the north part of the Site due to the M74 motorway and affects a large portion of the Site.

There are overshading issues due to the wide spread of trees and forestry especially in the western parts of the Site. Substation congestion is favourable; however, the eastern part of the Site is considered too far from the nearest substation connection point and clarifies why this is marked as technically constrained. The terrain aspect affects the banks adjacent to the River Clyde and the edges of the Site.

With these policy and technical aspects at play, the Site possesses 7.4 ha of unconstrained land located on empty space and can generate 3,143 MWh/y with the potential to supply 216 dwellings with heat energy.

Figure 5.4. Top 3 Sites in Carmyle and Mount Vernon South: Site 4980 (upper); Site 4991 (middle); Site 4757 (bottom).

5.4.1.1.2 Site 4991

The second identified Site is 4991 as shown in Figure 5.4 (middle) which contains of 6.3 ha of unconstrained land and is situated to the west of the Patersons of Greenoakhill quarry and northeast of Carmyle New Park with the M74 motorway running in-between.

Three policy aspect affects this Site: the biodiversity aspect mostly affects the perimeter of the Site and is overlaid with trees and plants leaving the central parts untouched; the developmental factor ‘Economic policy areas’ (2) overlaps the entire Site to promote economic investment; and the visual intrusion aspect affects the lower part of the Site due to the M74 motorway.

In terms of the technical aspects, overshading plays a significant role due to the amount of trees along the perimeter of the Site and groups of trees from within, and occurs slightly in the north part of the Site due to the moderately-sized infrastructure of buildings in the industrial park, an area which provides favourable substation congestion. An 11 kV electricity line runs through the centre of the Site but, due to its large area, only the central portion is given a favourable score. The outer parts of the Site, such as the northeast and southwest parts, are considered far from a connection point.

With these policy and technical aspects at play, the Site possesses 6.3 ha of unconstrained land located on empty space and can generate 2,644 MWh/y with the potential to supply 182 dwellings with heat energy.

5.4.1.1.3 Site 4757

The third Site examined is 4757 as shown in Figure 5.4 (bottom) which comprises of 3.3 ha of unconstrained land and is located on the southwest outskirts of the Carmyle community and directly east of an industrial complex.

In terms of the policy aspects, the biodiversity aspect covers significant areas of the Site due to the presence of trees which may harbour creature habitats. Two opposing environmental factors cover the same extent of the Site, these are the ‘Green corridors’ (1) and ‘Sites of importance for nature conservation’ (3) due to the groves of trees scattered throughout the Site. As Carmyle community is in close proximity in the northeast, parts of the Site are influenced by visual impact.

In terms of the technical aspects, overshading plays a significant role due to the spacing of trees scattered around the Site and along its perimeter. Substation congestion level is favourable as is the connection distance to a grid network line as it runs directly through the Site. The terrain aspect affects the majority of the Site due to its location along the banks of the River Clyde and some broken ground.

With these policy and technical aspects at play, the Site possesses 3.3 ha of unconstrained land located on empty space and can generate 1,368 MWh/y with the potential to supply 94 dwellings with heat energy.

5.4.2 Equal weightings

All policy and technical aspects are active and equally weighted for the assessment of VDL sites. The outputs of the assessment revealed that there is 185.5 ha of unconstrained VDL sites available across the city available for PVPS deployment. This amount of land available can generate an energy yield of 75,854 MWh/y, the equivalent of supplying around 7,092 dwellings with heat energy.

It is found that there is a total of 208 out of 766 sites (27%), which are located in 40 out of 115 Wards (35%). The results of this scenario for only those Wards containing areas of opportunity are listed in Table 5.5 in descending order in terms of energy yield. Further information such as combined site area, the output energy, the number of dwellings that can be supplied, and the ratio of dwellings supplied with the total number of inhabited dwellings within the Ward is also included.

As can be seen, the Ward with the highest energy yield is North Barlanark and Easterhouse South. With equal weightings applied, this Ward comprises 19.1 ha of unconstrained land with a potential to generate 7,992 MWh/y. With an average dwelling heat demand of 9.0 MWh/y, the energy generated is equivalent to the heating energy requirement of up to 884 dwellings and covers 45.8% of dwellings within the Ward.

Table 5.5. Scenario 1 – energy yield from equally weighted unconstrained VDL sites.

Ward	Site area (ha)	Output Energy (MWh/y)	No. of dwellings equivalent	Dwelling coverage within Ward (%)
North Barlanark and Easterhouse South	19.1	7,992	884	45.8
Carmyle and Mount Vernon South	18.7	7,811	536	8.6
Darnley East	22.1	7,720	712	15.7
Garrowhill East and Swinton	15.1	6,332	726	63.4
Cranhill, Lightburn and Queenslie South	9.0	3,753	246	6.3
Barlanark	8.4	3,501	378	15.9
Drumoyne and Shieldhall	8.3	3,446	348	4.1
Garrowhill West	7.5	3,149	241	15.0
Dalmarnock	5.8	2,409	212	4.2
Easterhouse East	5.7	2,387	255	33.5
Sighthill	5.6	2,351	318	5.8
Craigend and Ruchazie	4.6	1,941	210	6.9
Carnwadric West	4.6	1,914	226	8.8
Central Easterhouse	4.6	1,891	39	7.2
Old Shettleston and Parkhead North	4.2	1,731	173	7.2
Pollokshaws	3.9	1,605	262	39.7
Riddrie and Hogganfield	3.9	1,588	141	6.7
Parkhead East and Braidfauld North	3.5	1,428	172	2.2
Nitshill	3.1	1,289	101	4.2
Blackhill and Barmulloch East	2.8	1,164	73	2.3
Petershill	2.6	1,091	99	2.5
Craigton	2.5	1,062	82	1.7
Baillieston West	2.4	1,007	56	1.6
Govanhill West	2.3	953	115	2.6
Baillieston East	1.9	813	52	1.8
Anniesland East	1.7	701	70	1.6
Glasgow Harbour and Partick South	1.1	458	8	0.1
Kinning Park and Festival Park	0.8	331	53	0.9

Carntyne	0.8	320	17	0.7
Ibrox East and Cessnock	0.8	319	28	2.0
Roystonhill, Blochairn, and Provanmill	0.7	290	31	1.4
Springburn	0.6	218	20	0.6
Greenfield	0.5	203	17	0.6
Braidfauld	0.5	184	18	1.1
Parkhead West and Barrowfield	0.4	178	6	0.3
Toryglen and Oatlands	0.5	174	17	0.2
Crookston South	0.3	106	8	0.7
Drumchapel South	0.1	50	5	0.1
Yoker South	0.1	36	3	0.1
Darnley West	0.01	3	0.3	0.01
Total	**181.1**	**73,901**	**6,958**	**-**

North Barlanark and Easterhouse South is situated in the northeast of Glasgow as shown in Figure 5.5 and contains 12 VDL sites, the majority of which lie in the south and east of the Ward.

In terms of the policy reasons, the biodiversity aspect has presence covering most of the Ward particularly the woodland areas in the central region surrounding Gartloch Village and Bishop Loch. These woodland areas contain an abundance of trees and greenery making it an attractive hotspot for animal habitats to thrive. There are five developmental aspects which intersects the VDL within the Ward and include: ‘Green belt’ (2) which has an overwhelming presence in the top half of the Ward close to the town of Cardowan in the north and Bishop Loch in the east covering much of the open spaces available; ‘Green network opportunity areas’ (2) which overlapped areas from the central region going south towards Easterhouse; ‘Network of centres’ (2) which focused on the large shopping district in the southwest; and ‘Strategic development framework’ (2) which almost completely encompasses the entirety of North Barlanark and Easterhouse South save a tiny portion of dwellings which reside in Cardowan to the north. The final aspect is ‘Housing land supply – consented’ (3) which has plans based in the VDL of Gartloch Village in the central region. The environmental aspect overlaps the VDL sites with four factors: the ‘Local nature reserves’ (1) affect a small portion of VDL located in the west close to Blackfaulds farm; the ‘Old wood’ (2) and ‘Tree

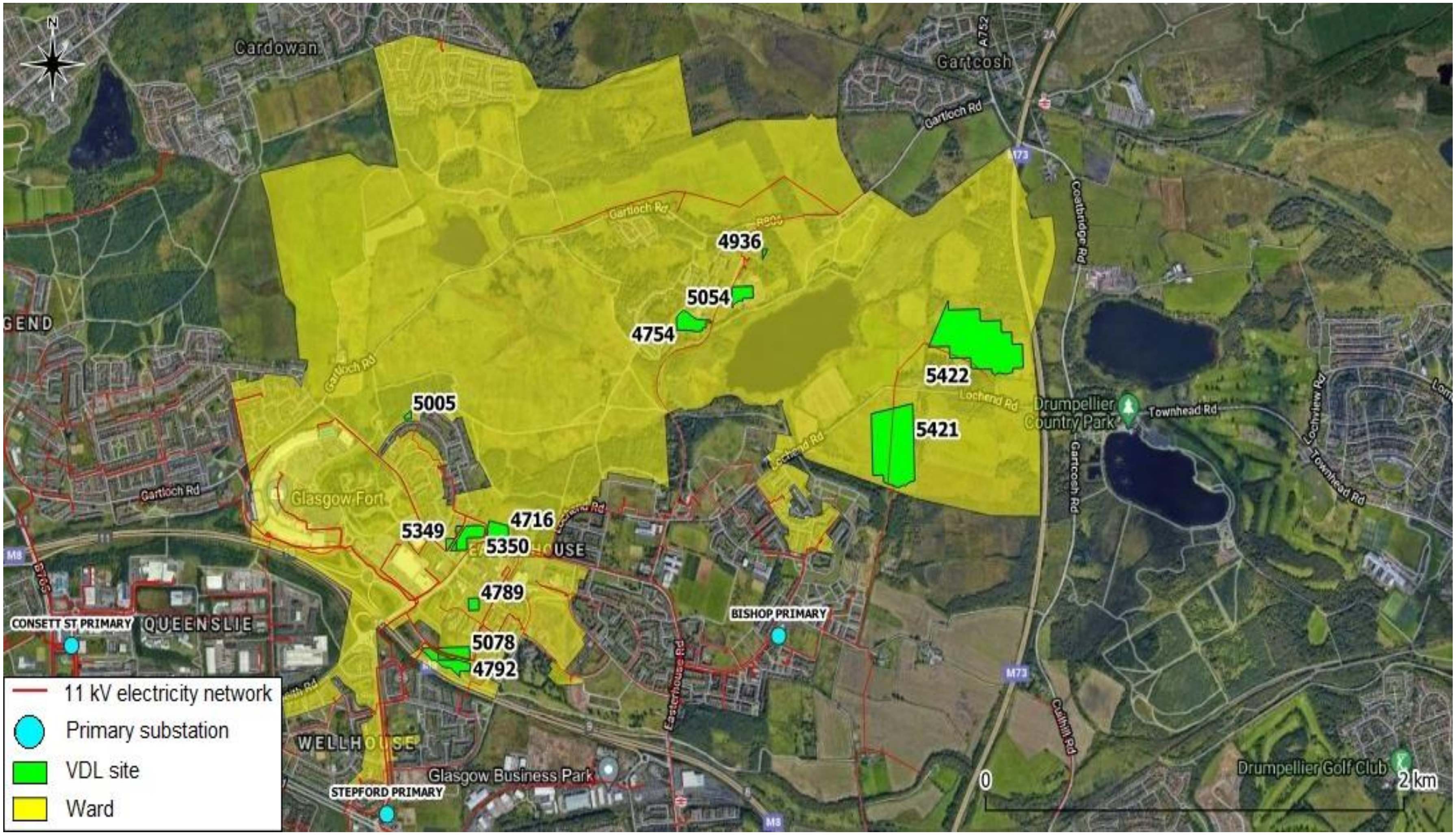


Figure 5.5. The North Barlanark and Easterhouse South Ward.

Preservation Order' (2) factors focus on Gartloch Village and its surrounding area in the central region of the ward; and 'Sites of importance for nature conservation' (3) intersecting a small part of the VDL north of Bishop Loch. The social aspect is mostly present due to dwellings situated in the communities of Cardowan in the north, Gartloch Village in the centre and Easterhouse in the south, although the majority of the VDL are based near the former two communities. The visual intrusion overlaps parts of the VDL based in the southwest where the M8 motorway passes.

In terms of the technical reasons, the overshading aspect focuses on areas where the majority of the VDL are not present such as the fields in the north close to Cardowan and the plots of land near Gartloch Village. There are two substations which are based in the south outside of the Ward; these are Stepford Primary and Bishop Primary. The congestion level for the entire ward is considered favourable due to its location in the outskirts of Glasgow close to North Lanarkshire on the northeast away from heavy industry and dense population. Due to this, the substation congestion in the eastern parts of Glasgow is measured to be low. The substation connection lines are prevalent in the Easterhouse community where they are within a favourable distance to the VDL based there. The connection lines become fewer when going northward towards the outskirts of Glasgow where some VDL near Gartloch Village score favourable. However, the large available space near Cardowan was deemed unlikely. This is due to the lack of spatial electric line data which did not extend outward of the Glasgow district.

5.4.2.1 VDL site analysis

From a deeper analysis with GOMap, this Ward has shown that 12 out of 19 sites (63%) are categorised as being suitable. Details of these sites are listed in Table 5.6 in descending order in terms of the energy yield and the top three sites are shown in Figure 5.6.

Table 5.6. Sites of opportunity in North Barlanark and Easterhouse South.

Site No.	Address	Area (ha)	Output energy (MWh/y)	No. of dwellings equivalent
5422	Manse Road	7.6	3,228	357
5421	Manse Road	6.1	2,559	283
4754	Gartloch Road	1.0	415	46
5350	1-11 Brunstane Road	0.9	365	40
4792	Kildermorie Road	0.9	351	39
4716	Westerhouse Road	0.8	323	36
5078	Arnisdale Road	0.6	262	29
5054	Gartloch Road	0.6	237	26
4789	Arnisdale Road	0.3	106	12
5349	Brunstane Road	0.2	79	9
4936	Gartloch Avenue	0.1	34	4
5005	Conisborough Road	0.1	32	4
Total	**-**	**19.1**	**7,992**	**884**

5.4.2.1.1 Site 5422

The largest of these sites is Site 5422 as shown in Figure 5.6 (upper) which comprises of 7.6 ha of unconstrained land and is situated on the east side of the Ward between the M73 motorway and Bishop Loch.

In terms of the policy aspects, the biodiversity aspect covers the southern parts of the Site due to the presence of trees which may harbour creature habitats. Two developmental factors are present: ‘Green belt’ (2) and ‘Strategic development framework’ (2), both of which cover the entirety of the Site. Four environmental factors overlap parts of the Site with ‘Local nature reserves’ (1) promoting development and overlapping the whole Site. The second factor ‘Old wood’ (2) classifies the southern areas of the Site as intermediate due to the presence of woodland. The two remaining factors ‘Sites of importance for nature conservation’ (3) and ‘SSLI’ (3) both overlap the entire Site due to the large amount of natural coverage. The M73 motorway on the eastern part of the Ward running southward intersects the Site discounting some land area.

Figure 5.6. Top 3 Sites in North Barlanark and Easterhouse South: Site 5422 (upper); Site 5421 (middle); Site 4754 (bottom).

For the technical aspects and in terms of overshading, the northern and southern parts of the Site are excluded due to its close proximity to the present woodland. As the sites and the Ward itself are on the outskirts of the City, the level of substation congestion is considered favourable throughout the Ward. There is also an electric network line in favourable distance to the Site.

With these policy and technical aspects at play, the Site possesses 7.6 ha of unconstrained land located on empty space and can generate 3,228 MWh/y with the potential to supply 357 dwellings with heat energy.

5.4.2.1.2 Site 5421

The second identified Site is 5421 as shown in Figure 5.6 (middle) which covers of 6.1 ha of unconstrained land and is situated directly south of Site 5422 across the rows of woodland.

There is a risk to potential creature habitats with a column of trees running down the central part of the Site which discounted a large section of the VDL. Similar to Site 5422, the developmental factors ‘Green belt’ (2) and ‘Strategic development framework’ (2) overlap the Site in addition to ‘Community growth masterplan area’ (2) due to its close proximity to the Easterhouse community. The environmental factor ‘Local nature reserves’ (1) promotes deployment affecting only the eastern part of the Site however, this is annulled due to the sensitivity of the two factors ‘Sites of special landscape importance’ (3) and ‘Sites of importance for nature conservation’ (3) overlapping the majority of the Site. As the Site is distant from nearby settlements and motorways, the visual impact and visual intrusion are negligible.

In terms of the technical aspects, there is risk of overshading in the central region of the Site due to a grove of trees. Substation congestion is favourable and with a grid connection line running down the western area of the site, parts of the western area of the Site is considered ideal for deployment.

With these policy and technical aspects at play, the Site possesses 6.1 ha of unconstrained land located on empty space and can generate 2,559 MWh/y with the potential to supply 283 dwellings with heat energy.

5.4.2.1.3 Site 4754

The third Site is 4754 as shown in Figure 5.6 (bottom) which contains 1.0 ha of unconstrained land and is situated in the central region of the Ward to the northwest of Bishop Loch.

In terms of the policy aspects, the biodiversity aspect covers the surrounding parts of the Site due to the presence of trees which may shelter creature habitats. Only two developmental factors affect the site, ‘Strategic development framework’ (2) and ‘Housing land supply – consented’ (3) both of which cover the most of the Site due to the large amount of unoccupied land available for development. Environmentally, the ‘Old wood’ (2) and ‘Tree Preservation Order’ (2) factors are present due to the Site being enclosed by an abundance of woodland which as a result also includes the ‘Sites of special landscape importance’ (3) factor for preservation purposes. As the Site is within a close proximity to Gartloch Village in the north, parts of the Site have been excluded due to its visual impact.

Technically, there is risk of overshading on the perimeters of the Site due to the woodland enclosure. Substation congestion is favourable as is the connection distance due to a network line running through the Site.

With these policy and technical aspects at play, the Site possesses 1.0 ha of unconstrained land located on empty space and can generate 415 MWh/y with the potential to supply 46 dwellings with heat energy.

5.5 Scenario 2: Policy aspect relaxation facilitated by community education program and disregarding glare from PVPS

Scenario 2 repeats Scenario 1 but with some pertinent policy aspects relaxed to explore the potential for policy-assisted development in future. The visual impact aspect is one of two aspects selected for relaxation with the assumption that local residents are educated in the benefits of installing PVPS in the surrounding areas for supplying heat energy, giving this priority over their personal views on aesthetics. Relaxing this aspect entails that social perspective from all areas examined are excluded from the assessment which, although it may not provide a realistic scenario, it is aimed to show what effects the social perspective has in releasing or constraining available VDL sites. The Visual intrusion aspect is also relaxed as there is no strong evidence to suggest that glare originating from a PVPS can be dangerous to pilots or drivers.

Therefore, the remaining biodiversity, environmental and developmental aspects remain active as do all technical aspects.

5.5.1 Non-equal weightings

Scenario 2 assesses the available VDL of all active policy and technical aspects with weightings applied shown in Table 5.7. As two policy aspects are relaxed, the weightings have been adjusted to reflect the original priorities of the remaining active policy aspects.

Table 5.7. Scenario 2 with non-equal weightings.

Policy aspect	Weightings
Biodiversity	0.429
Developmental	0.143
Environmental	0.429
Visual impact	-
Visual intrusion	-
Technical aspect	**Weightings**
Overshading	0.484
Substation congestion	0.168
Substation connection distance	0.231
Terrain	0.117

The outputs of the assessment revealed that there is 255.3 ha of unconstrained VDL sites available across the city available for PVPS deployment. This amount of land available can generate an energy yield of 106,355 MWh/y, the equivalent of supplying around 10,026 dwellings with heat energy.

It is found that there is a total of 354 out of 766 sites (46%), which are located in 63 out of 115 Wards (55%). The results of this scenario for only those Wards containing areas of opportunity are listed in Table 5.8 in descending order in terms of energy yield.

Further information such as combined site area, the output energy, the number of dwellings that can be supplied, and the ratio of dwellings supplied with the total number of inhabited dwellings within the ward is also included.

The Ward with the highest energy yield is Sighthill. With the weightings applied, this Ward comprises 12.8 ha of unconstrained land with a potential to generate 5,333 MWh/y. With an average dwelling heat demand of 7.4 MWh/y, the energy generated is equivalent to the heating energy requirement of up to 722 dwellings and covers 13.2% of dwellings within the Ward.

Table 5.8. Scenario 2 – energy yield from non-equally weighted unconstrained VDL sites.

Ward	Site area (ha)	Output Energy (MWh/y)	No. of dwellings equivalent	Dwelling coverage within Ward (%)
Sighthill	12.8	5,333	722	13.2
Carmyle and Mount Vernon South	12.2	5,073	348	5.6
Riddrie and Hogganfield	12.1	5,029	445	21.3
Maryhill East	11.0	4,620	457	14.1
Drumoyne and Shieldhall	10.4	4,322	437	5.1
Darnley East	9.7	4,094	378	8.3
Dalmarnock	8.8	3,631	320	6.3
North Barlanark and Easterhouse South	8.4	3,531	391	20.2
Garrowhill West	8.4	3,520	269	16.7
Barlanark	7.8	3,259	352	14.8
Cranhill, Lightburn and Queenslie South	7.7	3,205	210	5.4
Petershill	7.1	2,972	270	6.7
Keppochhill	6.6	2,760	53	2.7
Toryglen and Oatlands	6.6	2,755	272	3.5
Pollokshaws	6.5	2,722	445	67.3
Garrowhill East and Swinton	6.4	2,686	308	26.9
Blackhill and Barmulloch East	6.0	2,505	156	5.0
Easterhouse East	5.7	2,387	255	33.5
Glasgow Harbour and Partick	5.2	2,178	39	0.5

South				
Craigend and Ruchazie	5.1	2,146	232	7.6
Glenwood North	5.0	2,112	186	9.8
Anniesland East	5.0	2,048	205	4.6
Parkhead East and Braidfauld North	4.9	2,021	243	3.1
Castlemilk	4.8	1,998	90	1.2
Ruchill	4.8	1,990	195	2.6
Kinning Park and Festival Park	4.6	1,935	307	5.1
Old Shettleston and Parkhead North	4.6	1,905	190	7.9
Central Easterhouse	4.6	1,891	39	7.2
Craigton	4.1	1,674	129	2.7
Yoker South	3.6	1,487	136	2.6
Woodside	3.1	1,312	92	3.7
Nitshill	3.1	1,289	101	4.2
Parkhead West and Barrowfield	2.9	1,218	43	2.1
Gorbals and Hutchesontown	2.9	1,170	130	4.0
Drumchapel South	2.7	1,116	105	2.1
Baillieston West	2.7	1,104	61	1.8
Ibrox East and Cessnock	2.6	1,102	98	7.0
Possil Park	2.5	1,067	88	3.4
Baillieston East	2.5	1,031	66	2.3
Calton, Galllowgate and Bridgeton	2.5	1,024	298	5.1
Finnieston and Kelvinhaugh	2.1	873	151	4.7
Hillhead	1.6	648	68	0.9
Wyndford	1.5	597	40	13.8
Drumchapel North	1.4	550	59	9.4
Carnwadric West	1.3	534	63	2.4
Braidfauld	1.2	478	46	2.8
Milton West	1.1	465	39	4.2
Springburn	1.2	462	42	1.3
Kelvindale	0.8	327	20	0.6
Milton East	0.7	309	41	7.1
Govanhill West	0.7	292	35	0.8
Roystonhill, Blochairn, and Provanmill	0.6	266	29	1.3
Kelvinside and Jordanhill	0.6	228	14	0.2

Carntyne	0.6	228	12	0.5
Greenfield	0.5	203	17	0.6
Maryhill West	0.5	198	31	1.5
Drumry West	0.4	170	14	0.8
City Centre East	0.3	122	123	1.4
Maxwell Park	0.2	92	5	0.1
Laurieston and Tradeston	0.2	77	15	2.2
Cardonald South and East	0.02	8	0.6	0.02
Darnley West	0.01	3	0.3	0.01
Mosspark	0.01	2	0.2	0.05
Total	**255.3**	**106,355**	**10,026**	**-**

Sighthill is situated on the east side of Glasgow as shown in Figure 5.7 and contains 17 VDL sites across the Ward.

In terms of the policy aspects, the biodiversity aspect covers marginal areas of the Ward, in particular areas with groves of trees and bushes. With a weighting of 0.429, areas around these woodlands are immediately discouraged. There are five developmental factors which affected the VDL, three encouraged growth and were listed as ‘Master plan area’ (1), ‘Strategic economic investment locations’ (1) and ‘Transformational regeneration areas’ (1) which covers mostly the west and central part of the Ward where much of the industry were based. The remaining two factors ‘Industrial-business marketable land supply’ (2) and ‘Strategic development framework’ (2) concentrate on open space areas in the central and western regions, avoiding the communities of Foresthall in the northeast and Royston in the south. Although the developmental aspect has a weighting of 0.143, it plays a significant role in site suitability as it has a higher coverage of the Ward than the biodiversity and environmental aspects. With a weighting of 0.429, only the two environmental factors overlap the Ward but just a fraction of coverage intersects the VDL. These are the ‘Green corridors’ (1) and ‘Sites of importance for nature conservation’ (3) located in the northwest of the Ward.

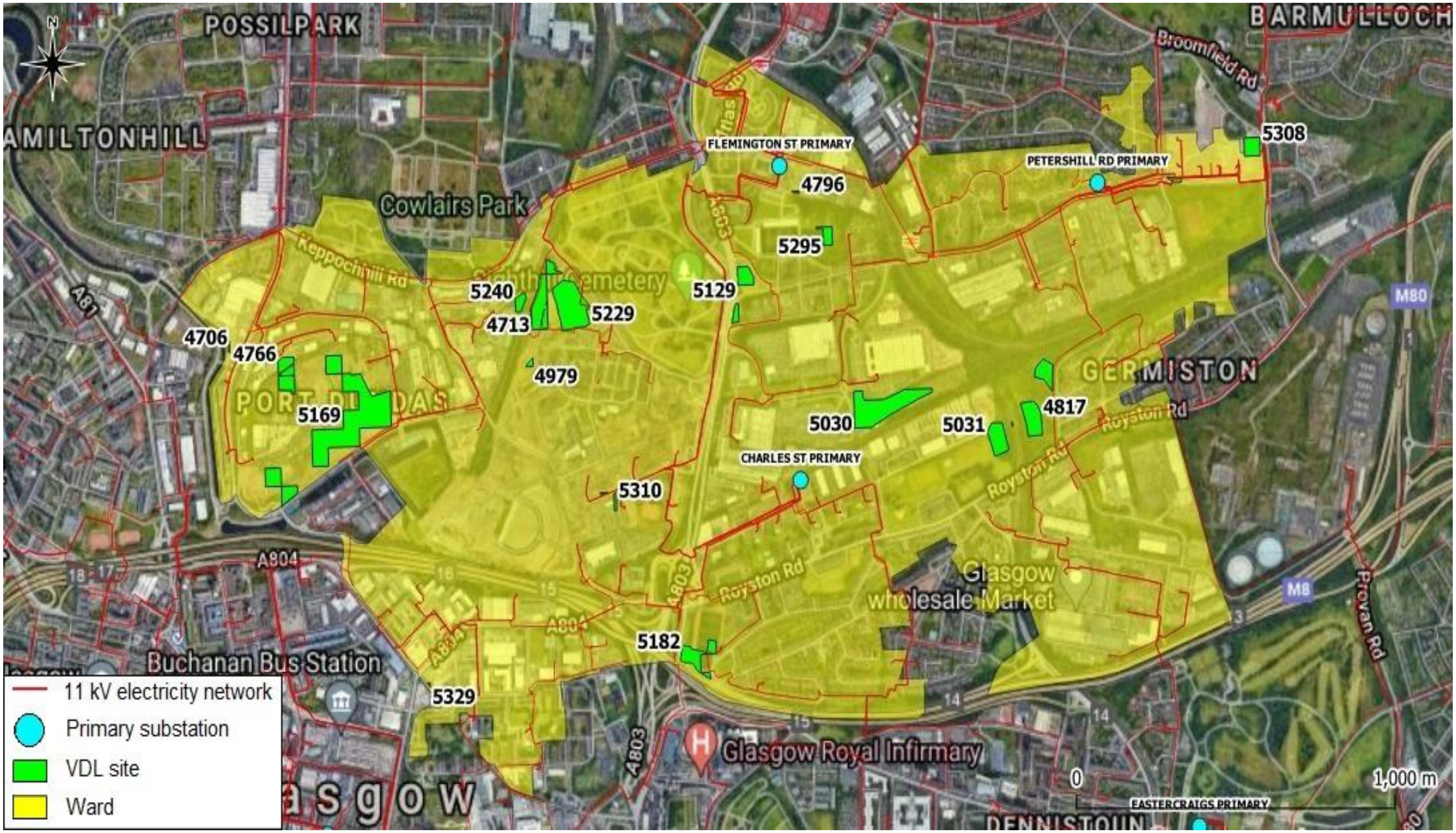


Figure 5.7. The Sighthill Ward.

In terms of the technical aspects, the overshading from buildings posed major problems to most areas of the ward as there are many industries present particularly in the southern and western areas, and are excluded due to the high overshading weighting of 0.484. The level of substation congestion is high and covers much of the Ward. There are three primary substations located within the Ward – Flemington St in the north, Petershill Rd in the northeast and Charles St in the central region. Although these substations are highly congested, the substation congestion aspect has a low weighting of 0.168. However, this number of substations provide a major benefit as most areas of the Ward are within a favourable substation connection distance which possesses a weighting of 0.231.

5.5.1.1 VDL site analysis

From a deeper analysis with GOMap, this Ward has shown that 17 out of 31 sites (55%) are categorised as being suitable. Details of these sites are listed in Table 5.9 in descending order in terms of the energy yield and the top three sites are shown in Figure 5.8.

Table 5.9. Sites of opportunity in Sighthill.

Site No.	Address	Area (ha)	Output energy (MWh/y)	No. of dwellings equivalent
5169	76-80 North Canal	3.4	1,438	195
5229	Fountainwell Ave	3.1	1,311	177
4817	West of Darnick St	2.2	940	127
5030	Springburn Road	1.3	529	72
4713	Fountainwell Place	0.7	288	39
5182	Rhymer Street	0.4	167	23
5031	Glenconner Park	0.4	163	22
5129	Springburn Road	0.3	128	17
5308	Red Road Court	0.3	125	17
4766	Craighall Street	0.2	94	13
5295	Adamswell Street	0.2	66	9
5240	Keppochill Drive	0.1	49	7
5310	16-18 Pinkston Drive	0.1	16	2
4979	Fountainwell Road	0.03	12	2

4796	198 Flemington Street	0.01	3	0.4
5329	22 Kyle Street	0.01	2	0.3
4706	Craighall Road	0.01	1	0.2
Total	**-**	**12.8**	**5,333**	**722**

5.5.1.1.1 Site 5169

The largest of these sites is Site 5169 as shown in Figure 5.8 (upper) which covers of 3.4 ha of unconstrained land and is situated on the west side of Sighthill.

In terms of policy aspects, only the developmental aspect influences the Site with three factors overlapping the Site. These are the ‘Master plan area’ (1), ‘Industrial-business marketable land supply’ (2) and ‘Strategic development framework’ (2).

In terms of technical aspects, there are overshading issues due to a number of industrial buildings within the Site. Substation congestion is also poor but with favourable connection distance to the nearest network line.

With these policy and technical aspects at play, the Site possesses 3.4 ha of unconstrained land located on empty space and can generate 1,438 MWh/y with the potential to supply 195 dwellings with heat energy.

5.5.1.1.2 Site 5229

The second identified Site is 5229 as shown in Figure 5.8 (middle) which contains of 3.1 ha of unconstrained land and is situated to the west of Sighthill Cemetery in the northwest of the Ward.

In terms of policy aspects and like Site 5169, only the developmental aspect influences the Site with two factors overlapping the Site. These are the ‘Transformational regeneration areas (1) and ‘Strategic development framework’ (2). In terms of technical aspects, substation congestion is again poor but with favourable connection distance to the nearest network line which runs across the Site.

With these policy and technical aspects at play, the Site possesses 3.1 ha of unconstrained land located on empty space and can generate 1,311 MWh/y with the potential to supply 177 dwellings with heat energy.

Figure 5.8. Top 3 Sites in Sighthill: Site 5169 (upper); Site 5229 (middle); Site 4817 (bottom).

5.5.1.1.3 Site 4817

The third Site examined is 4817 as shown in Figure 5.8 (bottom) which comprises of 2.2 ha of unconstrained land and is located on the east side of the Ward.

In terms of the policy aspects, only the environmental factor ‘Green corridors’ (1) is present within the Site.

In terms of the technical aspects, overshading plays a significant role due to the large number of trees around the Site. Substation congestion level is moderate but the connection distance to a grid network line if favourable as it runs along the perimeter of the Site.

With these policy and technical aspects at play, the Site possesses 2.2 ha of unconstrained land located on empty space and can generate 940 MWh/y with the potential to supply 127 dwellings with heat energy.

5.5.2 Equal weightings

The biodiversity, developmental and environmental policy aspects and all technical aspects are active and equally weighted for the assessment of VDL sites. The outputs of the assessment revealed that there is 183.2 ha of unconstrained VDL sites available across the city available for PVPS deployment. This amount of land available can generate an energy yield of 75,980 MWh/y, the equivalent of supplying around 7,273 dwellings with heat energy.

It is found that there is a total of 268 out of 766 sites (35%), which are located in 48 out of 115 Wards (42%). The results of this scenario for only those Wards containing areas of opportunity are listed in Table 5.10 in descending order in terms of energy yield. Further information such as combined site area, the output energy, the number of dwellings that can be supplied, and the ratio of dwellings supplied with the total number of inhabited dwellings within the ward is also included.

Table 5.10. Scenario 2 – energy yield from equally weighted unconstrained VDL sites.

Ward	Site area (ha)	Output Energy (MWh/y)	No. of dwellings equivalent	Dwelling coverage within Ward (%)
Garrowhill West	10.4	4,328	331	20.6
Carmyle and Mount Vernon South	10.1	4,210	289	4.6
Darnley East	9.8	4,148	383	8.4
Sighthill	9.5	3,970	538	9.8
Drumoyne and Shieldhall	9.5	3,938	398	4.6
North Barlanark and Easterhouse South	8.4	3,516	389	20.2
Riddrie and Hogganfield	8.0	3,327	294	14.1
Kinning Park and Festival Park	8.0	3,296	523	8.7
Blackhill and Barmulloch East	7.4	3,037	190	6.1
Old Shettleston and Parkhead North	7.3	2,991	299	12.4
Garrowhill East and Swinton	6.6	2,786	319	27.9
Carnwadric West	6.4	2,697	319	12.3
Petershill	6.6	2,694	245	6.1
Dalmarnock	5.8	2,409	212	4.2
Easterhouse East	5.7	2,387	255	33.5
Barlanark	5.3	2,162	233	9.8
Cranhill, Lightburn and Queenslie South	4.8	1,991	130	3.4
Central Easterhouse	4.6	1,891	39	7.2
Craigend and Ruchazie	4.4	1,871	202	6.6
Pollokshaws	3.9	1,605	262	39.7
Craigton	3.7	1,557	120	2.5
Parkhead East and Braidfauld North	3.5	1,428	172	2.2
Baillieston West	3.2	1,319	73	2.1
Roystonhill, Blochairn, and Provanmill	3.2	1,290	139	6.3
Nitshill	3.1	1,289	101	4.2
Govanhill West	2.4	993	119	2.7
Drumchapel South	2.3	922	87	1.8
Baillieston East	2.2	889	57	2.0

Anniesland East	1.9	782	78	1.7
Crookston South	1.9	773	58	5.0
Drumry West	1.8	737	59	3.3
Carntyne	1.6	662	35	1.5
Pollokshields East	1.3	557	40	2.0
Glasgow Harbour and Partick South	1.1	458	8	0.1
Springburn	1.0	377	34	1.1
Laurieston and Tradeston	0.8	328	62	9.5
Ibrox East and Cessnock	0.8	319	28	2.0
Shettleston North	0.8	313	24	0.5
Toryglen and Oatlands	0.8	311	31	0.4
Cardonald South and East	0.8	309	25	0.8
Carmunnock North	0.7	269	13	1.0
Greenfield	0.6	257	22	0.7
Braidfauld	0.5	184	18	1.1
Parkhead West and Barrowfield	0.4	178	6	0.3
Mount Vernon North and Sandyhills	0.3	100	4	0.2
Robroyston and Millerston	0.2	86	6	0.5
Yoker South	0.1	36	3	0.1
Darnley West	0.01	3	0.3	0.01
Total	**183.2**	**75,980**	**7,273**	**-**

As can be seen, the Ward with the highest energy yield is Garrowhill West. With the equal weightings applied, this Ward comprises 10.4 ha of unconstrained land with a potential to generate 4,328 MWh/y. With an average dwelling heat demand of 13.1 MWh/y, the energy generated is equivalent to the heating energy requirement of up to 331 dwellings and covers 20.6% of dwellings within the Ward.

Garrowhill West is situated on the east side of Glasgow and contains 7 VDL sites across the Ward as shown in Figure 5.9.

In relation to policy, the biodiversity aspect covers marginal areas of the Ward which is mostly concentrated in the southwest which is abundant in forestry. Three developmental factors are present: ‘Economic policy areas’ (2) which is active within the Barrachnie community and fully encloses the business park; ‘Housing land supply –

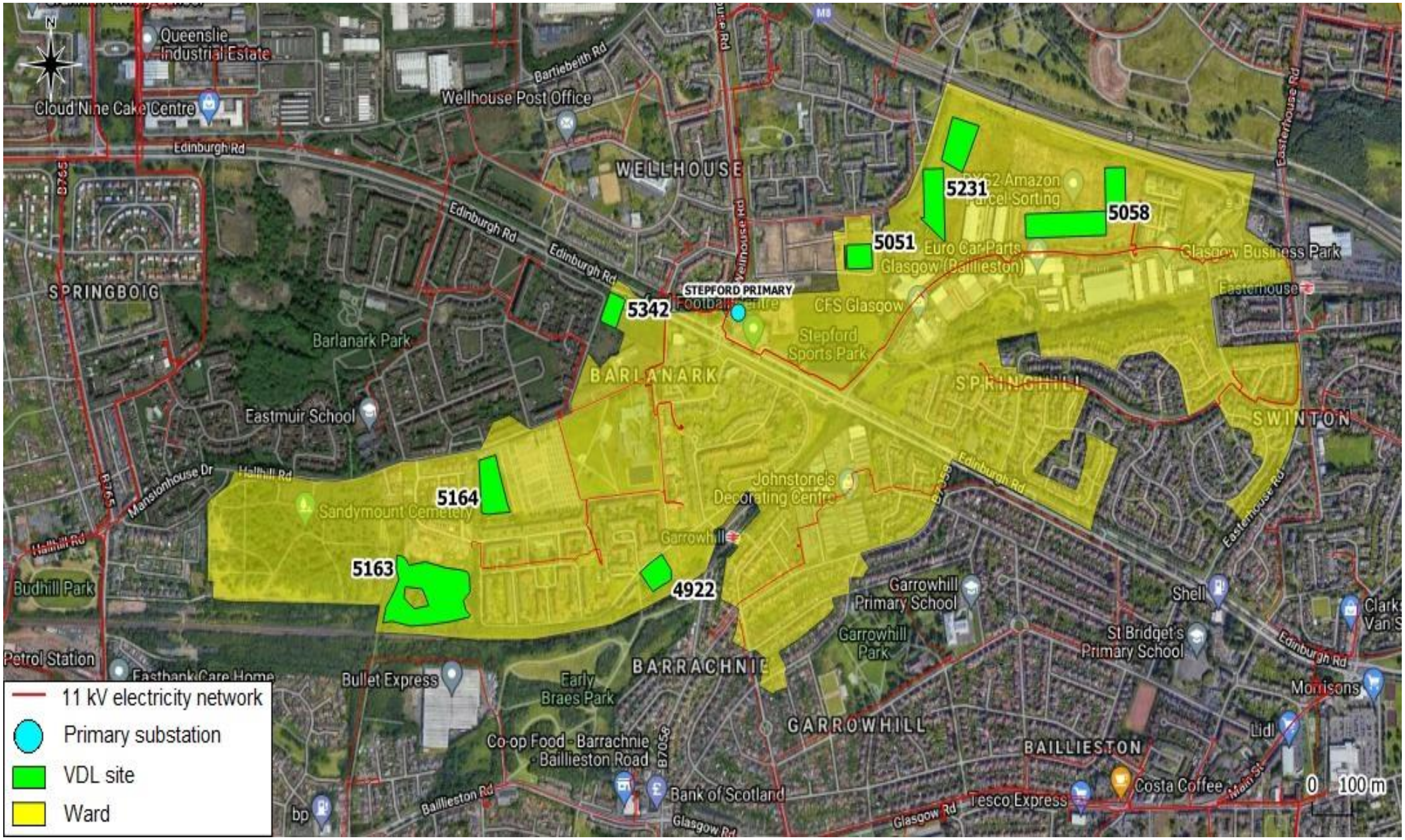


Figure 5.9. The Garrowhill West Ward.

potential' (2) which covers the northern part of the Ward; and 'Industrial-business marketable land supply' (2) which covers Glasgow Business Park in the northeast where most of the engineering industry and commerce trades are based. Much of the VDL is situated here but it receives an intermediate score as the surrounding land can be used for expansion by existing businesses or the construction of new ones. Environmentally, there are two factors which overlap with the VDL sites: 'Sites of importance for nature conservation' (3) and 'Tree Preservation Order' (2). The former is considered sensitive due to the conservation of natural surroundings. However, this only affects the fenced expanse containing trees and shrubbery adjacent to the Garrowhill railway track which crosses the Ward. The latter factor overlaps the Barrachnie community in the south parts where most of the trees are found on the outskirts. The visual impact has some effect on the outcome due to the number of dwellings, particularly the communities of Barrachnie in the south and Springcroft in the east portions of the Ward. Visual intrusion played a role in discounting parts of the VDL based in the north and east parts of the Ward due to the M8 motorway.

In relation to technical, the overshading from buildings would have posed major problem to most areas of the ward as there are a large number of industries and dwellings present. Fortunately, the majority of VDL are located in open areas near the business park to the east and Sandymount Cemetery to the west. There is only one substation to provide access to the grid which is located in the northern part of the Ward – Stepford Primary. The substation congestion level throughout the Ward is favourable as is the substation connection distance with electric lines in close proximity to much of the Ward. There are some terrain issues particularly in terms of broken ground around in the northeast and southwest of the Ward.

5.5.2.1 VDL site analysis

From a deeper analysis with GOMap, this Ward has shown that 7 out of 9 sites (77%) are categorised as being suitable. Details of these sites are listed in Table 5.11 in descending order in terms of the energy yield and the top three sites are shown in Figure 5.10.

Table 5.11. Sites of opportunity in Garrowhill West.

Site No.	Address	Area (ha)	Output energy (MWh/y)	No. of dwellings equivalent
5163	West of Sandaig Road	3.7	1,538	118
5164	223-241 Hallhill Road	3.3	1,381	106
5058	Glasgow Business Park	1.8	765	58
5231	Glasgow Business Park	0.7	275	21
5051	Stepford Road	0.3	131	10
4922	Pendeen Road	0.3	128	10
5342	Edinburgh Road	0.3	110	8
Total	**-**	**10.4**	**4,328**	**331**

5.5.2.1.1 Site 5163

The largest of these sites is Site 5163 as shown in Figure 5.10 (upper) which comprises of 3.7 ha of unconstrained land and is situated in the west part of the Ward.

In terms of the policy aspects, only the biodiversity aspect is present and covers the southern parts of the Site due to the presence of trees which may harbour creature habitats.

For the technical aspects and in terms of overshading, the outer areas and small patches in the central region of the Site are populated with trees. Substation congestion is favourable throughout the Site as is the connection distance with an electric line running perpendicular in the southern area. Terrain issues discounts the northern part of the Site due to broken ground.

With these policy and technical aspects at play, the Site possesses 3.7 ha of unconstrained land located on empty space and can generate 1,538 MWh/y with the potential to supply 118 dwellings with heat energy.

Figure 5.10. Top 3 Sites in Garrowhill West: Site 5163 (upper); Site 5164 (middle); Site 5058 (bottom).

5.4.2.1.2 Site 5164

The second identified Site is 5164 which covers of 3.3 ha of unconstrained land and is situated directly northeast of Site 5163 as shown in Figure 5.10 (middle).

In relation to the policy aspects, there is a risk to potential creature habitats with a column of trees running down the western perimeter of the Site which discounts this vertical section of the VDL.

In relation to the technical aspects, there is risk of overshading due to the column of trees in the western and several trees in southern parts of the Site. Substation congestion is favourable as is the connection distance throughout the Site with an electric line running south.

With these policy and technical aspects at play, the Site possesses 3.3 ha of unconstrained land located on empty space and can generate 1,381 MWh/y with the potential to supply 106 dwellings with heat energy.

5.4.2.1.3 Site 5058

The third Site is 5058 which contains 1.8 ha of unconstrained land and is situated in the central region of the Ward to the northwest of Bishop Loch as shown in Figure 5.10 (bottom).

In terms of the policy aspects, the developmental factor ‘Industrial-business marketable land supply’ (2) is the only policy information present and affects the entire Site.

In terms of the technical aspects, substation congestion and connection distance are both favourable throughout the Site with an electric line running around the perimeter in the east and southern perimeter. However, there are terrain issues in the central regions of the Site which relate to broken ground.

With these policy and technical aspects at play, the Site possesses 1.8 ha of unconstrained land located on empty space and can generate 765 MWh/y with the potential to supply 58 dwellings with heat energy.

5.6 Scenario 3: Technical aspect relaxation facilitated by upgrades to electric and substation network

Scenario 3 is as Scenario 1 but disregards the technical aspects associated with substations under the assumption that resources are made available in future to build new energy infrastructure. Therefore, all policy aspects and the remaining overshading and terrain technical aspects remain active.

5.6.1 Non-equal weightings

Scenario 3 assesses the available VDL of all active policy and technical aspects with weightings applied as shown in Table 5.12. As two technical aspects are relaxed, the weightings are adjusted to reflect the original priorities of the remaining active technical aspects.

Table 5.12. Scenario 3 with non-equal weightings.

Policy aspect	Weightings
Biodiversity	0.326
Developmental	0.114
Environmental	0.326
Visual impact	0.148
Visual intrusion	0.086
Technical aspect	**Weightings**
Overshading	0.750
Substation congestion	-
Substation connection distance	-
Terrain	0.250

The outputs of the assessment revealed that there is 305.8 ha of unconstrained VDL sites available across the city available for PVPS deployment. This amount of land available can generate an energy yield of 127,679 MWh/y, the equivalent of supplying around 11,740 dwellings with heat energy.

It is found that there is a total of 367 out of 766 sites (48%), which are located in 59 out of 115 Wards (51%). The results of this scenario for only those Wards containing areas of opportunity are listed in Table 5.13 in descending order in terms of energy yield. Further information such as combined site area, the output energy, the number of dwellings that can be supplied, and the ratio of dwellings supplied with the total number of inhabited dwellings within the ward is also included.

The Ward with the highest energy yield is Drumoyne and Shieldhall. With the weightings applied, this Ward comprises 15.5 ha of unconstrained land with a potential to generate 6,471 MWh/y. With an average dwelling heat demand of 9.9 MWh/y, the energy generated is equivalent to the heating energy requirement of up to 654 dwellings and covers 7.6% of dwellings within the Ward.

Table 5.13. Scenario 3 – energy yield from non-equally weighted unconstrained VDL sites.

Ward	Site area (ha)	Output Energy (MWh/y)	No. of dwellings equivalent	Dwelling coverage within Ward (%)
Drumoyne and Shieldhall	15.5	6,471	654	7.6
Toryglen and Oatlands	15.2	6,358	628	8.0
North Barlanark and Easterhouse South	14.9	6,249	691	35.8
Parkhead East and Braidfauld North	14.9	6,183	744	9.6
Maryhill East	13.9	5,832	577	17.8
Garrowhill West	13.0	5,462	417	25.9
Ruchill	12.5	5,280	517	6.8
Riddrie and Hogganfield	12.5	5,245	464	22.3
Carmyle and Mount Vernon South	11.4	4,790	329	5.3
Darnley East	11.2	4,721	436	9.6
Keppochhill	11.0	4,576	88	4.5
Garrowhill East and Swinton	9.7	4,072	467	40.8
Blackhill and Barmulloch East	9.5	4,033	252	8.0
Pollokshaws	9.6	4,012	656	99.2
Woodside	8.6	3,625	255	10.1
Easterhouse East	8.5	3,570	381	50.1
Barlanark	8.5	3,532	381	16.1

Castlemilk	7.5	3,137	141	1.9
Cranhill, Lightburn and Queenslie South	7.3	3,030	198	5.1
Glenwood North	6.6	2,781	244	12.8
Dalmarnock	6.3	2,631	232	4.6
Central Easterhouse	6.3	2,590	54	9.8
Anniesland East	5.3	2,154	216	4.8
Old Shettleston and Parkhead North	5.1	2,073	207	8.6
Nitshill	4.9	2,027	159	6.7
Craigend and Ruchazie	4.6	1,941	210	6.9
Sighthill	4.5	1,865	252	4.6
Drumchapel South	4.1	1,696	159	3.2
Craigton	4.1	1,691	130	2.7
Springburn	3.2	1,280	117	3.6
Crookston South	2.9	1,237	94	8.0
Parkhead West and Barrowfield	2.9	1,218	43	2.1
Possil Park	2.9	1,198	99	3.8
Baillieston West	2.7	1,104	61	1.8
Baillieston East	2.6	1,092	69	2.4
Petershill	0.7	284	18	0.4
Calton, Galllowgate and Bridgeton	2.5	1,024	298	5.1
Drumchapel North	1.8	768	83	13.2
Wyndford	1.7	685	46	15.8
Yoker South	1.6	678	62	1.2
Drumry West	1.5	635	51	2.9
Greenfield	1.4	589	50	1.6
Maryhill West	1.4	563	87	4.1
Carnwadric West	1.1	469	55	2.1
Kinning Park and Festival Park	1.2	467	74	1.2
Kelvindale	0.9	377	23	0.7
Roystonhill, Blochairn, and Provanmill	0.8	336	36	1.6
Milton West	0.8	319	27	2.9
Govanhill West	0.7	292	35	0.8
Hillhead	0.6	244	26	0.3
Kelvinside and Jordanhill	0.6	228	14	0.2
Carntyne	0.6	228	12	0.5

Braidfauld	0.5	184	18	1.1
Glasgow Harbour and Partick South	0.4	139	2	0.0
Darnley West	0.3	109	11	0.4
Milton East	0.3	106	14	2.4
Laurieston and Tradeston	0.2	77	15	2.2
Shettleston North	0.2	68	5	0.1
City Centre East	0.2	54	54	0.6
Total	**305.8**	**127,679**	**11,740**	**-**

Drumoyne and Shieldhall is situated on the west side of Glasgow and as shown in Figure 5.11 contains 15 VDL sites mostly in the central region of the Ward.

In relation to policy, three developmental factors with a weighting of 0.114 are present: ‘Economic policy areas’ (2) which covers the north part of the Ward close the Queen Elizabeth University Hospital; ‘Strategic development framework – river’ (2) affects the north region of the Ward due to the VDL being near to the Glasgow City Heliport located adjacent to the River Clyde; and ‘Strategic development framework’ (2) which overlaps almost half of the entire Ward and focuses on the centre and east regions. Environmentally, only the ‘Green corridors’ (1) affects a small number of VDL in the southeast portion of the Ward. This is due to the Ward being situated in the inner city where there is often a lack of available space for any kind of project deployment or expansion unless existing infrastructure is decommissioned. Although the coverage is small, it bears significance due to its high weighting of 0.326. Socially, there are many dwellings located in the Elder Park community in the east and, with a weighting of 0.148, will impact the VDL based in the central and eastern region. Visual intrusion covers the entire Ward and all sites within due to flying routes flown by helicopters which take off and land from the helipads based near the River Clyde and atop the Queen Elizabeth University Hospital. However, this aspect has the lowest weighting of 0.086, and therefore, other aspects overlapping the same area would take higher priority.

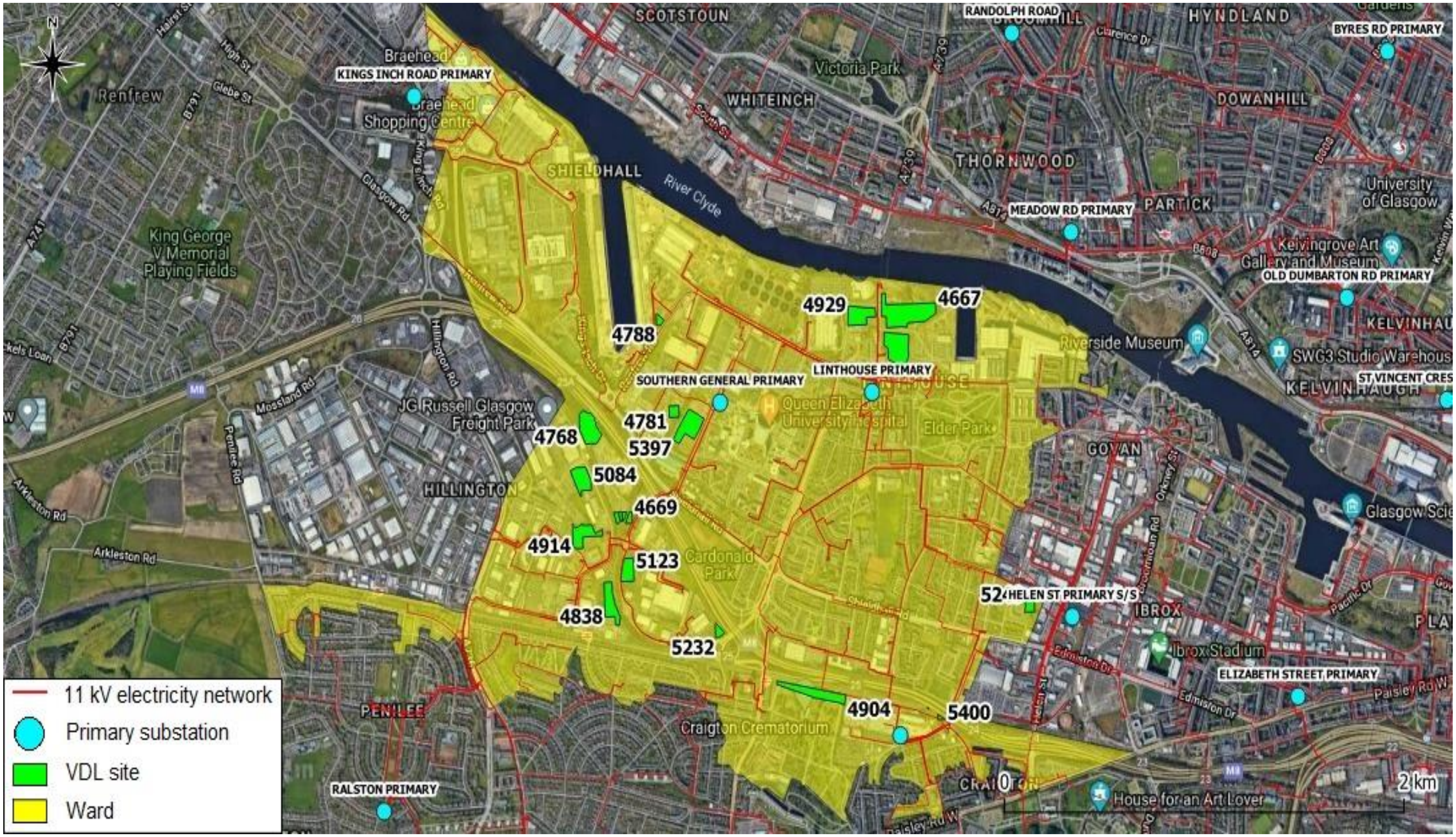


Figure 5.11. The Drumoyne and Shieldhall Ward.

In relation to technical issues, as the Ward is in the inner city, it has ample tall structures and dwellings with little open space. Most of the VDLs are affected by the overshading aspect which are discounted due to its high weighting of 0.750 and only a handful of Sites are untouched located in the northern part of the Ward. As the northern parts of the Ward are adjacent to the River Clyde, there are possible flood risks that could affect parts of the VDL due to unsuitable terrain. Although this aspect has a low weighting of 0.250, it influences large areas in the north where overshading has no bearing.

5.6.1.1 VDL site analysis

From a deeper analysis with GOMap, this Ward has shown that 15 out of 25 sites (60%) are categorised as being suitable. Details of these sites are listed in Table 5.14 in descending order in terms of the energy yield and the top three sites are shown in Figure 5.12.

Table 5.14. Sites of opportunity in Drumoyne and Shieldhall.

Site No.	Address	Area (ha)	Output energy (MWh/y)	No. of dwellings equivalent
4667	East of Holmfauld Rd	5.6	2,376	240
5397	110-140 Hardgate Rd	1.8	743	75
4929	West of Holmfauld Rd	1.7	710	72
4768	Bogmoor Road	1.3	520	53
4904	Berryknowes Road	1.1	445	45
4914	North of Hepburn Rd	0.8	349	35
4838	22 Chirnside Drive	0.8	345	35
5084	North of Hillington Rd	0.8	337	34
5123	Fifty Pitches Road	0.6	242	24
4781	125-187 Bogmoor Rd	0.3	106	11
5249	Arthurlie Street	0.2	94	10
4669	West of Fifty Pitches	0.2	72	7
5232	140 Fifty Pitches Road	0.2	64	6
4788	341 Renfrew Road	0.1	50	5
5400	Barfillan Drive	0.1	19	2
Total	**-**	**15.5**	**6,471**	**654**

Figure 5.12. Top 3 Sites in Drumoyne and Shieldhall: Site 4667 (upper); Site 5397 (middle); Site 4929 (bottom).

5.6.1.1.1 Site 4667

The largest of these sites is Site 4667 as shown in Figure 5.12 (upper) which covers of 5.6 ha of unconstrained land and is located in the north of the Ward close to the River Clyde.

In terms of policy aspects, four developmental factors affect the Site: ‘Economic policy areas’ (2) and ‘Industrial-business marketable land supply’ (2) due to their close proximity to businesses and industry; and ‘Strategic development framework’ (2) and its river counterpart due to large parts of the site lying adjacent to the River Clyde. As the visual intrusion aspect affects the whole Ward, this site is also under its influence.

In terms of technical aspects, the overshading aspect has a minor effect on the Site due specifically to the majority of buildings and outbuildings located away from the Site. Substation congestion is favourable but the major technical aspect that eliminates much of the available land at this Site is the substation connection distance as the closest 11 kV electric line only travels along the west part of the Site. Much of the east part of the Site is situated too far from an electricity line and is classed as being unlikely.

With these policy and technical aspects at play, the Site possesses 5.6 ha of unconstrained land located on empty space and can generate 2,376 MWh/y with the potential to supply 240 dwellings with heat energy.

5.6.1.1.2 Site 5397

The second identified Site is 5397 as shown in Figure 5.12 (middle) which contains of 1.8 ha of unconstrained land and is situated to the west of Sighthill Cemetery in the northwest of the Ward.

In terms of policy aspects, the Site is affected by two developmental factors: ‘Economic policy areas’ (2) and ‘Strategic development framework’ (2) due to the Site’s central location within an industrial complex. There are visual intrusion issues as it is close to the Queen Elizabeth University Hospital and the M8 motorway running to the west and south of the Site.

Technically, overshading plays a significant role due to the large number of trees around the Site. Substation congestion is favourable throughout the Site as is the connection distance with an electric line running around along most of the perimeter of the Site.

With these policy and technical aspects at play, the Site possesses 1.8 ha of unconstrained land located on empty space and can generate 743 MWh/y with the potential to supply 75 dwellings with heat energy.

5.6.1.1.3 Site 4929

The third Site examined is 4929 as shown in Figure 5.12 (bottom) which comprises of 1.7 ha of unconstrained land and is located on the east side of the Ward.

In relation to the policy aspects, it is similar to Site 4667 where the same developmental factors apply: ‘Economic policy areas’ (2), ‘Industrial-business marketable land supply’ (2), ‘Strategic development framework’ (2) and ‘Strategic development framework – river’ (2). The visual intrusion aspect also applies due to the heliport.

In relation to the technical aspects, the Site is remote from tall buildings and thus avoids overshading. In terms of substation congestion and connection distance, these are both considered favourable as the Site is near to the Linthouse Primary Substation with several electric network lines available close to the Site. Although it is close to the River Clyde, there is reduced risk of flooding due to mitigation measures put in place to protect the heliport which resides nearby.

With these policy and technical aspects at play, the Site possesses 1.7 ha of unconstrained land located on empty space and can generate 710 MWh/y with the potential to supply 72 dwellings with heat energy.

5.6.2 Equal weightings

All policy aspects and the overshading and terrain technical aspects are active and equally weighted for the assessment of VDL sites. The outputs of the assessment revealed that there is 508.9 ha of unconstrained VDL sites available across the city available for PVPS deployment. This amount of land available can generate an energy yield of 213,006 MWh/y, the equivalent of supplying around 19,615 dwellings with heat energy.

It is found that there is a total of 354 out of 766 sites (46%), which are located in 57 out of 115 Wards (50%). The results of this scenario for only those Wards containing areas of opportunity are listed in Table 5.15 in descending order in terms of energy yield. Further information such as combined site area, the output energy, the number of dwellings that can be supplied, and the ratio of dwellings supplied with the total number of inhabited dwellings within the ward is also included.

As can be seen, the Ward with the highest energy yield is Riddrie and Hogganfield. With the equal weightings applied, this Ward comprises 43.6 ha of unconstrained land with a potential to generate 18,303 MWh/y. With an average dwelling heat demand of 11.3 MWh/y, the energy generated is equivalent to the heating energy requirement of up to 1,619 dwellings and covers 77.7% of dwellings within the Ward.

Table 5.15. Scenario 3 – energy yield from equally weighted unconstrained VDL sites.

Ward	Site area (ha)	Output Energy (MWh/y)	No. of dwellings equivalent	Dwelling coverage within Ward (%)
Riddrie and Hogganfield	43.6	18,303	1,619	77.7
Darnley East	42.4	17,915	1,653	36.4
Carmyle and Mount Vernon South	41.8	17,492	1,201	19.2
North Barlanark and Easterhouse South	38.3	16,086	1,780	92.2
Garrowhill East and Swinton	37.3	15,661	1,795	156.9
Blackhill and Barmulloch East	36.4	15,403	962	30.7
Petershill	26.2	11,015	1,000	24.8
Sighthill	17.4	7,239	980	17.9
Toryglen and Oatlands	15.2	6,358	628	8.0
Parkhead East and Braidfauld North	14.8	6,129	738	9.5
Maryhill East	14.3	5,960	590	18.2
Drumoyne and Shieldhall	13.7	5,701	576	6.7
Garrowhill West	13.0	5,462	417	25.9
Ruchill	12.5	5,280	517	6.8
Keppochhill	11.0	4,576	88	4.5
Pollokshaws	9.6	4,012	656	99.2

Woodside	8.6	3,625	255	10.1
Easterhouse East	8.5	3,570	381	50.1
Barlanark	8.5	3,532	381	16.1
Castlemilk	7.3	3,034	137	1.9
Cranhill, Lightburn and Queenslie South	7.3	3,030	198	5.1
Glenwood North	6.6	2,781	244	12.8
Dalmarnock	6.3	2,631	232	4.6
Central Easterhouse	6.3	2,590	54	9.8
Anniesland East	5.2	2,131	213	4.8
Old Shettleston and Parkhead North	5.1	2,073	207	8.6
Nitshill	4.9	2,027	159	6.7
Craigend and Ruchazie	4.6	1,941	210	6.9
Craigton	4.1	1,691	130	2.7
Springburn	3.2	1,280	117	3.6
Parkhead West and Barrowfield	2.9	1,218	43	2.1
Possil Park	2.9	1,198	99	3.8
Baillieston West	2.7	1,104	61	1.8
Baillieston East	2.6	1,092	69	2.4
Crookston South	2.6	1,090	82	7.1
Calton, Galllowgate and Bridgeton	2.5	1,024	298	5.1
Maryhill West	2.5	1,024	159	7.5
Drumchapel South	2.0	854	80	1.6
Wyndford	1.7	685	46	15.8
Yoker South	1.6	675	62	1.2
Greenfield	1.4	589	50	1.6
Drumchapel North	1.2	501	54	8.6
Carnwadric West	1.1	469	55	2.1
Roystonhill, Blochairn, and Provanmill	1.0	405	44	2.0
Kelvindale	0.9	377	23	0.7
Kinning Park and Festival Park	0.9	332	53	0.9
Milton West	0.8	319	27	2.9
Govanhill West	0.7	292	35	0.8
Carntyne	0.6	250	13	0.6
Kelvinside and Jordanhill	0.6	228	14	0.2
Braidfauld	0.5	184	18	1.1

Drumry West	0.4	152	12	0.7
Darnley West	0.3	109	11	0.4
Milton East	0.3	106	14	2.4
Laurieston and Tradeston	0.2	77	15	2.2
Shettleston North	0.2	68	5	0.1
City Centre East	0.2	54	54	0.6
Total	**508.9**	**213,006**	**19,615**	**-**

Riddrie and Hogganfield is situated in the northeast of Glasgow and contains 13 VDL sites across the Ward as shown in Figure 5.13.

In terms of the policy aspects, the biodiversity aspect affects most of the central and northern regions of the Ward due to large amounts of woodland. There are six developmental aspects influencing the Ward: ‘Strategic economic investment locations’ (1) features predominantly in the western region where there are large open fields; ‘Green belt’ (2) which affects a small part of the VDL in the north of the Ward; ‘Green network opportunity areas’ (2) which crosses a small portion of the VDL in the field close to a large park; ‘Housing land supply – potential’ (2) which overlaps the sites near communities to the east and southwest; ‘Network of centres’ (2) which traverses a small field in the central region; and ‘Housing land supply – consented’ (3) which focuses in the northeast with large areas of open space. Unfortunately for the VDL situated here, it was immediately discounted. Two environmental factors are present: ‘Sites of importance for nature conservation’ (3) which overlaps the VDL in the east in the fields abundant in trees; and ‘Sites of special landscape importance’ (3) which covers the surrounding natural areas where the Wallace Monument is located. The visual impact aspect had a minor effect on discounting small portions of VDL in the narrow parts of the Ward, specifically in the central region. The visual intrusion had a significant affect particularly in the central and southern regions where the M8 motorway ran south.

Technically, the overshading factor played an insignificant role due to most of sites located in open fields away from tall buildings and trees. There are terrain issues in terms of broken ground particularly in the central and northern regions of the Ward.

Figure 5.13. The Riddrie and Hogganfield Ward.

5.6.2.1 VDL site analysis

From a deeper analysis with GOMap, this Ward has shown that that 13 out of 15 sites (87%) are categorised as being suitable. Details of these sites are listed in Table 5.16 in descending order in terms of the energy yield and the top three sites are shown in Figure 5.14.

Table 5.16. Sites of opportunity in Riddrie and Hogganfield.

Site No.	Address	Area (ha)	Output energy (MWh/y)	No. of dwellings equivalent
4773	Robroyston Business Park	19.9	8,404	744
5160	South of M80	13.5	5,675	502
5033	West of Station Road	4.2	1,785	158
4857	West of 90 Station Road	1.8	715	63
5207	Rear 1545-1557 Cumbernauld Road	1.3	553	49
4671	Robroyston Road	0.6	254	22
5301	Saughs Road	0.6	248	22
5040	Cumbernauld Road	0.6	238	21
5294	Robroyston Road	0.5	206	18
4856	1553 Cumbernauld Road	0.2	92	8
5289	Craigendmuir Street	0.2	68	6
5288	Craighead Avenue	0.2	63	6
4728	Robroyston Road	0.01	4	0.3
Total	**-**	**43.6**	**18,303**	**1,619**

5.6.2.1.1 Site 4773

The largest of these sites is Site 4773 as shown in Figure 5.14 (upper) comprising of 19.9 ha of unconstrained land and is situated in the west part of the Ward.

In terms of the policy aspects, the biodiversity aspect covers the southern parts of the Site due to the presence of woodland which may contain creature habitats. Three developmental factors overlap the Site: ‘Strategic economic investment locations’ (1) which covers the majority of the Ward; ‘Green network opportunity areas’ (2) and ‘Network of centres´ (2) both of which influences the north and southern parts of the Site. The visual intrusion aspect also affects the rightmost edges of the Site due to its location adjacent to the M80.

Figure 5.14. Top 3 Sites in Riddrie and Hogganfield: Site 4773 (upper); Site 5160 (middle); Site 5033 (bottom).

For the technical aspects and in terms of overshading, the outer areas and small patches in the central region of the Site are populated with trees. Terrain issues discounts the central part of the Site due to broken ground.

With these policy and technical aspects at play, the Site possesses 19.9 ha of unconstrained land located on empty space and can generate 8,404 MWh/y with the potential to supply 744 dwellings with heat energy.

5.6.2.1.2 Site 5160

The second identified Site is 5160 which covers of 13.5 ha of unconstrained land and is situated directly east of Site 4773 as shown in Figure 5.14 (middle).

In relation to the policy aspects, there is a risk to potential creature habitats with a grove of trees in the southwest of the Site. One environmental factor affects the natural woodlands of the Site: ‘Sites of importance for nature conservation’ (3). Similar to Site 4773, the visual intrusion aspect affects the leftmost edges of the Site due to the M80.

In relation to the technical aspects, there is risk of overshading due to the number of trees around parts of the perimeter and to the south of the Site.

With these policy and technical aspects at play, the Site possesses 13.5 ha of unconstrained land located on empty space and can generate 5,675 MWh/y with the potential to supply 502 dwellings with heat energy.

5.6.2.1.3 Site 5033

The third Site is 5033 which contains 4.2 ha of unconstrained land and is situated in the east of the Ward as shown in Figure 5.14 (bottom).

In terms of the policy aspects, the biodiversity aspect covers the entire Site due to the large presence of woodland which may contain creature habitats. Two developmental factors affect the Site, both of which concerns new build housing: ‘Housing land supply – potential’ (2) and ‘Housing land supply – consented’ (3), the latter of which discounts the northern part of the Site. One environmental factor overlaps the Site: ‘Sites of importance for nature conservation’ (3) due to the woodlands. With the lack of natural screening in some places, there is visual impact on the eastern parts of the Site from the nearby community.

For the technical aspects and in terms of overshading, the central region of the Site is mostly open space and free from the risks posed by the local trees. Terrain issues discounts the northwest and western part of the Site due to broken ground.

With these policy and technical aspects at play, the Site possesses 4.2 ha of unconstrained land located on empty space and can generate 1,785 MWh/y with the potential to supply 158 dwellings with heat energy.

5.7 Scenario 4: Identification of new unconstrained sites for PVPS deployment via screening process

The previous scenarios identified unconstrained land specifically for VDL sites. Scenario 4 now applies a city-wide approach in order to identify additional areas of unconstrained land not designated VDL throughout Glasgow that can be utilised for PVPS deployment. Certain conditions are set in order to identify ideal sites - such as comprising at least 1 ha of unconstrained land, requiring minimal clearing, located away from buildings and public roads, away from public areas to avoid risk of vandalism, and away from creature habitats to avoid damage by animals. The same weightings used in Scenario 1 are used here shown in Table 5.17. After satisfying these conditions, a site was identified based in Patersons of Greenoakhill quarry that lies adjacent to the M74 motorway based in Carmyle and Mount Vernon South as shown in Figures 5.15 and 5.16.

Table 5.17. Scenario 4 with non-equal weightings.

Policy aspect	Weightings
Biodiversity	0.326
Developmental	0.114
Environmental	0.326
Visual impact	0.148
Visual intrusion	0.086
Technical aspect	**Weightings**
Overshading	0.484
Substation congestion	0.168
Substation connection distance	0.231
Terrain	0.117

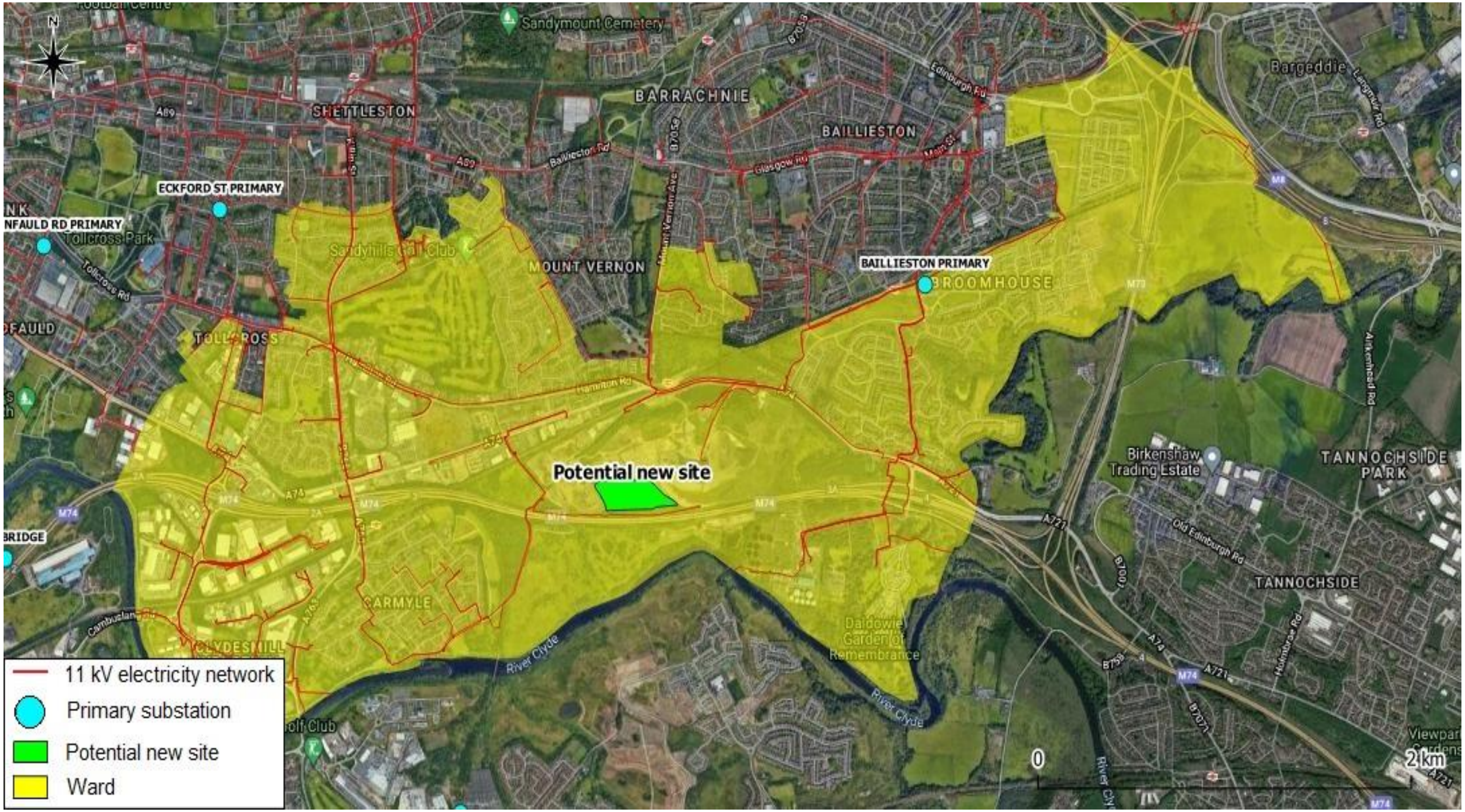


Figure 5.15. The Carmyle and Mount Vernon South Ward.

Figure 5.16. Potential new land site in the Carmyle and Mount Vernon South Ward.

The site lies adjacent to the M74 motorway in a quarry where there is road access nearby and a row of trees between the site and the motorway. These trees can help screen any visual intrusion affecting drivers. The outputs of the assessment are shown in Table 5.18 and identified 5.5 ha of available unconstrained land for PVPS deployment. This amount of land can give an energy yield of 2,342 MWh/y. With an average dwelling heat demand of 14.6 MWh/y, the energy generated is the equivalent of supplying around 161 dwellings with heat energy and covers 2.6% of dwellings within the Ward.

Table 5.18. Scenario 4 results.

Ward	Site area (ha)	Output Energy (MWh/y)	No. of dwellings equivalent	Dwelling coverage within Ward (%)
Carmyle and Mount Vernon South	5.5	2,342	161	2.6

In relation to policy, there are two intermediate developmental factors that affects the Site. The first is ‘Economic policy areas’ (2), which affects a small portion west of the Site due to a number of industries; the second is ‘Green belt’ (2), which affects the remainder of the Site due to land situated immediately to the east containing large empty fields. Visual intrusion is present and affects the bottom half portion of the Site due to the M8 motorway.

Technically, there is no overshading as the Site is not near any buildings, neither is there any substation congestion nor terrain problems. The only technical issue is the connection distance to the nearest 11 kV electricity line, which runs along the Site parallel to the M74. Although the bottom portion of the Site is at a favourable distance, the top portion is slightly too distant. However, this is superseded by the overshading aspect possessing a higher weighting.

The site comprises 5.5 ha of empty space that is suitable for PVPS deployment. The potential energy yield was calculated at 2,342 MWh/y, can supply heat energy to up to 161 local dwellings.

5.8 Scenario 5: EV charging points in multi-story car parks

The previous scenarios explored the deployment of PVPS on unconstrained land dispersed around the city of Glasgow. This scenario explores the deployment of PVPS on multi-story car park canopies for the purpose of charging EVs. In the UK, the average EV energy consumption is within the range of 0.10 kWh/km and 0.20 kWh/km (Al-Wreikat *et al* 2022, Al-Wreikat *et al* 2021, Raugei *et al* 2018). The average annual distance travelled per car in the UK is within the range of 9,500 km and 15,000 km (Raugei *et al* 2021, Logan *et al* 2020, Brunert 2019). Taking the average of both ranges equates to an energy consumption of 0.15 kWh/km at a distance of 12,250 km which results in an average annual EV electrical consumption of 1,838 kWh/y.

This scenario assumes that it may be more common in the future for car parks to provide a recharge service to EVs by providing energy collected from PV arrays when connected to the electricity network instead of local battery storage to ensure that there is always an available supply. This scenario examines 8 multi-story car parks in Glasgow as shown in Table 5.19.

Table 5.19. Multi-story car parks in Glasgow city centre.

Car park	Postcode	No. of parking spaces	Area (ha)
SEC	G3 8YW	1600	0.90
Duke Street	G4 0UW	1170	0.38
Concert Square	G4 0LH	698	0.36
Charing Cross	G2 4PR	433	0.18
Cambridge Street	G3 6RU	812	0.17
Cadogan Square	G2 7PA	325	0.07
Dundasvale	G4 0HY	460	0.05
NCP	G1 1XQ	274	0.03
Total	**-**	**5,772**	**2.14**

Figure 5.17 shows the 8 multi-story car parks in the city centre with their names in blue. Substation locations and the 11 kV electric network are also shown for context.

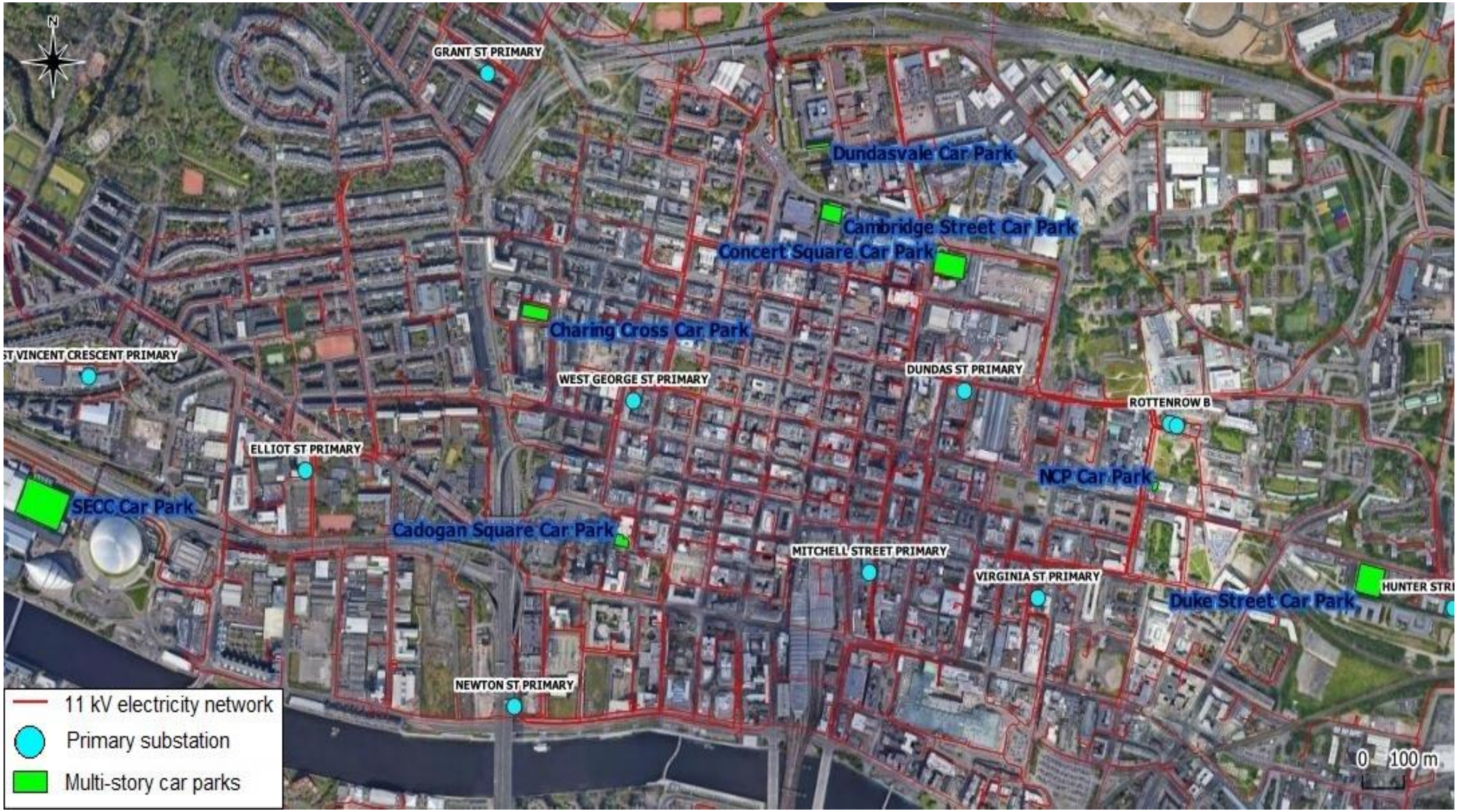


Figure 5.17. The 8 multi-story car parks in Glasgow city centre.

Before the land use assessment was conducted, each policy and technical aspect was scrutinised to determine if they held any impact on the car parks. In terms of the policy aspects, the biodiversity aspect is considered negligible as no animal habitats should exist on the car park canopies. Since the car parks are existing structures, the developmental and environmental aspects have no influence and are therefore not active. The visual impact aspect is active but since the PV arrays are installed on the car park roof they are unlikely to be overlooked from nearby dwellings. The visual intrusion aspect is included since it may impact on a pilot's visual line of sight.

In terms of the technical aspects, the overshading aspect requires updating as the previous information concerned shading on VDL sites on the ground. For this scenario, the focus is on multi-story car park canopies and any shading affecting these areas are likely to originate from surrounding tall structures such as trees or buildings. Similar to the method described in Section 3.2.2.2.1 in calculating the overshading, height data is obtained from a DSM from Ordnance Survey for the car parks and all surrounding tall structures within a 100 m radius (Ordnance Survey - OS Terrain 2021). The difference in height between the tall structures and the car parks is calculated and the structures with a higher height value than the car park are used for the next step, all other heights are ignored as the shadows created by the shorter structures would not affect the taller canopies. The height difference of all remaining structures in conjunction with hourly solar elevation angles for the spring and autumn equinoxes; and the summer and winter solstices are used to calculate the shadows which are superimposed to give a reasonable, composite annual overshading footprint as shown in Figure 5.18. The substation congestion aspect plays an important role as it affects the availability of connection to the electric grid network within the city centre as does the substation connection distance aspect in terms of reducing the risk of installing new transmission lines. Both these aspects are included. However. the terrain aspect has no influence on the car park canopies and is therefore not included.

Given these considerations, only two policy aspects, ‘Visual impact’ and ‘Visual intrusion’, and three technical aspects, ‘Overshading’, ‘Substation congestion’ and ‘Substation connection distance’ are included and weighted as shown in Table 5.20. The weightings are adjusted to reflect the original priorities of the remaining active

Figure 5.18. Overshading influence on multi-story car parks.

aspects with the visual impact and visual intrusion aspects weighted at 0.667 and 0.333 respectively. Similarly, the overshading, substation congestion and substation connection distance aspects are weighted at 0.589, 0.159 and 0.252 respectively.

Table 5.20. Scenario 5 with non-equal weightings.

Policy aspect	Weightings
Biodiversity	-
Developmental	-
Environmental	-
Visual impact	0.667
Visual intrusion	0.333
Technical aspect	**Weightings**
Overshading	0.589
Substation congestion	0.159
Substation connection distance	0.252
Terrain	-

The assessment output revealed only 3 of the 8 multi-story car parks are suitable for PVPS deployment with 1.46 ha of available canopy area and can provide an energy yield of 572 MWh/y, the equivalent of satisfying the charging requirements of 311 EVs.

Table 5.21 shows the 3 multi-story car parks listed in descending order in terms of their energy yield.

Table 5.21. Statistical summary of opportunities for multi-story car parks.

Car park	Postcode	No. of parking spaces	Area (ha)	Output energy (MWh/y)	No. of EVs equivalent
SEC	G3 8YW	1600	0.72	287	156
Duke Street	G4 0UW	1170	0.38	145	79
Concert Square	G4 0LH	698	0.36	139	76
Total	**-**	**3,468**	**1.46**	**572**	**311**

It is found that the multi-story car park with the largest canopy area is the SEC car park which, although it had an original area of 0.9 ha, there was overshading by nearby structures affecting the southern portion of the canopy. This shade reduces the overall area to 0.72 ha which can potentially produce 287 MWh/y. This canopy area is almost double the area of the next largest car park located in Duke Street, which has an area of 0.38 ha and can produce 145 MWh/y.

The car park with the smallest area is located in Concert Square which has a canopy area of 0.36 ha and is capable of producing 139 MWh/y. If all canopies are utilised for PVPS, the possible energy produced from a combined area of 1.46 ha can generate 572 MWh/y and supply up to 311 EVs.

5.9 Scenario 6: Identification of new unconstrained sites for new build homes to tackle Glasgow’s homeless issue

This scenario employs GOMap to identify unconstrained VDL sites suitable for residential house building as a way to address the city’s homeless problem. In 2018-19, for example, Glasgow had 17.8 dwellings per hectare (National Records of Scotland 2018) and received 36,465 homeless applications (Shelter Scotland 2019).

Several aspects are relaxed in this scenario: the visual intrusion policy aspect and the overshading technical aspects are relaxed as these are specific to PVPS technology which is not examined here; the remaining substation congestion, substation connection distance and terrain aspects are also relaxed assuming housing developments would involve geotechnical methods in creating solid foundation for dwellings and the installation of new electric cables along with other necessary works. Therefore, only four policy aspects are weighted accordingly as shown in Table 5.22. The biodiversity and environmental aspects ensure housing developments do not entrench over protected areas; the developmental aspect highlights potential areas where new build housing could benefit the local economy; and the visual impact to discount areas where major housing projects could not only be considered unappealing to local residents but residents may also be unsupportive particularly if the developed area could instead be used for recreational areas for the betterment of the community (Doberstein 2020).

Although this scenario uses existing policy information originally targeted for PVPS deployment and a basic footprint of 17.8 dwellings per hectare, it demonstrates how the GOMap tool could be used to determine ideal sites for other developmental projects including new build housing where the assessment could be improved by importing policy and technical information relevant to the project such as comprehensive dimensions for the new dwellings or estates, soil suitability for the areas of interest, connection points to the mains water supply etc (Thomson & Hardin 2000).

Table 5.22. Scenario 6 with non-equal weightings.

Policy aspect	Weightings
Biodiversity	0.371
Developmental	0.107
Environmental	0.371
Visual impact	0.151
Visual intrusion	-
Technical aspect	**Weightings**
Overshading	-
Substation congestion	-
Substation connection distance	-
Terrain	-

The GOMap results indicate that there is a total of 154 out of 766 sites (20%), located in 47 out of 115 Wards (41%). Table 5.23 list the results per Ward in descending order.

Table 5.23. Unconstrained VDL for house building.

Ward	Postcode	Area (ha)	No. of new-build houses
Sighthill	G21 2	9.0	161
Garrowhill West	G33 4	6.3	112
Blackhill and Barmulloch East	G33 1	5.7	102
Drumoyne and Shieldhall	G51 4	5.3	93
Maryhill East	G22 6	5.1	91
Carnwadric West	G46 7	4.6	81
Cranhill, Lightburn and Queenslie South	G33 2	4.4	78
Petershill	G21 1	4.2	75

Yoker South	G13 4	3.9	69
Kinning Park and Festival Park	G41 1	3.5	62
Springburn	G21 1	3.3	59
Govanhill West	G42 8	3.0	53
Old Shettleston and Parkhead North	G33 2	2.5	45
Barlanark	G33 3	2.5	44
Calton, Galllowgate and Bridgeton	G1 2	2.2	39
Toryglen and Oatlands	G5 0	2.1	37
Glasgow Harbour and Partick South	G11 7	2.1	37
Baillieston West	G69 7	2.1	37
Anniesland East	G13 1	1.6	28
Riddrie and Hogganfield	G33 1	1.4	25
Darnley West	G53 7	1.3	23
Roystonhill, Blochairn, and Provanmill	G31 2	1.2	21
Pollokshields East	G41 4	1.1	19
North Barlanark and Easterhouse South	G33 5	0.9	16
Hillhead	G11 6	0.9	16
Baillieston East	G69 6	0.9	15
Craigton	G52 1	0.8	14
Parkhead East and Braidfauld North	G31 1	0.7	12
Keppochhill	G22 6	0.6	11
Parkhead West and Barrowfield	G31 1	0.5	9
Drumchapel North	G61 4	0.4	7
Laurieston and Tradeston	G41 1	0.4	7
Maryhill West	G20 0	0.3	6
Drumchapel South	G15 6	0.3	6
Whiteinch	G14 9	0.3	6
Kelvinside and Jordanhill	G13 1	0.3	5
Drumry West	G81 2	0.3	5
Carntyne	G33 2	0.3	5
Crookston South	G53 6	0.3	4
Craigend and Ruchazie	G33 3	0.2	4
Gorbals and Hutchesontown	G5 9	0.2	4
Finnieston and Kelvinhaugh	G3 8	0.2	3
Garrowhill East and Swinton	G34 0	0.1	2
Shettleston North	G32 7	0.1	2
Carntyne West and Haghill	G31 1	0.1	1
Carmunnock North	G44 5	0.03	1
Darnley East	G43 1	0.03	1
Total	**-**	**87.3**	**1,554**

The Ward with the greatest opportunity is Sighthill as shown in Figure 5.19, which shows 9 VDL sites. This Ward is situated on the east side of Glasgow and contains 9.0 ha with a potential build of 161 new dwellings.

A number of policy aspects affecting Sighthill have previously been described in Section 5.5.1, these will be briefly summarised. The biodiversity aspect covers marginal areas of woodland around the Ward which are discounted due to its weighting of 0.371. Five developmental factors overlap the Ward: ‘Master plan area’ (1), ‘Strategic economic investment locations’ (1) and ‘Transformational regeneration areas’ (1) which covers the west and central; ‘Industrial-business marketable land supply’ (2) and ‘Strategic development framework’ (2) which covers open spaces in the central and western regions. With the lowest weighting of 0.107, it only has major influence on areas not overlapped by other aspects. Two environmental factors overlap the Ward: ‘Green corridors’ (1) and ‘Sites of importance for nature conservation’ (3) located in the northwest of the Ward which, with a high weighting of 0.371, discounts these areas. The visual impact has influence on the Ward due to a moderate weighting of 0.151 and with several communities within a close proximity to VDL sites in the eastern and southern regions.

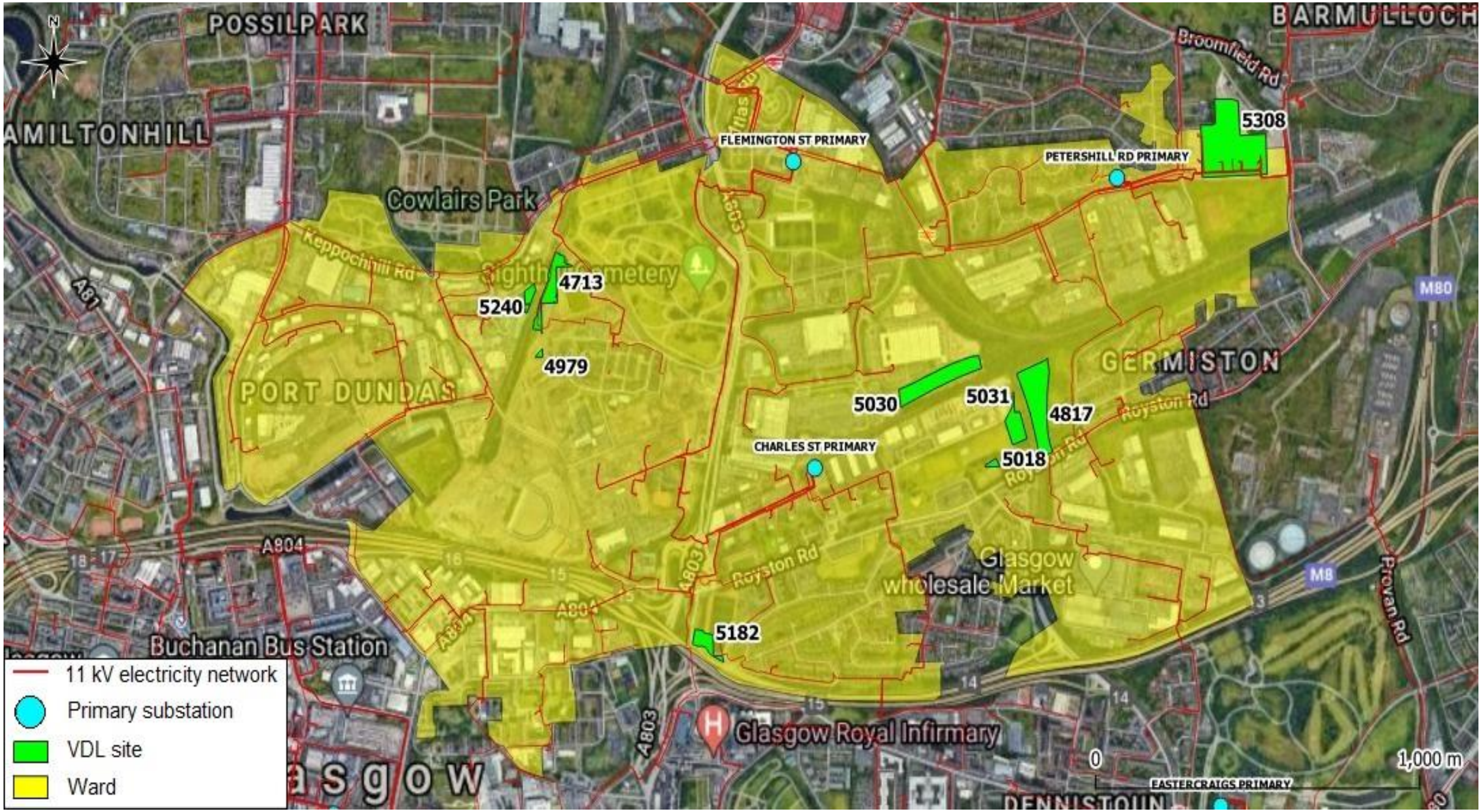


Figure 5.19. Sighthill Ward.

5.9.1 VDL site analysis

Studying this Ward in closer detail reveals that 9 out of 31 sites (29%) are categorised as being suitable. These sites are listed in Table 5.24, presented in descending ordered by area and the top three sites are shown in Figure 5.20.

Table 5.24. Sites of opportunity in Sighthill.

Site ID	Address	Area (ha)	No. of new-build housing
5308	Red Road Court	3.2	58
4817	West of Darnick St	2.3	41
5030	Springburn Road	1.9	33
4713	Fountainwell Place	0.6	11
5031	Charles Street	0.5	8
5182	Rhymer Street	0.3	6
5240	Keppochill Drive	0.2	3
5018	Glenconner Park	0.1	1
4979	Fountainwell Road	0.03	1
Total	**-**	**9.0**	**161**

5.9.1.1 Site 5308

The largest of these sites is Site 5308 which comprises of 3.2 ha of unconstrained land and is situated in the northeast part of the Ward as shown in Figure 5.20 (upper).

The developmental factor ‘Transformational regeneration areas’ (1) has a positive influence on the Site which fully encourages development and affects the whole VDL Site. However, the environmental factor ‘Sites of importance for nature conservation’ (3) overlaps a small portion of the Site in the southeast. The visual impact aspect also affects the east and west sides of the Site due to nearby settlements.

With these policy aspects at play, the Site possesses 3.2 ha of unconstrained land equivalent to 58 homes.

Figure 5.20. Top 3 Sites in Sighthill: Site 5308 (upper); Site 4817 (middle); Site 5030 (bottom).

5.9.1.2 Site 4817

The second largest Site is 4817 situated in the eastern region of the Ward and comprises of 2.3 ha as shown in Figure 5.20 (middle).

In terms of the policy aspects, the environmental factor ‘Green corridors’ (1) influences the western areas of the Site; the visual impact aspect influences the eastern areas of the Site due to the local community.

With these policy aspects at play, the Site possesses 2.3 ha of unconstrained land equivalent to 41 homes.

5.9.1.3 Site 5030

The third Site identified is 5030 with an acreage of 1.9 ha and situated in the central region of the Ward as shown in Figure 5.20 (bottom).

Only two policy aspects affect the Site: the biodiversity aspect influences the northeast region of the Site due to the abundance of woodland and discounts a small area of land; the developmental factor ‘Network of centres’ (2) affects the western part of the Site.

With these policy aspects at play, the Site possesses 1.9 ha of unconstrained land equivalent to 33 homes.

5.10 Discussion of results

The GOMap tool has been applied to assess PVPS deployments at unconstrained VDL sites, identified a new site not previously designated VDL, assess PV canopies applied to city multi-storey car park roofs, and assess areas for housing development. The results are tabulated in Table 5.25.

Table 5.25. Summary of scenario results.

Scenario	Weighting method	Area (ha)	Output energy (MWh/y)	No. of dwellings equivalent	No. of EVs equivalent
1	Non-equal	327.1	136,474	12,714	74,251
	Equal	181.1	73,901	6,958	40,207
2	Non-equal	255.3	106,355	10,026	57,865
	Equal	183.2	75,980	7,273	41,338
3	Non-equal	305.8	127,679	11,740	69,466
	Equal	508.9	213,006	19,615	115,890

4	Non-equal	5.5	2,342	161	1,274
5	Non-equal	1.46	572	44[13]	311
6	Non-equal	87.3	-	1,554[14]	-

The city land use assessment has shown that the base case Scenario 1, where all policy and technical aspects are active and non-equally weighted, results in a VDL area of 327.1 ha, which can generate 136,474 MWh/y of energy supply. This is equivalent to the heating needs of around 12,714 dwellings. When equally weighted, results in a VDL area of 181.1 ha, which can generate 73,901 MWh/y of energy supply. This is equivalent to the heating needs of around 6,958 dwellings. It is clear when applying non-equal weightings, 81% more land is released for utilisation of PVPS deployment compared to when equal weightings are applied.

Scenario 2, with some pertinent policy aspects relaxed, explores the potential for policy-assisted development in future. When non-equally weighted, this results in VDL sites with an area of 255.3 ha, which can generate 106,355 MWh/y of energy, equivalent to heating around 10,026 dwellings. When equally weighted, this results in VDL sites with an area of 183.2 ha, which can generate 75,980 MWh/y of energy, equivalent to heating around 7,273 dwellings. Similar to Scenario 1, non-equal weightings release more unconstrained land with an additional 39% compared to equal weightings. The results from Scenario 1 and 2 suggests that prioritising certain aspects over others may be more beneficial than balancing all aspects equally.

Scenario 3 examines a case that disregards most technical aspects on the basis that resources are made available in future to create new energy infrastructure. When non-equally weighted, the result is VDL sites with an area of 305.8 ha, which can generate 127,679 MWh/y to heat up to 11,740 dwellings. When equally weighted, the result is VDL sites with an area of 508.9 ha, which can generate 213,006 MWh/y to heat up to 19,615 dwellings. Conversely, compared to Scenarios 1 and 2, the application of equal weightings releases more unconstrained land with an additional 66% compared to non-equal weightings. The results contradict the previous conjecture concerning the benefits of prioritising certain aspects as this scenario has shown the opposite. This suggests that it is difficult to determine whether non-equal

[13] Equivalent to an average annual energy consumption of a Glasgow dwelling (13 MWh/y).
[14] Equivalent to developing new build housing (17.8 dwellings/ha).

weightings are more beneficial than equal weightings or vice-versa, implying that discussions between policy and decision makers would need to establish which weighting method is suitable for the needs of each individual project.

From the perspective of determining which Ward can supply most of its dwellings based on the average dwelling heat demand, it is often the smaller Wards which can achieve this. For Scenario 1 when non-equally weighted, although the Ward which can provide the most energy is Carmyle and Mount Vernon South at 12,079 MWh/y and provide for 829 dwellings (13.3%), the Ward which can supply the majority of its dwellings is Pollokshaws where if all its sites were utilised, could cover 445 dwellings (67.3%) with an energy output of 2,722 MWh/y. When equally weighted, North Barlanark and Easterhouse South can generate the most energy at 7,992 MWh/y and provide for 884 dwellings (45.8%) of its dwellings. However, Garrowhill East and Swinton which can generate a lesser output of 6,332 MWh/y can provide for more of its dwellings with 726 (63.4%). For Scenario 2 when non-equally weighted, the Ward providing the most energy at 5,333 MWh/y is Sighthill for 722 dwellings (13.2%), but the Ward which can supply the majority of its dwellings is, similar to Scenario 1, Pollokshaws which could cover 445 dwellings (67.3%) with an energy output of 2,722 MWh/y. When equally weighted, Garrowhill West can generate the most energy at 4,328 MWh/y and provide for 331 dwellings (20.6%) of its dwellings. However, Pollokshaws which can generate an output of 1,605 MWh/y can provide for more of its dwellings with 262 (39.7%). For Scenario 3 when non-equally weighted, the Ward providing the most energy at 6,471 MWh/y is Drumoyne and Shieldhall for 654 dwellings (7.6%), but the Ward which can supply the majority of its dwellings is Pollokshaws which could cover 656 dwellings (99.2%) with an energy output of 4,012 MWh/y. When equally weighted, Riddrie and Hogganfield can generate the most energy at 18,303 MWh/y and provide for 1,619 dwellings (77.7%) of its dwellings. However, Garrowhill East and Swinton which can generate an output of 15,661 MWh/y can provide not only for all of its 1,144 inhabited dwellings, but also a surplus of 651 amounting to 1,795 (156.9%) dwellings.

Although Scenarios 2 and 3 have shown the effects of relaxing certain aspects, it is likely that in a decision-making process, all available information should be included in the assessment to make a reasonable judgement. It is also likely that non-equal weightings would be applied due to the significance of certain aspects over others particularly those related to the environmental and ecological systems of the land. Therefore, Scenario 1 with non-equal weightings may be the more effective and informative scenario.

GOMap also quantified the potential of exploiting a quarry for PVPS deployment covering an area of 5.5 ha. This is capable of produce 2,342 MWh/y to provide heating energy for around 161 (2.6%) dwellings within the Carmyle and Mount Vernon South Ward. While this is a relatively small number, there are several such sites throughout the city that could be exploited. These additional sites were not examined here as this Scenario was aimed to test the tool's capabilities in identifying new potential sites which matched several requirements.

GOMap was also used to explore the potential of deploying PVPS on the roofs of 3 multi-story car parks in Glasgow's city centre. This would produce 572 MWh/y from a combined area of 1.46 ha and is the equivalent of the annual charging requirements of 311 EVs.

Finally, GOMap was used to identify areas of opportunity for housing development to tackle the city's homeless crisis. With 87.3 ha of unconstrained land available, 1,554 new dwellings could be built to accommodate 4.3% of the homeless community. The Ward with the greatest opportunity was Sighthill which contains 9.0 ha of available land with a potential to build 161 new dwellings.

In summary, the GOMap tool has been applied to assess PVPS deployments at unconstrained VDL sites, used to assess PV canopies applied to city multi-storey car parks, and used to assess areas for housing development. The results are tabulated in Table 5.25 where it is shown that the base case Scenario 1 with all aspect information active and non-equally weighted gives rise to 327.1 ha of VDL that could supply 12,714 of Glasgow's dwellings. Alternatively, if this energy was instead used for EV charging, it would be the equivalent to 74,251 EVs. Given that the proportion of households with one or more cars is 49% (Glasgow City Council 2018), and the number of inhabited households is approximately 310,000, the energy yield for EV charging would cover 49% of Glasgow's car fleet.

For each of scenarios 1 through 5, a land utilisation factor is set to ensure the ratio of the combined total PVPS array area does not exceed 50% of the total site area. This is to safeguard adequate space to deploy and maintain the PVPS installation. It would be possible to utilise a greater portion of the unconstrained land if necessary, however, there can be unacceptable consequences to this approach, such as increasing the risk of environmental damage to soil and plants, increasing the risk of damage to property or components of the PVPS, and increasing the risk of vandalism and theft. Another major concern is using more land for PVPS reduces the overall amount of land that could be used for other vital purposes such as farming or new housing developments. The final decision will, as always, be a political and economic one.

GIS tools are routinely used by local authorities to provide maps representing various types of information as required to support policy setting and development control. Care must be taken when aligning geographical information with satellite imagery as the information imported into a mapping tool may not be up-to-date. For example, there may be situations where information from 2019 suggests a site contains no vegetation but satellite imagery from 2022 conversely shows some form of growing vegetation. Therefore, it is essential to use the latest information available to generate accurate, high-quality opportunity maps.

GOMap is designed to extend the support for the planning system by bringing different information types together within opportunity maps that identify sites of opportunity for new and renewable energy technology deployment. Such a streamlined process has the potential to directly encourage potential developments while nurturing a partnership approach between developers and local authorities.

Chapter 6 – GOMap application to cities in other climates

6.1 Overview

In Chapter 5, the GOMap tool was applied to assess PVPS deployments in Glasgow. In this chapter, the tool will be applied to other cities on local sites designated for urban renewal development to test the effectiveness of the tool when transferred to other locations using local information. Six cities were selected to represent climates at various latitudes to assess potential energy provided by PVPS deployment. The results are presented in terms of the energy yield, the number of equivalent dwellings and EVs.

6.2 Context

The selected cities are Berlin, Cape Town, Madrid, Melbourne, Paris and Tokyo. Local councils/governments designated sites for urban renewal development within their cities for purposes including additional housing and recreational areas; new offices and industry etc. Datasets including these sites were collected for each city in shapefiles from publicly available sources. However, comprehensive policy and technical information were not available. Instead, overshading and terrain information were used to determine site suitability in the form of DSM and DTM respectively, both of which were provided by CEDA. With a lack of detailed information, both overshading and terrain aspects were weighted at 0.750 and 0.250 respectively using the same assumptions in Section 5.6.1, to discount areas within sites affected by overshading and/or broken ground or risks of flooding. Figures for each site depict ‘Favourable’ areas in green; ‘Unsuitable’ areas in red. The land utilisation factor was set at 50% on a grid resolution of 10 x 10 m similar to city-wide exploration of VDL sites used for Glasgow. Hourly weather data (ambient temperature, direct normal solar and diffuse horizontal solar radiation) were obtained (Suncalc 2020, Solcast 2020) and introduced into GOMap’s PVPS model. Output energy is used to estimate the number of dwellings equivalent in the local city by its average space heating/cooling requirement. Number of EVs equivalent is derived from local information regarding the average annual distance travelled by cars and their typical energy consumption. Results of the number of dwellings and EVs equivalent are shown for each city in Table 6.1 in descending order in terms of PVPS

Table 6.1. City information and results.

City	Latitude & longitude	Site name	Original site area (ha)	Utilised site area (ha)	Data source	Output energy (MWh/y)	No. of dwellings equivalent	No. of EVs equivalent
Berlin	52.5 N, 13.4 W	Tempelhofer Feld	300[15]	204	Berlin Open Data[16]	80,267	6,222	34,975
Cape Town*	-34.0 N, 18.6 W	Swartklip	510[17]	209	City of Cape Town Open Data Portal[18]	199,088	75,872	55,302
Madrid*	40.6 N, -3.7 W	Tres Cantos	329[19]	118	Geofabrik[20]	88,572	20,408	40,078
Melbourne*	-37.8 N, 144.9 W	Fishermans Bend	455[21]	57	City of Melbourne Open Data[22]	64,066	17,447	38,946
Paris	47.2 N, -1.5 W	Paris Rive-Gauche	130[23]	8.5	Open platform for French public data[24]	7,886	974	3,568
Tokyo*	35.7 N, 139.5 W	Tokyo Metropolitan Area	340[25]	17.1	Geospatial Information Authority of Japan [26]	11,040	3,678	4,346

* Cities which require space heating and cooling.

15 Oppla 2017.
16 Berlin Open Data 2021.
17 The City of Cape Town's Transport and Urban Development Authority 2018.
18 City of Cape Town Open Data Portal 2018.
19 Ciudad FCC 2020.
20 Geofabrik 2021.
21 Plan Melbourne 2017.
22 City of Melbourne 2021.
23 The Conversation 2018.
24 Open platform for French public data 2021.
25 Japan Property Central 2019.
26 Geospatial Information Authority of Japan 2021.

energy yield. Information including site name, site coordinates, site area and data sources are included. Additional PVPS and city information is shown in APPENDIX II.4 Table A2.20.

6.3 Berlin

The Site used in the analysis is Tempelhofer Feld, an area which comprises of 300 ha previously used as a military and civilian airport and eventually designated as open green space (Oppla 2017) as shown in Figure 6.1. Application of the overshading and terrain information reduces the Site area to 204 ha for PVPS utilisation.

The average heating requirement for Berlin's dwellings is 12,900 kWh/y (Odyssee-Mure 2020). For EVs, the average annual commute was taken to be 13,500 km (Kalinowska & Kuhfeld 2006) and with a rate of 0.17 kWh/km (Pasaoglu *et al* 2013), this results in an annual consumption of 2,295 kWh/y. The output energy was calculated to be 298 kWh/m^2.y with an optimal PV tilt angle of 28^o. The ideal azimuth was found to be 217^o from due North with a minimum inter-row spacing calculated to be 6.0 m.

This calculates in an energy output of 80,267 MWh/y, capable of supporting 6,222 dwellings or 34,975 EVs.

6.4 Cape Town

The Site used in the analysis is Swartklip, an area which comprises of 510 ha and is recognised by the City of Cape Town's Municipal Spatial Development Framework as a unique spatial transformation area to integrate communities and the wider region (The City of Cape Town's Transport and Urban Development Authority 2018) as shown in Figure 6.2. Application of the overshading and terrain information reduces the Site area to 209 ha for PVPS utilisation.

South Africa experiences high temperatures throughout the year with the warmest occurring during Winter and as a result, many households are equipped with air-conditioning systems for space cooling. In the Summer when ambient temperatures drop, space heating may be used and is usually produced by Warm Air Ducted Heating system or portable electrical heaters. Primarily, more energy is consumed for space cooling than for space heating but as both influences attribute to a dwelling's thermal comfort level, the heating and cooling requirements are combined.

Figure 6.1. Tempelhofer Feld, Berlin.

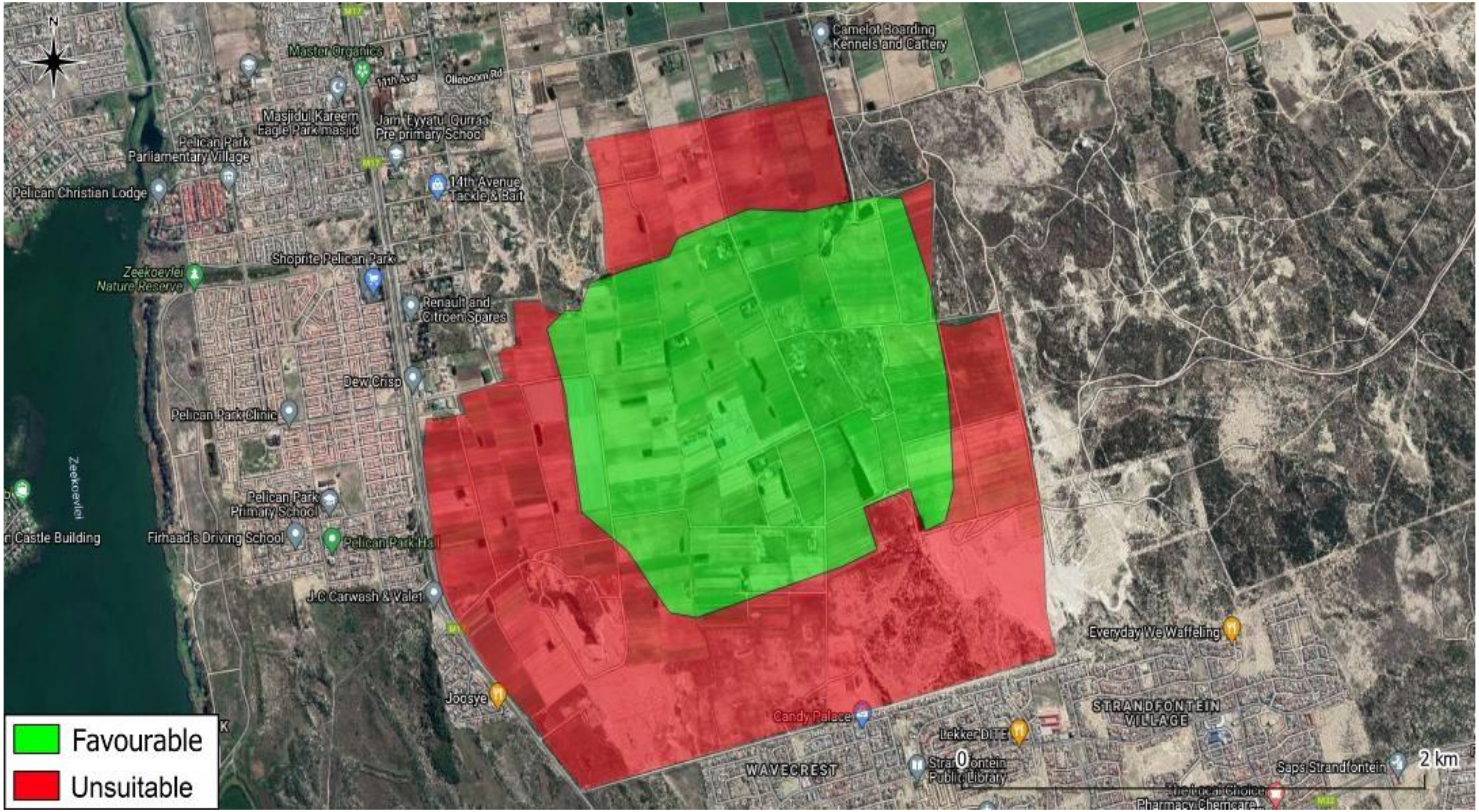


Figure 6.2. Swartklip, Cape Town.

The heating/cooling requirement for an average dwelling is 30% of the overall electricity consumption (City of Cape Town 2013). For a typical dwelling with an annual electricity consumption of 8,748 kWh/y (City of Cape Town 2011), the heating/cooling energy requirement was found to be 2,624 kWh/y. For EVs, the average daily commute by car was taken to be 50 km, which amounts to 11.8 kWh per day or 300 kWh per month, representative of current EV fuel economy (City of Cape Town 2018). This in turn would result in an annual total of 3,600 kWh/y over 18,250 km.

The output energy was calculated to be 372 kWh/m^2.y with an optimal PV tilt angle of 30^o. The ideal azimuth was found to be 15^o from due North with a minimum inter-row spacing calculated to be 5.5 m. As Cape Town is in the southern hemisphere and due to the tilt of the Earth at 23.45^o, the city receives considerably more direct sunlight than the other cities examined and as a result, more output energy is generated by the PVPS.

This calculates in an energy output of 199,088 MWh/y, capable of supporting 75,872 dwellings or 55,302 EVs.

6.5 Madrid

The Site used in the analysis is Tres Cantos, a municipality which comprises of 329 ha and is located north of Madrid in a privileged location within a high-value environment (Ciudad FCC 2020) as shown in Figure 6.3. Application of the overshading and terrain information reduces the Site area to 118 ha for PVPS utilisation.

As with Cape Town, Madrid has a greater demand for space cooling than for space heating. The average heating/cooling requirement for Madrid's local dwellings is 4,340 kWh/y (Gobierno De España 2011). For EVs, the average annual commute was taken to be 13,000 km (European Commission 1999) and with a rate of 0.17 kWh/km (Pasaoglu *et al* 2013), this results in an annual consumption of 2,210 kWh/y.

The PVPS output energy was calculated to be 329 kWh/m^2.y with an optimal tilt angle at 34^o. The minimum inter-row spacing was estimated to be 7.1 m at an azimuth of 160^o.

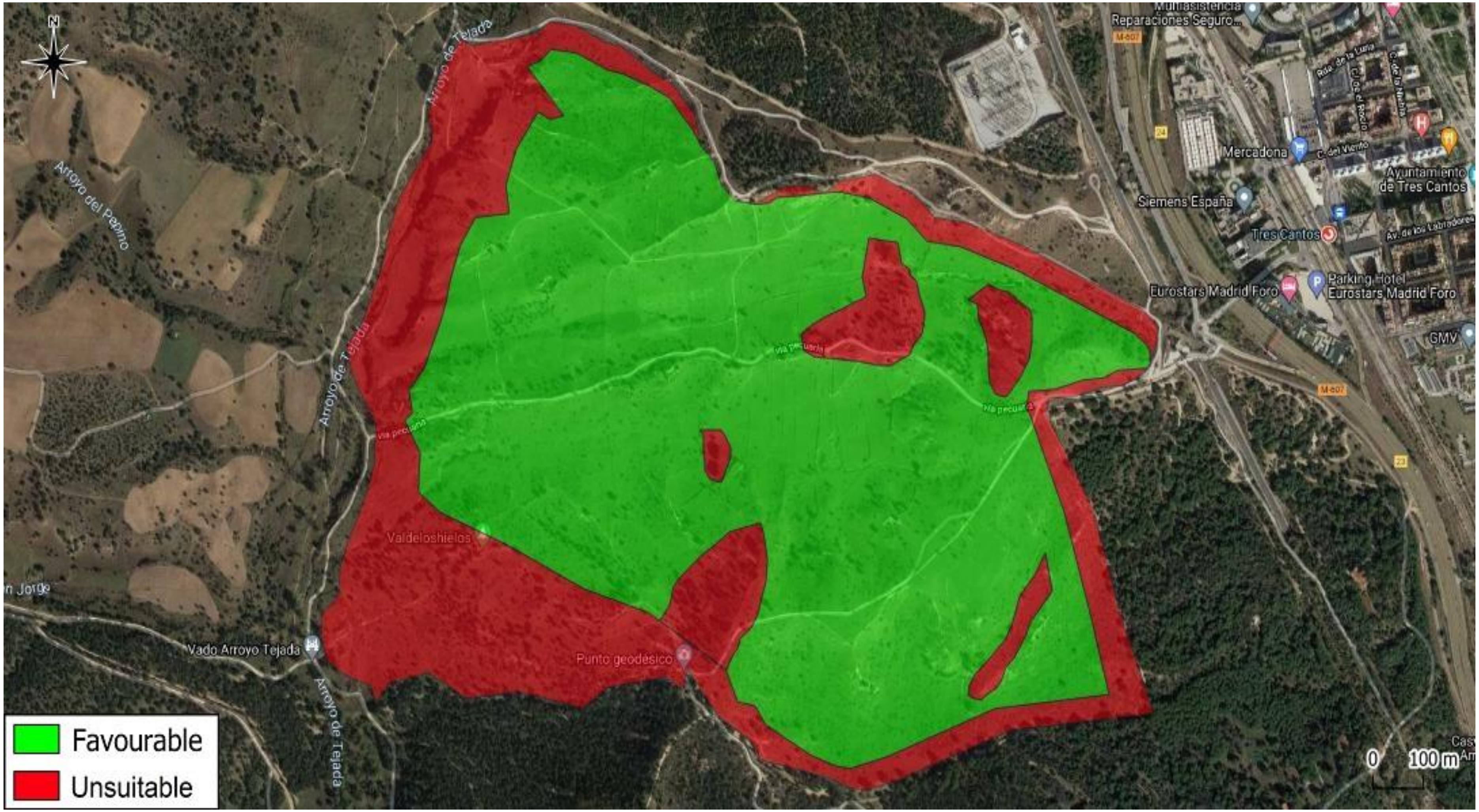


Figure 6.3. Tres Cantos, Madrid.

This calculates in an energy output of 88,572 MWh/y, capable of supporting 20,408 dwellings or 40,078 EVs.

6.6 Melbourne

The Site used in the analysis is Fishermans Bend, an innovation cluster which comprises of 455 ha and has the potential to enhance manufacturing productivity with a focus on research and development (Plan Melbourne 2017) as shown in Figure 6.4. Application of the overshading and terrain information reduces the Site area to 57 ha for PVPS utilisation due to most of the area having being developed.

As with the previous two cities examined, more demand is given to space cooling than to space heating, which when totalled for an average dwelling is 40% of the overall electricity consumption. This is found to be 3,672 kWh/y (Australian Government 2020, Mount Alexander Shire Council 2018). For EVs, the average annual commute was taken to be 12,000 km and with a rate of 0.137 kWh/km, this results in an annual consumption of 1,645 kWh/y (Kara *et al* 2017).

The output energy was calculated as 341 kWh/m^2.y with an optimal PV tilt angle at 32^o. The ideal azimuth is calculated to be 10^o from due North with a minimum inter-row spacing of 5.2 m. Similar to Cape Town, Melbourne is also in the southern hemisphere and although slightly lower than Cape Town, still receives considerably more direct sunlight than the other cities examined.

This calculates in an energy output of 64,066 MWh/y, capable of supporting 17,447 dwellings or 38,946 EVs.

6.7 Paris

The Site used in the analysis is Paris Rive-Gauche, an area which comprises of 130 ha situated in the east of Paris, on the banks of the Seine with the aim to redevelop industrial wasteland located around the Austerlitz train station (The Conversation 2018) as shown in Figure 6.5. Application of the overshading and terrain information reduces the Site area to 8.5 ha for PVPS utilisation.

The average heating requirement for Paris's local dwellings is 8,100 kWh/y (Enerdata 2011). For EVs, the average annual commute was taken to be 13,000 km (Odyssee-Mure 2020) and with a rate of 0.17 kWh/km (Pasaoglu *et al* 2013), this results in an annual consumption of 2,210 kWh/y.

Figure 6.4. Fishermans Bend, Melbourne.

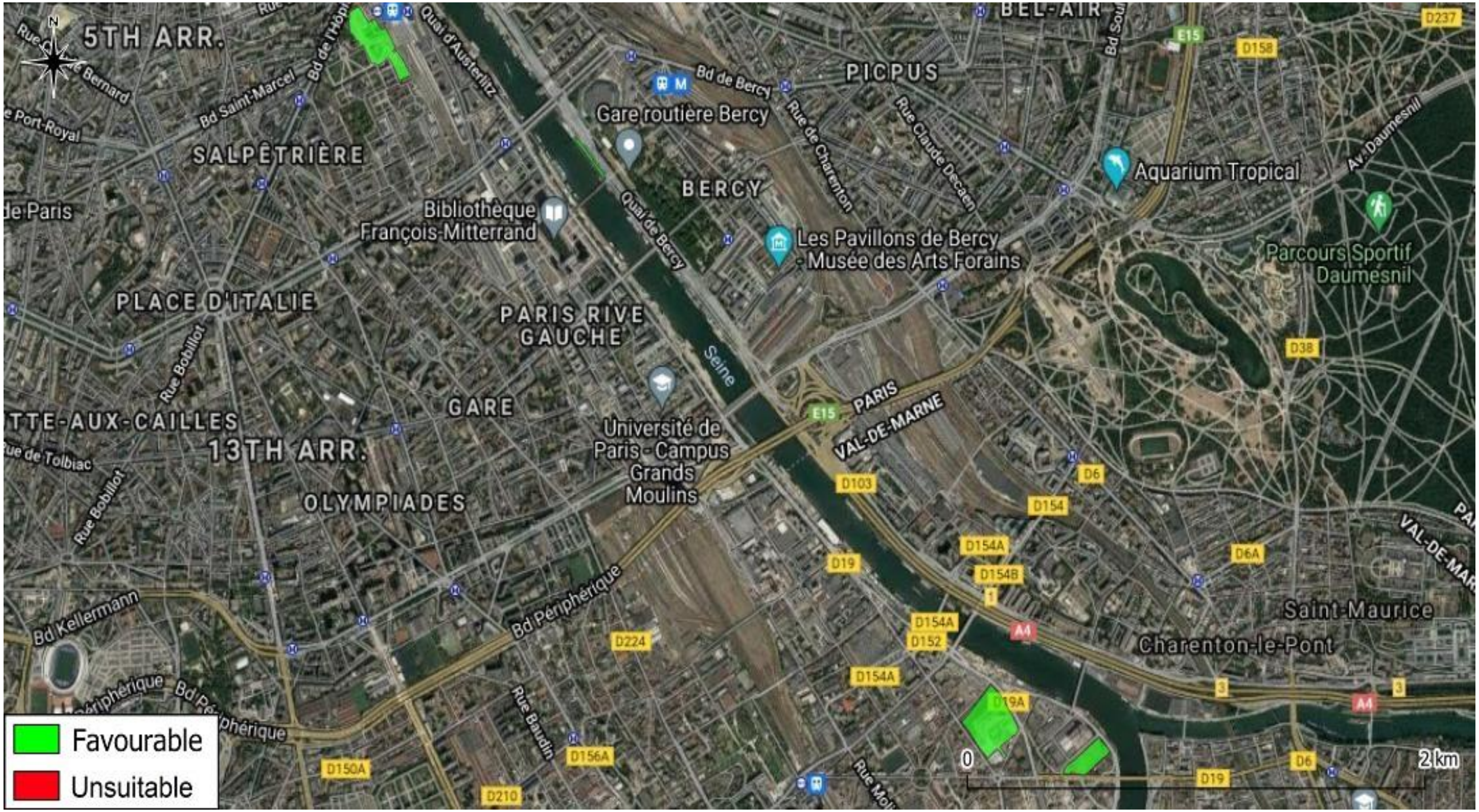


Figure 6.5. Paris Rive-Gauche, Paris.

The output energy was calculated to be 220 kWh/m^2.y with an optimal PV tilt angle of 41°. The ideal azimuth was found to be 183° from due North with a minimum inter-row spacing calculated to be 7.9 m.

This calculates in an energy output of 7,886 MWh/y, capable of supporting 974 dwellings or 3,568 EVs.

6.8 Tokyo

The Site used in the analysis is Tokyo Metropolitan Area, an area which comprises of 340 ha of vacant land which is undergoing efforts including developing transportation infrastructure, promoting urban development to establish a low-carbon city and building an urban environment rich in greenery (Japan Property Central 2019) as shown in Figure 6.6. Application of the overshading and terrain information reduces the site area to 17.1 ha for PVPS utilisation.

Tokyo experiences warm humid summers and generally cool winters and therefore, many households are equipped with an air conditioning system where the average electrical consumption for a typical dwelling is 10,000 kWh/y (Bureau of Environment Tokyo Metropolitan Government 2016). With roughly 30% of this consumption used for space heating and cooling, this amounts to an annual heating/cooling demand of 3,000 kWh/y (Murakami *et al* 2007). This low value for a country that is neither too hot during the Summer nor too cold during the Winter could be accounted for due to almost half of the dwellings in Tokyo are habited by a single person (Bureau of Environment Tokyo Metropolitan Government 2016) and where many dwellings are small, comprising one-bedroom apartments with an average floor space of 37.5 m^2 (Nakagawa *et al* 2007). For EVs, the average annual commute was taken to be 15,000 km, and with a consumption rate of 6.96 kWh/day, this results in an annual consumption of 2,540 kWh/y (Nansai *et al* 2002).

The output energy was calculated to be 217 kWh/m^2.y with an optimal tilt angle at 35°. The minimum inter-row spacing was calculated to be 6.7 m with an ideal azimuth of 187°.

This calculates in an energy output of 11,040 MWh/y, capable of supporting 3,678 dwellings or 4,346 EVs.

Figure 6.6. Tokyo Metropolitan Area, Tokyo.

6.9 Discussion of results

GOMap was tested to determine if the tool can be transferred to other locations and identify unconstrained land using local information. The PVPS model was configured with local weather data for other cities to estimate the output energy yield from the PVPS. Land availability was determined by publicly available information for sites, buildings, structure heights and topography. Local data from the selected cities regarding annual space heating and cooling requirements and annual consumption of EVs are used to determine the number of dwellings and EVs equivalent when deploying PVPS.

This assessment has shown that the South African city of Cape Town provided the largest amount of PVPS output energy generation at 372 kWh/m^2.y. This is closely followed by Melbourne with 341 kWh/m^2.y and Madrid with 329 kWh/m^2.y. These top three cities possess a climate that provides higher temperatures throughout the year and, as a result, requires a greater demand for space cooling than for space heating. The remaining cities include Berlin with an energy output of 298 kWh/m^2.y followed by Paris with 220 kWh/m^2.y and Tokyo close behind with 217 kWh/m^2.y. Excluding Tokyo, the last two cities have a greater demand for space heating than for space cooling.

In terms of space heating/cooling energy requirement, the European cities possess the highest demand, with Berlin requiring 12,900 kWh/y followed by Paris and Madrid with 8,100 kWh/y and 4,340 kWh/y respectively. The first two of these cities place greater emphasis on heating. Conversely, Madrid and all remaining cities place greater emphasis on cooling, with Melbourne requiring 3,672 kWh/y followed by Tokyo and Cape Town with 3,000 kWh/y and 2,624 kWh/y respectively.

In terms of EVs, Cape Town has the highest electrical consumption at 3,600 kWh/y per EV followed by Tokyo with 2,540 kWh/y. Berlin is next with 2,295 kWh/y followed closely by Madrid and Paris with a joint value of 2,210 kWh/y. EVs in Melbourne have an annual consumption of 1,645 kWh/y.

For the inter-row spacing distance, Paris possessed the longest distance with 7.9 m of space required between rows of PV arrays. This is subsequently followed by Madrid with 7.1 m, Tokyo with 6.7 m and Berlin with 6.0 m. These four cities lie in the northern hemisphere within the range of 35^o N and 55^o N. The final two remaining cities, which lie in the southern hemisphere between -33^{o} N and -38^{o} N, have the lowest inter-row spacing distances; these are Cape town with 5.5 m and Melbourne with 5.2 m.

Using the land available for each city based on the sites designated for urban renewal development, the largest site area utilised for potential PVPS deployment is Swartklip, Cape Town which comprises of 209 ha, can generate an output energy of 199,088 MWh/y and can supply 75,872 dwellings or 55,302 EVs. This can be compared to Tempelhofer Feld, Berlin in terms of utilised site area which is only several hectares less at 204 ha but with a lower PVPS energy generation, can output 80,267 MWh/y, the equivalent of 6,222 dwellings or 34,975 EVs. Tres Cantos, Madrid comprises of less utilised site area than Berlin at 118 ha but can output more energy at 88,572 MWh/y which can supply 20,408 dwellings or 40,078 EVs. Fishermans Bend, Melbourne which has a utilised site area of 57 ha can output 64,066 MWh/y, the equivalent of 17,447 dwellings or 38,946 EVs. The Tokyo Metropolitan Area consists of 17.1 ha and can generate 11,040 MWh/y which can provide for 3,678 dwellings or 4,346 EVs.

The results show that GOMap could potentially be used as a standard tool for any city by using basic local information (e.g. site, building height to calculate overshading, and terrain) to identify areas of opportunity for PVPS utilisation. These results could be improved if additional comprehensive policy and technical information were included as this would generate more accurate opportunity maps. Additionally, the results may also show how information such as energy yield could determine if PVPS is a suitable RET when the heating/cooling demands for a city is highlighted or if another RET could be beneficial.

Chapter 7 – Conclusions

7.1 Overview

This chapter summarises the main contributions of the work which relates back to the aims and objectives; a discussion on the application of the GOMap tool and its limitations; suggested future work; and concluding remarks.

7.2 Contribution

The stated aim of this research project was the development and application of a new site selection evaluation method that combines policy and technical considerations relating to energy supply within the planning process for any urban city. The following outlines the main contributions of the presented work.

- **Development of a new site selection evaluation method** – A new site selection evaluation method was designed to bring together comprehensive and detailed policy and technical aspect information into a single composite opportunity map and determine the PVPS energy potential of a city utilising available land that is both policy and technically unconstrained. The development process underwent a series of stages beginning from consultancy and workshops with GCC and SPEN regarding policy and technical aspect information respectively. Relevant factors associated with each policy and technical aspects that may affect site selection for PVPS deployment were identified with scores and weightings assigned. Three systems were designed to enable evaluation of all collected information: a 10 m x 10 m grid system to create a high-resolution spatial relationship between all policy and technical information; a scoring system to differentiate between factors supporting, curtailing or remaining neutral in PVPS deployment; and a weighting system to prioritise the significance of each aspect determined using the MCDM/AHP and Weighted Overlay Analysis methods. These systems and all policy and technical information are encapsulated in an interactive Geospatial Opportunity Mapping tool, named GOMap, capable of identifying sites for PVPS deployment. The tool allows users to change input parameters at any time including enabling/disabling certain aspects due to specific scenarios or altering the weightings which would immediately update the final opportunity map in real-time. Finally, these sites are exported to a

PVPS model designed to calculate optimal parameters such as panel azimuth, tilt angle, inter-row spacing and energy yield based on local hourly weather information including ambient temperature, direct normal solar radiation and diffuse horizontal solar radiation to provide measurements of output energy generation.

- **Application of GOMap to Glasgow** – The application of the tool allowed the identification of unconstrained land within a city that is available for the deployment of PVPS. Initially, the tool was verified by a case study following an ongoing planning application for an area in Glasgow by a spatial planning expert within the Development Plan Group at GCC who compared the tool's outputs with the results of the planning application assessment. The tool was then applied to the city of Glasgow to identify unconstrained land designated VDL for the deployment of PVPS. Several scenarios were devised for future development intended to encourage the availability of greater land areas and enable a comparison of alternative land use strategies through policy and technical aspect relaxation for purposes including: to supply energy for dwellings in regards to the heating requirements as part of the Scottish Government's Energy Strategy commitment to electrify home heating; to supply energy for EVs in regards to the electrical requirements; and to identify sites for new build homes to tackle Glasgow's homeless issue.
- **Application of GOMap to other cities** – GOMap was tested on cities of varying latitudes and climates to determine if the tool can be transferred to other locations to identify land availability on sites designated for urban renewal development. Site and building information were collected from local government and other publicly available sources for each city in combination with technical information used to discount areas where overshading and unsuitable ground are present. Local hourly weather data was introduced into the PVPS model. The output energy was then used to estimate the number of dwellings equivalent in the local city determined by the city's average space heating or space cooling requirement. The number of EVs equivalent was derived from local information regarding the average annual distance travelled by cars and their typical energy consumption. Although the tool was limited to two technical aspects, it showed the assessment could be greatly improved if

additional policy and technical information were included which could provide a comprehensive and detailed opportunity map as was done for Glasgow.

In summary, a new site selection evaluation method has been developed and encapsulated using GIS technology to allow the identification of areas of opportunity in cities suitable for the deployment of PVPS in an urban environment. The opportunity maps generated are based on policy and technical aspects scored on a 10 m x 10 m resolution city grid. For application in Glasgow, scores were arrived at in collaboration with planning and utility personnel from GCC and SPEN respectively. After verification, the tool was applied to the city of Glasgow to determine the opportunity for the deployment of PVPS on VDL sites under scenarios corresponding to possible policy and technical relaxations in combination with aspect weightings. Application of the tool was transferred to other international cities to identify land availability on local sites designated for urban renewal development for PVPS deployment and the supply of heating/cooling and electrical energy to dwellings and EVs respectively based on limited publicly available data.

7.3 Research findings for Glasgow City

The city land use assessment was initially applied to Glasgow with several scenarios devised for future development intended to encourage the availability of greater land areas and enable a comparison of alternative land use strategies through policy and technical aspect relaxation. Non-equal weightings were applied throughout and will be discussed here as these, when compared to equal weightings, are more likely to be used in a decision-making process as all available information can be included in the final assessment to make a reasonable judgement due to the significance of certain aspects over others particularly those related to the environmental and ecological systems of sites. For each of Scenarios 1 through 5, a land utilisation factor was set to ensure the ratio of the combined total PVPS array area did not exceed 50% of the total site area to safeguard adequate space for the deployment and maintenance of PVPS installation. For Scenario 6, the land utilisation factor was set to 100% as this scenario explored new build housing taking into account the average number of dwellings in Glasgow per hectare.

The base case Scenario 1, where all policy and technical aspects are active, results in a VDL area of 327.1 ha, which can generate 136,474 MWh/y of energy supply.

This is equivalent to the heating needs of around 12,714 dwellings. The Ward which can provide the most energy is Carmyle and Mount Vernon South at 12,079 MWh/y and provide for 829 dwellings (13.3%) of its inhabited dwellings. Site 4980 of the same Ward possessed the largest amount of unconstrained land at 7.4 ha located on empty space and can generate 3,143 MWh/y with the potential to supply 216 dwellings with heat energy. Alternatively, the Ward which can supply the majority of its dwellings is Pollokshaws where if all its sites were utilised, could cover 445 dwellings (67.3%) with an energy output of 2,722 MWh/y.

Scenario 2, with some pertinent policy aspects relaxed to explore the potential for policy-assisted development in future, resulted in VDL sites with an area of 255.3 ha, which can generate 106,355 MWh/y of energy, equivalent to heating around 10,026 dwellings. The Ward providing the most energy at 5,333 MWh/y is Sighthill for 722 dwellings (13.2%), with Site 5169 comprised of 3.4 ha of unconstrained land which can generate 1,438 MWh/y with the potential to supply 195 dwellings with heat energy. Alternatively, the Ward which can supply most of its dwellings is again Pollokshaws which could cover 445 dwellings (67.3%) with an energy output of 2,722 MWh/y.

Scenario 3 examined a case that disregards most technical aspects on the basis that resources are made available in future to create new energy infrastructure. The results show that VDL sites with an area of 305.8 ha can generate 127,679 MWh/y to heat up to 11,740 dwellings. The Ward providing the most energy at 6,471 MWh/y is Drumoyne and Shieldhall for 654 dwellings (7.6%), with Site 4667 possessing 5.6 ha of unconstrained land and can generate 2,376 MWh/y with the potential to supply 240 dwellings with heat energy. Alternatively, the Ward which can supply the majority of its dwellings is Pollokshaws which could cover 656 dwellings (99.2%) with an energy output of 4,012 MWh/y.

Scenario 4 examined the identification of additional areas of unconstrained land within Glasgow which were not previously designated VDL for PVPS deployment. A potential site was found in the form of a quarry covering an area of 5.5 ha. This can produce 2,342 MWh/y to provide heating energy for around 161 (2.6%) dwellings within the Carmyle and Mount Vernon South Ward. Several sites were identified throughout the city that could be exploited but were not examined for this thesis as this Scenario was designed to test the tool's capabilities in identifying new potential sites subject to several criteria.

Scenario 5 explored the potential of deploying PVPS on the roofs of 3 multi-story car parks in Glasgow's city centre which were identified as being suitable. This would produce 572 MWh/y from a combined area of 1.46 ha and is the equivalent of the annual charging requirements of 311 EVs. The car park with the largest canopy area is the SEC car park which possessed a reduced area of 0.72 ha due to overshading by nearby tall structures affecting the southern portion of the canopy and can potentially produce 287 MWh/y, equivalent to 156 EVs.

Scenario 6 explored the identification of unconstrained land for housing development to tackle the city's homeless crisis. With 87.3 ha of unconstrained land available, 1,554 new dwellings could be built to accommodate 4.3% of the homeless community. The Ward with the greatest opportunity is Sighthill which comprises of 9.0 ha of unconstrained land with a potential to develop 161 new dwellings. The largest site of unconstrained land is Site 5308 possessing 3.2 ha equivalent to 58 homes.

To summarise, the GOMap tool has been applied to assess PVPS deployments at unconstrained VDL sites, multi-story car park canopies, and assess areas for housing development in Glasgow. Considering all available information should be included in the assessment during a decision-making process to make a reasonable judgement, particularly with non-equal weightings due to the significance of certain aspects, Scenario 1 is more likely to be the more informative scenario. Therefore, Scenario 1 with all aspect information active and non-equally weighted gives rise to 327.1 ha of VDL that could supply 12,714 of Glasgow's dwellings. Alternatively, if this energy was instead used for EV charging, it would be the equivalent to 74,251 EVs or 49% of Glasgow's car fleet.

7.4 Research findings for other cities

After assessing Glasgow, GOMap was applied to six other cities to represent climates at various latitudes to identify unconstrained land of sites designated for urban renewal development and the PVPS potential. Local information corresponding to sites, buildings, structure heights, topography, annual space heating/cooling requirements and annual electrical consumption of EVs were collected. The cities include Berlin, Cape Town, Madrid, Melbourne, Paris and Tokyo. The findings had shown that each city possessed varying PVPS potential, heating/cooling and EV energy requirements, and sites of varying unconstrained areas. As with Glasgow, a land utilisation factor is set to 50% to ensure adequate space for the deployment and maintenance of PVPS installation.

The Site possessing the largest amount of unconstrained land was Swartklip, Cape Town which comprised of 209 ha, can generate an output energy of 199,088 MWh/y and can supply 75,872 dwellings or 55,302 EVs. The second largest was Tempelhofer Feld, Berlin with an area of 204 ha can output 80,267 MWh/y, the equivalent of 6,222 dwellings or 34,975 EVs. Tres Cantos, Madrid comprises of 118 ha and can produce output energy of 88,572 MWh/y which can supply 20,408 dwellings or 40,078 EVs. Fishermans Bend, Melbourne which has a utilised site area of 57 ha can output 64,066 MWh/y, the equivalent of 17,447 dwellings or 38,946 EVs. The Tokyo Metropolitan Area consists of 17.1 ha and can generate 11,040 MWh/y which can provide for 3,678 dwellings or 4,346 EVs.

To summarise, using available site, building, overshading and terrain information, the amount of land available for PVPS deployment was identified with optimal parameters and energy output of a PVPS determined by using local weather information. The potential output energy and its equivalence to the local city's heating/cooling and EV requirements were calculated. Although the tool was populated with limited information when transferred to other locations, it has shown that GOMap could be applied to any urban city provided the relevant information is available to produce a comprehensive and detailed opportunity map.

7.5 Discussion

GOMap is configured with a PVPS model to determine potential energy output from available land. Other models can be introduced into the tool for RETs such as wind and local district heating, both of which are based on basic models as shown in APPENDIX I.2 but were not included in any assessments as these models, at the time of this thesis, did not reach the required level necessary for rigorous testing and analysis. However, these models were introduced to show the tool's capabilities in supporting new RET models.

In general, concerns must be raised when dealing with land use. One common example would be if certain parcels of land are utilised for RET deployment, it would no longer be available for arable purposes or new buildings. Displacing land which would otherwise be used for crops or housing development can pose issues and raise questions such as whether the generated energy produced from a possible PVPS farm is considered more important and desirable than extra food supplies and/or accommodation. These questions are beyond the scope of this thesis but highlight the concerns which would need to be addressed by the local authority.

If other technologies are to be assessed by GOMap, some policy and technical information will need to be adapted and new RET models introduced which the tool can support. Technical aspects and evaluation criteria would likely be different for each renewable technology, i.e. the method of creating opportunity maps based on technical aspects for a technology such as PVPS could be directly applied to other cities. However, each local authority may have its own approach to policy aspects and these would need to be evaluated in accordance with local procedures. For example, if a new RET is introduced in Glasgow, a new set of policy and technical evaluations may be required and others relaxed as they may no longer apply. However, if a different local authority wanted to produce a similar RET opportunity map, they can apply the same technical aspects but may need to adjust the scoring criteria and introduce their own policy factors.

GOMap itself is designed to provide opportunity maps for decision-makers and encourage collaboration between city planners and utility specialists. It does not address issues of technical design, costs, revenues or opportunities to enhance integration with commercial development. Neither does it remove the requirement to go through the normal planning control process for a new development.

7.6 Future tool development

In the foreseeable future, GOMap may be expanded to include other low carbon technologies that may be applicable across cities, and to include additional policy and technical factors as required. One such example could be the exploitation of mine water beneath cities via boreholes and using heat pumps for heat extraction. This low carbon technology may include policy factors such as: ecological measurements of the gases and waters underground to ensure these are within safety limits; land acquisition or requesting permission to access suitable sites particularly if privately owned. Other technical factors may include: temperature and water movement to determine the amount of space heating which can be extracted by the heat pumps; level of depth required to reach the energy supply; and the feasibility of delivering this energy to nearby buildings.

A major refinement to GOMap is the possibility to evolve as a standalone GIS application with capabilities to communicate with energy systems simulation software such as ESP-r (Clarke 2001, Strachan *et al* 2008). Using building stock models within the ESP-r package, annual heating or electrical requirements can be simulated considering stochastic parameters such as occupancy behaviour and control of devices and systems such as windows, lighting and heating equipment (Clarke *et al* 2009). Importing this information into GOMap enables the creation of high-level energy requirement maps for community-level technology appraisal. Further investigation of these maps can help determine which areas of a city should be given priority or assist in tackling fuel poverty.

A second possible extension to GOMap is the implementation of additional technology models such as wind power and local district heating networks. While basic models have been developed in this regard, as described in APPENDIX I.2, introducing detailed models for such technologies will greatly expand the accuracy and scope of the GOMap approach.

To further verify GOMap as an effective decision-support tool, other cities could be examined using similar high-quality information as was collected and utilised in this work for the city of Glasgow. However, some policy and technical information may not be publicly available or not easily accessed. To remedy this, contact with the city’s local authority may be the recommended solution and could prove beneficial with a successful proposal of a research project. This can provide access to information which in turn can lead to the requirement of further material from local utility providers encouraging positive collaboration between different parties. This has the potential of opening discussion on future projects.

7.7 Concluding remarks

The primary aim of the presented work was to design a method to determine the renewable energy potential of any city utilising available land that is policy and technically unconstrained. This was encapsulated in a high-resolution geospatial opportunity mapping tool to allow the identification of unconstrained land within an urban environment and to assess the potential of utilising this land for PVPS deployment. With much interest in the current climate for deploying clean energy systems, it is hoped that the GOMap tool presented here can be used as a decision support tool to aid policy makers and developers and encourage RET deployment within an urban city or elsewhere.

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APPENDIX I: GOMap features

I.1 Data sources

The various sets of data examined throughout this thesis were obtained from the sources listed below.

For Glasgow:

- CEDA – DSM and DTM for structure heights and terrain information respectively.
- Edina – Building and neighbouring council information.
- ESRU – Technical information concerning PVPS.
- GCC – Policy information involved in decision-making.
- OS – DSM, DTM and locations of inhabited dwellings.
- SEPA – Flood maps.
- SPEN – Technical information concerning electrical distribution networks.

For other cities:

- Berlin Open Data – Site and building information for Berlin.
- CEDA – DSM and DTM for structure heights and terrain information respectively.
- City of Cape Town Open Data Portal – Site and building information for Cape Town.
- City of Melbourne Open Data – Site and building information for Melbourne.
- Geofabrik – Site and building information for Madrid.
- Geospatial Information Authority of Japan – Site and building information for Tokyo.
- Open platform for French public data – Site and building information for Paris.

I.2 Scripts and models

The following Python script and models provide additional analytical tools extending GOMap's functionality.

I.2.1 Identifying northerly- or southerly-facing rooftops

Identifying roofs facing the northerly or southerly direction requires two sets of input data: a high-resolution DSM; and a polygon building dataset representing rooftops. For this example, the script has been applied to Glasgow with a DSM resolution of 2 m; and a polygon dataset that contains approximately 190,000 buildings (dwellings, commercial and industrial properties).

A workflow outline is designed and implemented to estimate the southerly-facing area of rooftops using the DSM source file as shown in Figure A1.1 for Glasgow (situated in the northern hemisphere), which shows the outputs at each stage in a series of geospatial procedures. First, the DSM image file is processed into an aspect raster. The aspect raster identifies the downslope direction of the maximum direction of change in value from each cell to its neighbours. Each individual cell of the resulting raster contains a value which indicates the compass direction the surface faces at that location (due north is 0º, east 90º etc.).

The aspect raster is reclassified to simpler values This reclassification sets the pixel value (or cell value) to 1 if the factor is between the southern-facing direction of 135º and 225º from north; otherwise it is set to 0. This step optimises the entire workflow by allowing later procedures to extract simple Boolean values and work with a greatly reduced file size.

The reclassified raster is polygonised. This procedure converts the reclassified raster into a polygon dataset. This allows each group of cells representing a building, to be transformed into a group of vectors. This is done to allow the data to be queried and the surface area calculated.

Now that each polygon contains a Boolean value, a filter is executed to extract all polygon features with a value of 1; those with a value of 0 are ignored. This provides a vector layer of southerly-facing areas

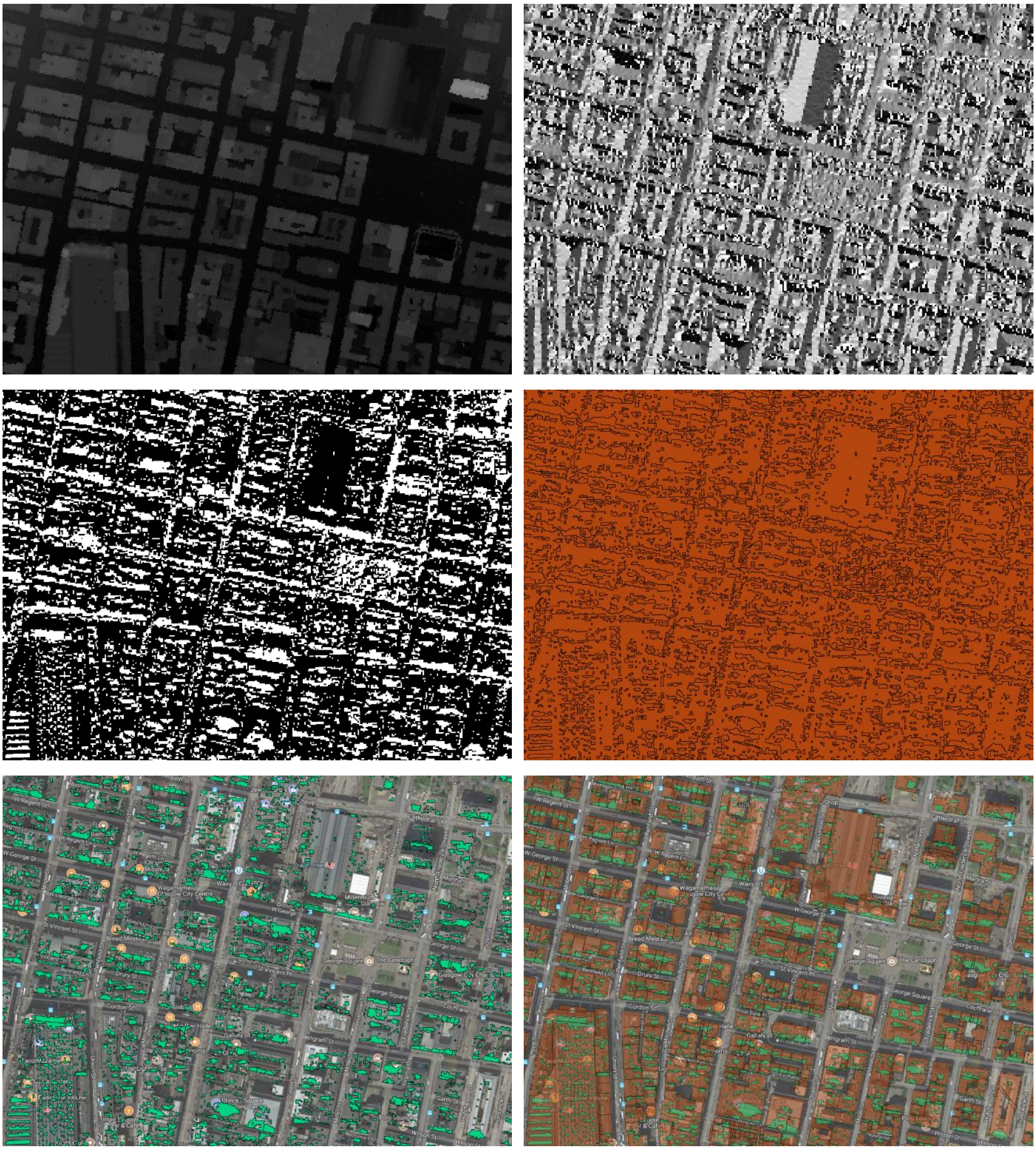

Figure A1.1. Southerly-facing rooftop procedure: Original DSM image file (upper-left); Process the DSM into an aspect raster (upper-right); Reclassify the factor raster to simpler values (middle-left); Polygonise the reclassified raster (middle-right); Filter and intersect surface area polygons with building polygons (bottom-left); Final result showing southerly-facing parts of rooftops in green overlaying orange buildings (bottom-right).

The filtered vector layer is intersected onto the building polygon layer to provide a final layer containing the estimated southerly-facing areas of rooftops. Polygons are generated to represent parts of southerly-facing rooftops (as the view is top-to-bottom, these polygons can be treated as rooftops), selected by the user as shown in Figure A1.2. The result can then be used as a scope for the installation for PVPS as shown in Figure A1.3. The PVPS model will set the azimuth of each polygon to automatically match the azimuth of the rooftop by retrieving the angle values from the aspect raster. Although this workflow focused on southerly-facing rooftops, the same logical workflow is applied for northerly-facing rooftops when selected.

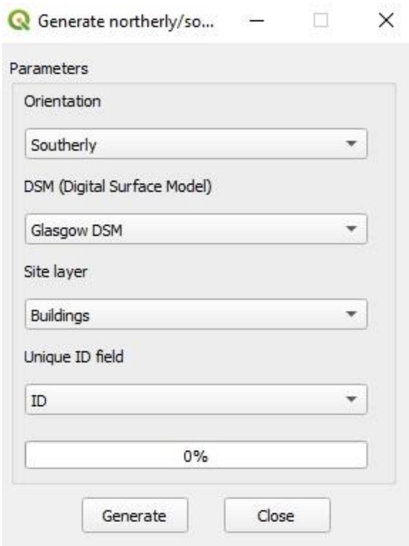

Figure A1.2. Configuration interface for generating northerly- or southerly-facing rooftops.

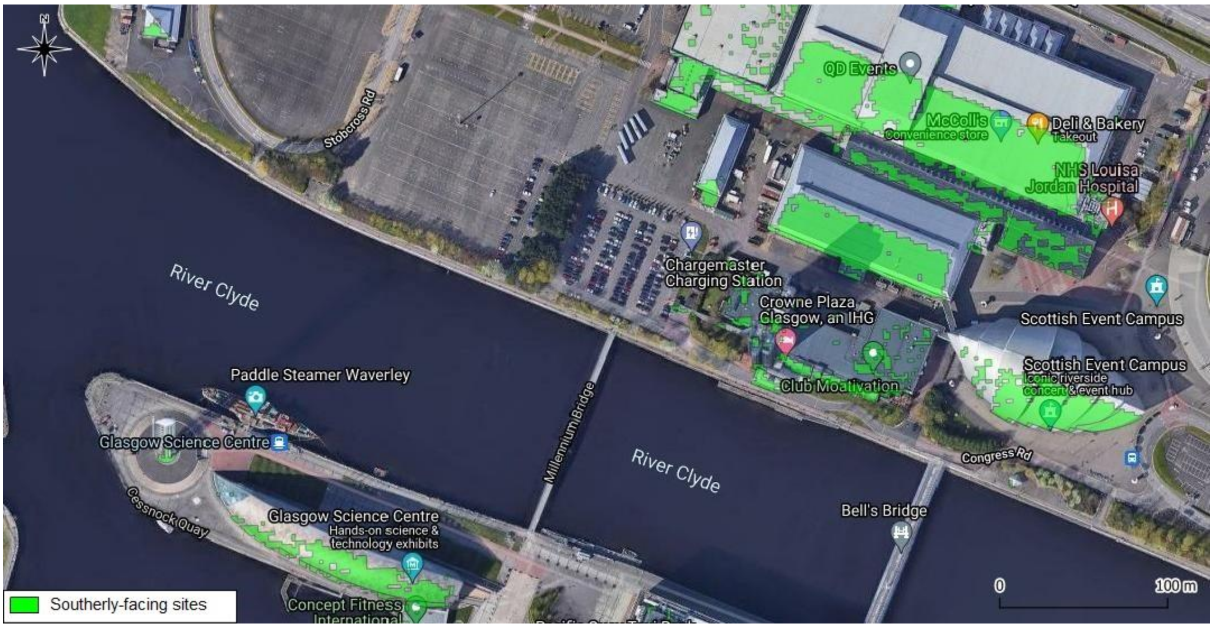

Figure A1.3. Southerly-facing rooftops generated over the SEC in Glasgow.

I.2.2 Wind model

In addition to the PVPS model as described in Section 3.3.3, a wind model generates point features representing wind turbines with specifications such as rotor diameter and minimum distance between turbines to identify suitable placements for wind turbine installation. These parameters can be configured from the model interface as shown in Figure A1.4.

Figure A1.5 shows the Cathkin Braes, an area of hills to the southeast of Glasgow, which sites a 3 MW wind turbine installed since 2013. Assuming there are two unconstrained sites available nearby, the script can generate points shown as wind turbines within a boundary depicting the minimum distance ensuring the turbines are not in close proximity to one another or a residential area.

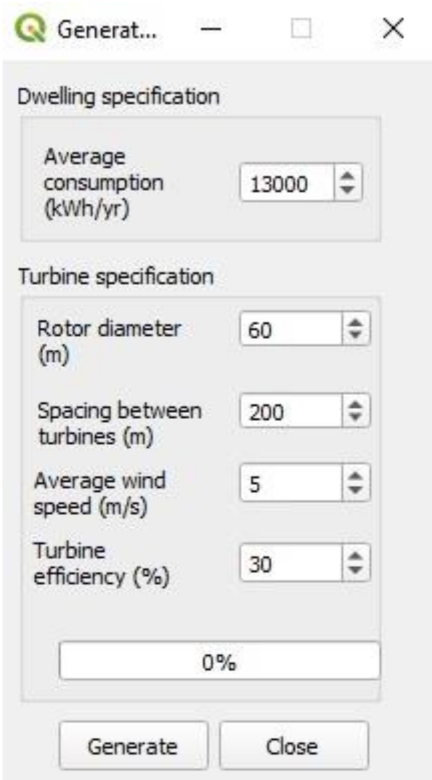

Figure A1.4. Wind model interface.

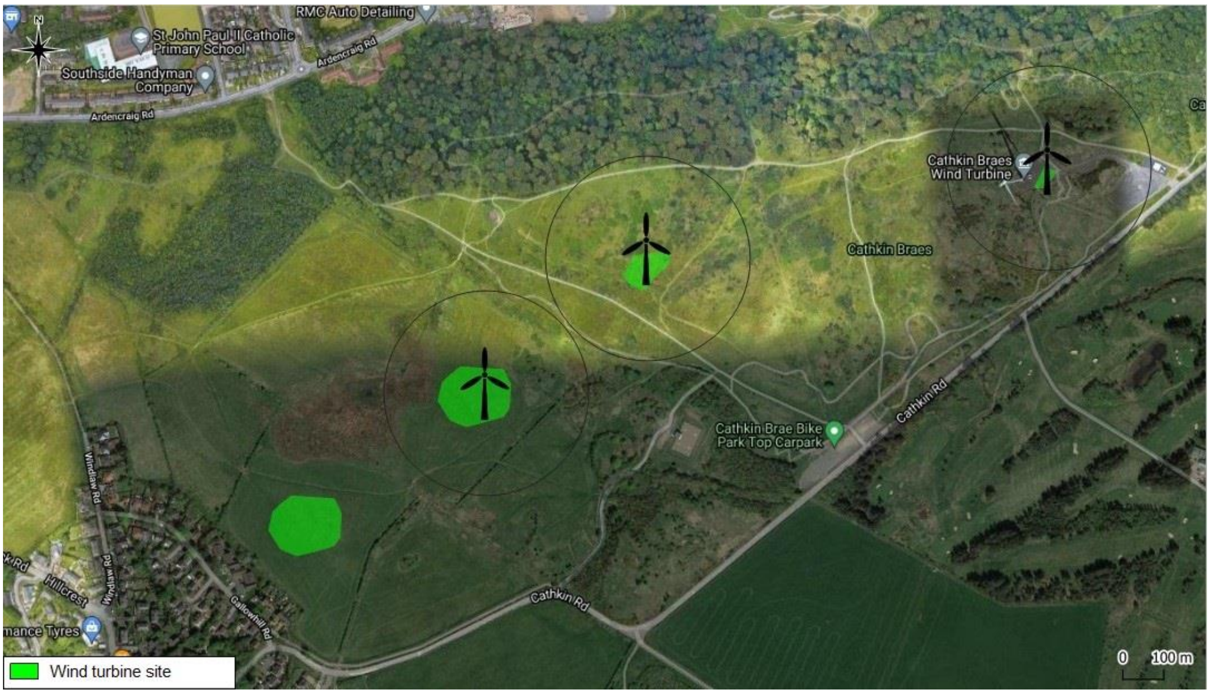

Figure A1.5. Wind turbines generated over unconstrained land at Cathkin Braes.

I.2.3 Local district heating model

Another model introduced to GOMap is the local district heating model which generates both points and polygons with specifications such as the estimated proximity radius that the network would supply, energy capacity, coefficient of performance, and percentage heat loss. These parameters can be configured from the model interface as shown in Figure A1.6. The points represent the source location of the local district heating scheme; the polygons represent the buildings within the specified radius, which can either be supplied by the network (marked as green) or not (marked as red) as shown in Figure A1.7.

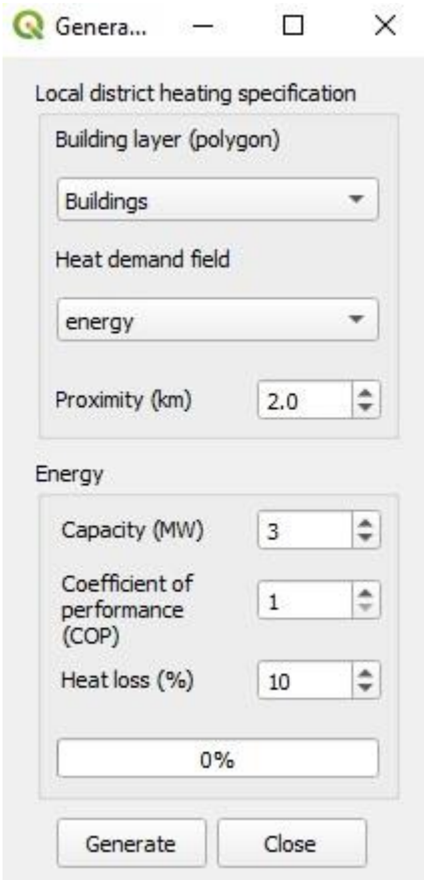

Figure A1.6. Local district heating network model interface.

Figure A1.7. Local district heating network able to supply a nearby dwellings.

APPENDIX II: Supplementary tables.

II.1 MCDM/AHP method to determine weightings and CR

II.1.1 CR for policy and technical aspects in Scenarios 1 & 4

Table A2.1. Calculations to determine CR for policy aspects in Scenarios 1 & 4.

Criteria	Calculations
Biodiversity consistency vector	$\frac{(1.000 * 0.326) + (3.000 * 0.114) + (1.000 * 0.326) + (3.000 * 0.148) + (3.000 * 0.086)}{0.326} = 5.201$
Developmental consistency vector	$\frac{(0.333 * 0.326) + (1.000 * 0.114) + (0.333 * 0.326) + (0.500 * 0.148) + (2.000 * 0.086)}{0.114} = 5.045$
Environmental consistency vector	$\frac{(1.000 * 0.326) + (3.000 * 0.114) + (1.000 * 0.326) + (3.000 * 0.148) + (3.000 * 0.086)}{0.326} = 5.201$
Visual impact consistency vector	$\frac{(0.333 * 0.326) + (2.000 * 0.114) + (0.333 * 0.326) + (1.000 * 0.148) + (2.000 * 0.086)}{0.148} = 5.174$
Visual intrusion consistency vector	$\frac{(0.333 * 0.326) + (0.500 * 0.114) + (0.333 * 0.326) + (0.500 * 0.148) + (1.000 * 0.086)}{0.086} = 5.069$
λ	$\frac{5.201 + 5.045 + 5.201 + 5.174 + 5.069}{5.000} = 5.138$
CI	$\frac{5.138 - 5.000}{5.000 - 1.000} = 0.035$
RI	1.120
CR	$\frac{0.035}{1.120} = 0.031 < 0.100$

Table A2.2. Calculations to determine CR for technical aspects in Scenarios 1 & 4.

Criteria	Calculations
Overshading consistency vector	$\frac{(1.000*0.484)+(3.000*0.168)+(3.000*0.231)+(3.000*0.117)}{0.484}=4.197$
Substation congestion consistency vector	$\frac{(0.333*0.484)+(1.000*0.168)+(0.500*0.231)+(2.000*0.117)}{0.168}=4.050$
Substation connection distance consistency vector	$\frac{(0.333*0.484)+(2.000*0.168)+(1.000*0.231)+(2.000*0.117)}{0.231}=4.163$
Terrain consistency vector	$\frac{(0.333*0.484)+(0.500*0.168)+(0.500*0.231)+(1.00*0.117)}{0.117}=4.079$
λ	$\frac{4.197+4.050+4.163+4.079}{4.000}=4.122$
CI	$\frac{4.122-4.000}{4.000-1.000}=0.041$
RI	0.900
CR	$\frac{0.041}{0.900}=0.045<0.100$

II.1.2 Weightings and CR for policy aspects in Scenario 2

Table A2.3. Pairwise comparison matrix of the evaluation criteria for policy aspects in Scenario 2.

Aspects	Biodiversity	Developmental	Environmental
Biodiversity	1.000	3.000	1.000
Developmental	0.333	1.000	0.333
Environmental	1.000	3.000	1.000
Σ	2.333	7.000	2.333

Table A2.4. Weighting by pairwise comparison for policy aspects in Scenario 2.

Aspects	Biodiversity	Developmental	Environmental	Weighting
Biodiversity	0.429	0.429	0.429	0.429
Developmental	0.143	0.143	0.143	0.143
Environmental	0.429	0.429	0.429	0.429
Σ	1.000	1.000	1.000	1.000

Table A2.5. Calculations to determine CR for policy aspects in Scenario 2.

Criteria	Calculations
Biodiversity consistency vector	$\frac{(1.000 * 0.429) + (3.000 * 0.143) + (1.000 * 0.429)}{0.429} = 3.000$
Developmental consistency vector	$\frac{(0.333 * 0.429) + (1.000 * 0.143) + (0.333 * 0.429)}{0.143} = 3.000$
Environmental consistency vector	$\frac{(1.000 * 0.429) + (3.000 * 0.143) + (1.000 * 0.429)}{0.429} = 3.000$
λ	$\frac{3.000 + 3.000 + 3.000}{3.000} = 3.000$
CI	$\frac{3.000 - 3.000}{3.000 - 1.000} = 0.000$
RI	1.120
CR	$\frac{0.000}{1.120} = 0.000 < 0.100$

II.1.3 Weightings and CR for technical aspects in Scenario 3

Table A2.6. Pairwise comparison matrix of the evaluation criteria for technical aspects in Scenario 3.

Aspects	Overshading	Terrain
Overshading	1.000	3.000
Terrain	0.333	1.000
Σ	1.333	4.000

Table A2.7. Weighting by pairwise comparison for technical aspects in Scenario 3.

Aspects	Overshading	Terrain	Weighting
Overshading	0.750	0.750	0.750
Terrain	0.250	0.250	0.250
Σ	1.000	1.000	1.000

Table A2.8. Calculations to determine CR for technical aspects in Scenario 3.

Criteria	Calculations
Overshading consistency vector	$\frac{(1.000 * 0.750) + (3.000 * 0.250)}{0.750} = 2.000$
Terrain consistency vector	$\frac{(0.333 * 0.750) + (1.000 * 0.250)}{0.250} = 2.000$
λ	$\frac{2.000 + 2.000}{2.000} = 2.000$
CI	$\frac{2.000 - 2.000}{2.000 - 1.000} = 0.000$
RI	0.000
CR	$\frac{0.000}{0.000} = 0.000 < 0.100$

II.1.4 Weightings and CR for policy and technical aspects in Scenario 5

Table A2.9. Pairwise comparison matrix of the evaluation criteria for policy aspects in Scenario 5.

Aspects	Visual impact	Visual intrusion
Visual impact	1.000	2.000
Visual intrusion	0.500	1.000
Σ	1.500	3.000

Table A2.10. Weighting by pairwise comparison for policy aspects in Scenario 5.

Aspects	Biodiversity	Developmental	Weighting
Visual impact	0.667	0.667	0.667
Visual intrusion	0.333	0.333	0.333
Σ	1.000	1.000	1.000

Table A2.11. Calculations to determine CR for policy aspects in Scenario 5.

Criteria	Calculations
Visual impact consistency vector	$\frac{(1.000 * 0.667) + (2.000 * 0.333)}{0.667} = 2.000$
Visual intrusion consistency vector	$\frac{(0.500 * 0.667) + (1.000 * 0.333)}{0.333} = 2.000$
λ	$\frac{2.000 + 2.000}{2.000} = 2.000$
CI	$\frac{2.000 - 2.000}{2.000 - 1.000} = 0.000$
RI	0.000
CR	$\frac{0.000}{0.000} = 0.000 < 0.100$

Table A2.12. Pairwise comparison matrix of the evaluation criteria for technical aspects in Scenario 5.

Aspects	Overshading	Substation congestion	Substation connection distance
Overshading	1.000	3.000	3.000
Substation congestion	0.333	1.000	0.500
Substation connection distance	0.333	2.000	1.000
Σ	1.667	6.000	4.500

Table A2.13. Weighting by pairwise comparison for technical aspects in Scenario 5.

Aspects	Overshading	Substation congestion	Substation connection distance	Weighting
Overshading	0.600	0.500	0.667	0.589
Substation congestion	0.200	0.167	0.111	0.159
Substation connection distance	0.200	0.333	0.222	0.252
Σ	1.000	1.000	1.000	1.000

Table A2.14. Calculations to determine CR for technical aspects in Scenario 5.

Criteria	Calculations
Overshading consistency vector	$\frac{(1.000 * 0.589) + (3.000 * 0.159) + (3.000 * 0.252)}{0.589} = 3.094$
Substation congestion consistency vector	$\frac{(0.333 * 0.589) + (1.000 * 0.159) + (0.500 * 0.252)}{0.159} = 3.023$
Substation connection distance consistency vector	$\frac{(0.333 * 0.589) + (2.000 * 0.159) + (1.000 * 0.252)}{0.252} = 3.044$
λ	$\frac{3.094 + 3.023 + 3.044}{3.000} = 3.054$
CI	$\frac{3.054 - 3.000}{3.000 - 1.000} = 0.027$
RI	0.580
CR	$\frac{0.027}{0.580} = 0.046 < 0.100$

II.1.5 Weightings and CR for policy and technical aspects in Scenario 6

Table A2.15. Pairwise comparison matrix of the evaluation criteria for policy aspects in Scenario 6.

Aspects	Biodiversity	Developmental	Environmental	Visual impact
Biodiversity	1.000	3.000	1.000	3.000
Developmental	0.333	1.000	0.333	0.500
Environmental	1.000	3.000	1.000	3.000
Visual impact	0.333	2.000	0.333	1.000
Σ	2.667	9.000	2.667	7.500

Table A2.16. Weighting by pairwise comparison for policy aspects in Scenario 6.

Aspects	Biodiversity	Developmental	Environmental	Visual impact	Weighting
Biodiversity	0.375	0.333	0.375	0.400	0.371
Developmental	0.125	0.111	0.125	0.067	0.107
Environmental	0.375	0.333	0.375	0.400	0.371
Visual impact	0.125	0.222	0.125	0.133	0.151
Σ	1.000	1.000	1.000	1.000	1.000

Table A2.17. Calculations to determine CR for policy aspects in Scenario 6.

Criteria	Calculations
Biodiversity consistency vector	$\frac{(1.000 * 0.371) + (3.000 * 0.107) + (1.000 * 0.371) + (3.000 * 0.151)}{0.371} = 4.090$
Developmental consistency vector	$\frac{(0.333 * 0.371) + (1.000 * 0.107) + (0.333 * 0.371) + (0.500 * 0.151)}{0.107} = 4.019$
Environmental consistency vector	$\frac{(1.000 * 0.371) + (3.000 * 0.107) + (1.000 * 0.371) + (3.000 * 0.151)}{0.371} = 4.090$
Visual impact consistency vector	$\frac{(0.333 * 0.371) + (2.000 * 0.107) + (0.333 * 0.371) + (1.000 * 0.151)}{0.151} = 4.046$
λ	$\frac{4.090 + 4.019 + 4.090 + 4.046}{4.000} = 4.061$
CI	$\frac{4061 - 4.000}{4.000 - 1.000} = 0.020$
RI	0.900
CR	$\frac{0.020}{0.900} = 0.023 < 0.100$

II.2 Total heat demand per ward and average heat demand per dwelling

Table A2.18. Total heat demand per ward and average heat demand per dwelling.

Ward	Postcode	Area of Ward (ha)	No of VDL sites	Total area of VDL sites (ha)	No of inhabited dwellings	Total Ward heat demand (MWh/y)	Average dwelling heat demand (MWh/y)
Anderston	G3 8	26.7	1	0.43	1,243	731	0.6
Anniesland East	G13 1	320.8	19	17.19	4,476	44,719	10.0
Baillieston East	G69 6	176.5	6	3.56	2,886	45,359	15.7
Baillieston West	G69 7	171.7	2	3.81	3,414	61,615	18.0
Balornock	G21 3	13.3	-	-	272	3,640	13.4
Barlanark	G33 3	194.8	22	18.78	2,369	21,962	9.3
Barmulloch	G21 3	10.1	-	-	122	1,162	9.5
Battlefield	G41 2	11.5	-	-	1,184	7,838	6.6
Blackhill and Barmulloch East	G33 1	240.2	13	53.43	3,131	50,153	16.0
Blairdardie East	G13 1	118.4	-	-	3,067	36,694	12.0
Braidfauld	G40 3	52.2	3	2.54	1,644	17,124	10.4
Broomhill	G11 7	22.7	-	-	1,111	33,009	29.7
Calton, Galllowgate and Bridgeton	G1 2	104.4	15	9.89	5,803	19,976	3.4
Cardonald North	G52 3	17.0	-	-	521	4,830	9.3
Cardonald South and East	G52 1	192.2	3	1.6	2,977	36,954	12.4
Cardonald West and Central	G53 5	358.0	1	0.95	6,485	84,833	13.1
Carmunnock North	G44 5	57.6	2	1.44	1,412	28,275	20.0
Carmunnock South	G76 8	110.4	-	-	1,061	18,904	17.8
Carmyle and Mount Vernon South	G32 8	950.6	27	74.73	6,249	91,022	14.6
Carntyne	G33 2	117.0	4	3.71	2,286	43,407	19.0

Carntyne West and Haghill	G31 1	43.3	1	0.61	3,382	21,389	6.3
Carnwadric East	G43 2	73.5	-	-	1,484	27,058	18.2
Carnwadric West	G46 7	112.3	6	10.84	2,582	21,855	8.5
Castlemilk	G44 5	782.4	16	18.94	7,282	161,643	22.2
Cathcart	G44 4	45.6	-	-	3,188	26,238	8.2
Central Easterhouse	G69 8	40.1	10	11.84	552	26,443	47.9
City Centre East	G1 2	315.8	26	9.52	8,743	8,726	1.0
City Centre West	G3 6	16.7	-	-	1,237	5,880	4.8
Craigend and Ruchazie	G33 3	269.2	12	16.81	3,063	28,321	9.2
Craigton	G52 1	321.6	11	12.35	4,847	63,027	13.0
Cranhill, Lightburn and Queenslie South	G33 2	296.8	17	20.67	3,881	59,319	15.3
Crookston North	G53 5	35.0	-	-	598	9,185	15.4
Crookston South	G53 6	59.2	4	5.08	1,168	15,443	13.2
Dalmarnock	G40 1	258.2	31	29.56	5,078	57,639	11.4
Darnley East	G43 1	491.8	8	50.47	4,547	49,285	10.8
Darnley North	G53 6	46.2	1	0.48	1,000	10,008	10.0
Darnley West	G53 7	170.4	12	6.28	2,713	26,179	9.6
Dennistoun	G31 2	7.8	-	-	827	8,290	10.0
Dowanhill	G12 8	16.4	-	-	1,088	14,331	13.2
Drumchapel North	G61 4	84.7	8	15.72	628	5,825	9.3
Drumchapel South	G15 6	273.5	23	20.54	4,947	52,648	10.6
Drumoyne and Shieldhall	G51 4	635.6	25	35.78	8,565	84,760	9.9
Drumry West	G81 2	118.7	21	14.96	1,763	22,127	12.6
Easterhouse East	G69 8	61.0	11	20.14	760	7,119	9.4
Finnieston and Kelvinhaugh	G3 8	63.7	6	5.92	3,203	18,527	5.8
Gallowgate North and Bellgrove	G31 1	14.8	-	-	1,049	10,433	9.9
Garrowhill East and Swinton	G34 0	219.9	10	45.85	1,144	9,981	8.7

Garrowhill West	G33 4	140.0	9	21.53	1,609	21,054	13.1
Garthamlock, Auchinlea and Gartloch	G69 8	7.3	-	-	308	1,815	5.9
Glasgow Harbour and Partick South	G11 7	189.3	8	18.32	8,437	472,135	56.0
Glenwood North	G45 9	82.4	2	9.29	1,902	21,647	11.4
Glenwood South	G45 9	18.4	-	-	416	6,888	16.6
Gorbals and Hutchesontown	G5 9	97.7	7	9.88	3,297	29,553	9.0
Govanhill West	G42 8	71.2	7	7.72	4,462	37,082	8.3
Greenfield	G32 6	135.9	2	5.03	3,058	36,047	11.8
Hillhead	G11 6	248.2	6	6.75	7,966	76,040	9.5
Hillington	G52 4	25.1	-	-	666	7,339	11.0
Ibrox	G51 4	18.4	1	1.62	607	6,892	11.4
Ibrox East and Cessnock	G51 2	39.2	6	9.62	1,403	15,755	11.2
Kelvindale	G12 0	114.5	3	4.02	3,481	56,053	16.1
Kelvingrove and University	G4 9	42.1	-	-	1,877	31,084	16.6
Kelvinside and Jordanhill	G13 1	300.7	2	3.94	7,639	126,043	16.5
Keppochhill	G22 6	87.1	22	22.42	1,933	101,042	52.3
Kingspark North	G44 4	13.3	-	-	279	4,557	16.3
Kingspark South	G44 5	64.1	-	-	1,418	25,724	18.1
Kinning Park and Festival Park	G41 1	325.5	22	22.56	6,003	37,812	6.3
Knightswood East	G13 3	259.2	-	-	5,709	67,309	11.8
Knightswood Park East	G13 1	104.8	-	-	2,697	35,142	13.0
Knightswood Park West	G15 6	19.4	-	-	418	7,459	17.8
Knightswood West	G13 4	18.5	-	-	301	3,645	12.1
Langside	G41 3	12.4	-	-	1,331	12,690	9.5
Laurieston and Tradeston	G41 1	15.1	4	1.35	651	3,465	5.3
Maryhill East	G22 6	862.5	17	27.82	3,247	32,825	10.1
Maryhill West	G20 0	66.6	6	6.63	2,119	13,649	6.4
Maxwell Park	G41 4	735.5	8	3.87	5,195	86,510	16.7

Merrylee and Millbrae	G43 2	130.7	-	-	4,539	77,933	17.2
Milton East	G22 7	17.3	2	2.78	585	4,366	7.5
Milton West	G22 7	32.9	2	4.16	930	10,997	11.8
Mosspark	G52 1	21.2	1	0.65	410	4,849	11.8
Mount Florida	G42 0	8.5	-	-	478	4,824	10.1
Mount Vernon North and Sandyhills	G32 0	108.8	1	0.26	1,652	44,237	26.8
Muirend and Old Cathcart	G44 3	177.6	1	0.55	4,063	63,440	15.6
Newlands	G43 2	18.1	-	-	925	5,885	6.4
Nitshill	G53 6	136.0	10	10.55	2,386	30,338	12.7
North Barlanark and Easterhouse South	G33 5	645.0	19	74.62	1,931	17,450	9.0
North Kelvin	G20 6	19.8	1	0.58	1,377	9,276	6.7
Old Shettleston and Parkhead North	G33 2	149.6	15	15.82	2,417	24,195	10.0
Parkhead East and Braidfauld North	G31 1	364.5	27	29.74	7,737	64,294	8.3
Parkhead West and Barrowfield	G31 1	103.0	17	14.75	2,089	59,333	28.4
Partick	G11 5	34.3	-	-	2,564	18,572	7.2
Partickhill and Hyndland	G12 9	29.1	-	-	1,220	25,215	20.7
Penilee	PA1 3	38.4	-	-	974	10,871	11.2
Petershill	G21 1	174.1	19	35.74	4,028	44,363	11.0
Pollok South and West	G78 1	106.7	-	-	1,290	17,580	13.6
Pollokshaws	G53 6	76.4	4	22.85	661	4,043	6.1
Pollokshields East	G41 4	83.3	1	1.35	2,044	28,471	13.9
Possil Park	G22 6	160.4	16	21.23	2,567	31,198	12.2
Riddrie and Hogganfield	G33 1	389.0	15	65.34	2,085	23,566	11.3
Robroyston and Millerston	G33 1	62.2	2	0.8	1,185	16,467	13.9
Roystonhill, Blochairn, and Provanmill	G31 2	69.2	7	5.99	2,201	20,438	9.3
Ruchill	G20 7	230.7	15	25.19	7,576	77,326	10.2
Scotstoun North and East	G14 9	15.3	-	-	1,040	6,172	5.9

Shawlands West	G43 2	5.1	-	-	491	1,709	3.5
Shettleston North	G32 7	163.5	7	2.72	4,388	57,931	13.2
Sighthill	G21 2	410.0	31	43.64	5,481	40,485	7.4
Springburn	G21 1	230.1	5	7.63	3,253	35,606	10.9
Strathbungo	G42 8	214.1	1	0.12	7,359	89,464	12.2
Summerston North	G23 5	39.9	-	-	1,355	11,878	8.8
Toryglen and Oatlands	G5 0	372.4	14	27.08	7,843	79,428	10.1
Whiteinch	G14 9	123.3	1	0.31	2,746	35,401	12.9
Woodlands	G3 6	21.6	-	-	2,275	25,699	11.3
Woodside	G4 9	61.4	9	12.72	2,523	35,924	14.2
Wyndford	G20 0	10.0	3	1.66	293	4,324	14.8
Yoker North	G13 4	7.7	-	-	234	2,726	11.6
Yoker South	G13 4	200.5	11	13.24	5,220	57,106	10.9
Total	**-**	**17,515.6**	**766**	**1,168.9**	**313,876**	**4,104,522**	**-**

II.3 Aspect influence on Glasgow Wards

Table A2.19. Aspect influence on Glasgow Wards.

Ward	Biodiversity	Developmental	Environmental	Visual impact	Visual intrusion	Overshading	Substation congestion	Substation connection distance	Terrain
Anderston	✗	✓	✓	✓	✓	✓	✓	✓	✗
Anniesland East	✗	✓	✓	✓	✗	✓	✓	✓	✓
Baillieston East	✓	✓	✓	✓	✓	✓	✓	✓	✓
Baillieston West	✓	✓	✓	✓	✗	✓	✓	✓	✓
Balornock	✓	✗	✓	✓	✗	✓	✓	✓	✗
Barlanark	✗	✓	✓	✓	✓	✓	✓	✓	✗
Barmulloch	✓	✓	✗	✓	✗	✓	✓	✓	✗
Battlefield	✗	✓	✓	✓	✗	✓	✓	✓	✗
Blackhill and Barmulloch East	✓	✓	✓	✓	✓	✓	✓	✓	✓
Blairdardie East	✗	✓	✓	✓	✗	✓	✓	✓	✗
Braidfauld	✓	✓	✓	✓	✗	✓	✓	✓	✓
Broomhill	✗	✓	✓	✓	✓	✓	✓	✓	✓
Calton, Galllowgate and Bridgeton	✗	✓	✓	✓	✗	✓	✓	✓	✓
Cardonald North	✗	✗	✗	✓	✓	✓	✓	✓	✗
Cardonald South and East	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cardonald West and Central	✓	✓	✓	✓	✓	✓	✓	✓	✓
Carmunnock North	✓	✓	✓	✓	✗	✓	✓	✓	✓

Carmunnock South	✓	✓	✓	✓	✗	✓	✓	✓	✓
Carmyle and Mount Vernon South	✓	✓	✓	✓	✓	✓	✓	✓	✓
Carntyne	✗	✓	✓	✓	✓	✓	✓	✓	✗
Carntyne West and Haghill	✗	✓	✓	✓	✗	✓	✓	✓	✗
Carnwadric East	✓	✗	✓	✓	✗	✓	✓	✓	✓
Carnwadric West	✓	✓	✓	✓	✗	✓	✓	✓	✓
Castlemilk	✓	✓	✓	✓	✗	✓	✓	✓	✓
Cathcart	✗	✓	✓	✓	✗	✓	✓	✓	✓
Central Easterhouse	✓	✓	✓	✓	✗	✓	✓	✓	✓
City Centre East	✓	✓	✓	✓	✓	✓	✓	✓	✓
City Centre West	✗	✓	✓	✓	✓	✓	✓	✓	✗
Craigend and Ruchazie	✓	✓	✓	✓	✓	✓	✓	✓	✓
Craigton	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cranhill, Lightburn and Queenslie South	✓	✓	✓	✓	✓	✓	✓	✓	✓
Crookston North	✗	✗	✓	✓	✗	✓	✓	✓	✓
Crookston South	✓	✓	✓	✓	✗	✓	✓	✓	✓
Dalmarnock	✓	✓	✓	✓	✗	✓	✓	✓	✓
Darnley East	✓	✓	✓	✓	✓	✓	✓	✓	✓
Darnley North	✓	✓	✓	✓	✗	✓	✓	✓	✗
Darnley West	✓	✓	✓	✓	✗	✓	✓	✓	✓
Dennistoun	✗	✓	✓	✓	✗	✓	✓	✓	✗
Dowanhill	✗	✓	✓	✓	✓	✓	✓	✓	✗
Drumchapel North	✗	✓	✓	✓	✗	✓	✓	✓	✓
Drumchapel South	✗	✓	✓	✓	✗	✓	✓	✓	✓

Drumoyne and Shieldhall	✗	✓	✓	✓	✓	✓	✓	✓	✓
Drumry West	✗	✓	✓	✓	✗	✓	✓	✓	✓
Easterhouse East	✓	✓	✓	✓	✗	✓	✓	✓	✗
Finnieston and Kelvinhaugh	✗	✓	✓	✓	✓	✓	✓	✓	✓
Gallowgate North and Bellgrove	✗	✓	✓	✓	✗	✓	✓	✓	✗
Garrowhill East and Swinton	✓	✓	✓	✓	✓	✓	✓	✓	✓
Garrowhill West	✓	✓	✓	✓	✓	✓	✓	✓	✓
Garthamlock, Auchinlea and Gartloch	✓	✓	✓	✓	✗	✓	✓	✓	✓
Glasgow Harbour and Partick South	✗	✓	✓	✓	✓	✓	✓	✓	✓
Glenwood North	✓	✓	✓	✓	✗	✓	✓	✓	✗
Glenwood South	✓	✓	✓	✓	✗	✓	✓	✓	✗
Gorbals and Hutchesontown	✗	✓	✓	✓	✓	✓	✓	✓	✓
Govanhill West	✗	✓	✓	✓	✓	✓	✓	✓	✗
Greenfield	✗	✓	✓	✓	✗	✓	✓	✓	✗
Hillhead	✗	✓	✓	✓	✓	✓	✓	✓	✓
Hillington	✗	✗	✗	✓	✓	✓	✓	✓	✗
Ibrox	✗	✓	✓	✓	✓	✓	✓	✓	✓
Ibrox East and Cessnock	✗	✓	✓	✓	✓	✓	✓	✓	✓
Kelvindale	✗	✓	✓	✓	✓	✓	✓	✓	✓
Kelvingrove and	✗	✓	✓	✓	✓	✓	✓	✓	✗

University									
Kelvinside and Jordanhill	✗	✓	✓	✓	✓	✓	✓	✓	✓
Keppochhill	✓	✓	✓	✓	✗	✓	✓	✓	✗
Kingspark North	✗	✗	✓	✓	✗	✓	✓	✓	✗
Kingspark South	✗	✗	✓	✓	✗	✓	✓	✓	✓
Kinning Park and Festival Park	✓	✓	✓	✓	✓	✓	✓	✓	✓
Knightswood East	✗	✓	✓	✓	✓	✓	✓	✓	✓
Knightswood Park East	✗	✓	✓	✓	✗	✓	✓	✓	✗
Knightswood Park West	✗	✗	✓	✓	✗	✓	✓	✓	✗
Knightswood West	✗	✗	✓	✓	✓	✓	✓	✓	✗
Langside	✗	✓	✓	✓	✗	✓	✓	✓	✓
Laurieston and Tradeston	✗	✓	✓	✓	✓	✓	✓	✓	✓
Maryhill East	✓	✓	✓	✓	✗	✓	✓	✓	✓
Maryhill West	✗	✓	✓	✓	✗	✓	✓	✓	✓
Maxwell Park	✓	✓	✓	✓	✓	✓	✓	✓	✓
Merrylee and Millbrae	✗	✓	✓	✓	✗	✓	✓	✓	✓
Milton East	✓	✓	✓	✓	✗	✓	✓	✓	✓
Milton West	✓	✓	✗	✓	✗	✓	✓	✓	✓
Mosspark	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mount Florida	✗	✓	✓	✓	✗	✓	✓	✓	✗
Mount Vernon North and Sandyhills	✓	✓	✓	✓	✗	✓	✓	✓	✓
Muirend and Old Cathcart	✗	✓	✓	✓	✗	✓	✓	✓	✓

Newlands	✗	✗	✓	✓	✗	✓	✓	✓	✓
Nitshill	✓	✓	✓	✓	✗	✓	✓	✓	✓
North Barlanark and Easterhouse South	✓	✓	✓	✓	✓	✓	✓	✓	✗
North Kelvin	✗	✓	✓	✓	✓	✓	✓	✓	✗
Old Shettleston and Parkhead North	✓	✓	✓	✓	✗	✓	✓	✓	✓
Parkhead East and Braidfauld North	✓	✓	✓	✓	✓	✓	✓	✓	✓
Parkhead West and Barrowfield	✓	✓	✓	✓	✗	✓	✓	✓	✓
Partick	✗	✓	✓	✓	✓	✓	✓	✓	✓
Partickhill and Hyndland	✗	✓	✓	✓	✓	✓	✓	✓	✗
Penilee	✗	✗	✗	✓	✓	✓	✓	✓	✗
Petershill	✗	✓	✓	✓	✗	✓	✓	✓	✓
Pollok South and West	✓	✓	✓	✓	✗	✓	✓	✓	✓
Pollokshaws	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pollokshields East	✗	✓	✓	✓	✓	✓	✓	✓	✗
Possil Park	✓	✓	✓	✓	✗	✓	✓	✓	✓
Riddrie and Hogganfield	✓	✓	✓	✓	✓	✓	✓	✓	✓
Robroyston and Millerston	✓	✓	✓	✓	✓	✓	✓	✓	✓
Roystonhill, Blochairn, and Provanmill	✗	✓	✓	✓	✓	✓	✓	✓	✗
Ruchill	✓	✓	✓	✓	✓	✓	✓	✓	✓
Scotstoun North and East	✗	✓	✓	✓	✓	✓	✓	✓	✓

Shawlands West	✗	✓	✓	✓	✗	✓	✓	✓	✓
Shettleston North	✗	✓	✓	✓	✗	✓	✓	✓	✓
Sighthill	✓	✓	✓	✗	✗	✓	✓	✓	✗
Springburn	✓	✓	✓	✓	✗	✓	✓	✓	✓
Strathbungo	✓	✓	✓	✓	✗	✓	✓	✓	✓
Summerston North	✗	✓	✓	✓	✗	✓	✓	✓	✗
Toryglen and Oatlands	✗	✓	✓	✓	✓	✓	✓	✓	✓
Whiteinch	✗	✓	✓	✓	✓	✓	✓	✓	✓
Woodlands	✗	✓	✓	✓	✓	✓	✓	✓	✗
Woodside	✓	✓	✓	✓	✓	✓	✓	✓	✗
Wyndford	✗	✓	✓	✓	✗	✓	✓	✓	✗
Yoker North	✗	✗	✓	✓	✓	✓	✓	✓	✓
Yoker South	✓	✓	✓	✓	✓	✓	✓	✓	✓

II.4 PVPS information for other cities

Table A2.20. PVPS information for cities.

City	Latitude & longitude	No. of households (millions)	Heating / cooling energy requirement (kWh/y)	Average commute (km/y)	EV energy requirement (kWh/y)	PVPS output energy (kWh/m^2.y)	PVPS tilt angle (º)	PVPS azimuth from due North (º)	Inter-row spacing distance (m)
Berlin	52.5 N, 13.4 W	2.00[27]	12,900	13,500	2,295	298	28	217	6.0
Cape Town	-34.0 N, 18.6 W	1.26[28]	2,624	18,250	3,600	372	30	15	5.5
Glasgow	55.5 N, -4.15 W	0.30[29]	13,000	12,550	1,500	173	37	205	7.4
Madrid	40.6 N, -3.7 W	2.59[30]	4,340	13,000	2,210	329	34	160	7.1
Melbourne	-37.8 N, 144.9 W	1.80[31]	3,672	12,000	1,645	341	32	10	5.2
Paris	47.2 N, -1.5 W	5.10[32]	8,100	13,000	2,210	220	41	183	7.9
Tokyo	35.7 N, 139.5 W	6.69[33]	3,000	15,000	2,540	217	35	187	6.7

[27] Amt für StatistikBerlin-Brandenburg (Statistics office of Berlin-Brandenburg) 2018. Kleine berlin-statistik (Overview statistics of Berlin).
[28] Western Cape Government 2017. Socio-Economic Profile, City of Cape Town.
[29] National Records of Scotland 2018.
[30] Instituto Nacional de Estadística (National Statistics Institute of Spain) 2018. Household Projections 2018.
[31] State Government of Victoria 2018. Greater Melbourne demographics.
[32] World Cities Culture Forum 2015. Number of households.
[33] Statistics Division, Bureau of General Affairs 2017. Tokyo Statistical Yearbook 2017.