Department of Chemical and Process Engineering

UK Energy Storage and determining the upper boundary of revenue available from the time-shifting of bulk electrical energy.

I.A. Grant Wilson

http://orcid.org/0000-0003-4083-597X

A thesis submitted to the University of Strathclyde

in fulfilment of the requirements for the

Degree of Doctor of Philosophy

2013

Copyright declaration

‘We are like tenant farmers chopping down the fence around our house for fuel when we should be using Nature's inexhaustible sources of energy — sun, wind and tide. ... I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.’

Thomas Alva Edison (1847-1931).

Abstract

Energy storage is a critical component of historical and future energy systems. The drivers behind the growing importance given to electrical energy storage in the UK has been investigated, with the development of an objective model to calculate the upper boundary of revenue available to storage operators that time-shift electrical energy through the UK's power exchange markets.

The results display clearly that the UK is moving rapidly to greater import dependence of its primary energy needs, and that pre-conversion stores of energy in stockpiles of fuels available to the electrical network dwarf the post-conversion rechargeable pumped-hydro energy storage schemes with an indicative ratio of ~1300:1 in favour of fossil-fuel stocks (nuclear fuel stock data was not included in this ratio as it is unavailable).

The time-shifting model contained a novel approach by including a timedependent efficiency loss that provided the ability to consider the self-discharge of a storage device, and uses a non-deterministic random walk approach. The results of the model revealed that there is a large annual variation of potential revenues from the time-shifting of electrical energy through power exchange markets in the UK (*e.g.* Figure 98, page 176). It is proposed that the added complexity of a model to include a time-dependent efficiency loss is probably not warranted for the study of bulk electrical energy storage arbitrage revenues, as in the UK, the storage device will default to a diurnal cycle of charging and discharging in order to maximise revenue. The self-discharge rate of a storage device would have to be impractically large to have a significant influence on a diurnal cycle (*e.g.* Figure 115, page 188) and therefore the results from the inclusion of a self-discharge variable are not thought to differ significantly from a simpler modelling approach that would not include a self-discharge element.

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Professor Peter Hall, for the opportunity to undertake this project and for his guidance, patience and support throughout.

This work was supported by the Engineering and Physical Sciences Research Council under grant reference EP/D031672/1 ‘Supergen Energy Storage programme’ and EP/H019596/1 ‘SUPERGEN - The Energy Storage Consortium: CORE Proposal’.

Special thanks are also due to:

Chris Watkin for the sanity breaks, Philip Glass and Matt Rubin for the music, and to my colleagues Dr Fiona Sillars and Dr Anthony Rennie for their ongoing help, common sense and humour throughout. Edward Barbour of Edinburgh University and Simon Gill of the University of Strathclyde with code development and idea sharing. Dr Leo Lue, Dr Paul Mulheran and Dr Richard Martin of the University of Strathclyde for their help with shell scripts, programming methods and accessing the High Performance Computing resource.

Dr Scott Strachan and Dr Michael Dolan for the opportunity to join the Gambia Solar Project in 2011.

Professor Peter McGregor, as joint supervisor, whose enthusiasm, knowledge and continued support were unbridled.

Lastly to my Rachael, Isla and James, without whose patience, support, understanding and joy of life, this work would not have been possible.

Outputs resulting from this work

June 2013	Communication - Wilson, I.A.G, Rennie, A.J.R., Ding, Y., Eames, P.C., Hall, P.J., and Kelly, N.J., ‘Historical daily gas and electrical energy flows through Great Britain's transmission networks and the decarbonisation of domestic heat’. doi:10.1016/j.enpol.2013.05.110

February 2013	Paper – Gill, S., Barbour, E., Wilson, I.A.G., Infield, D. 'Maximising revenue for non-firm distributed wind generation with energy storage in an active management scheme'. Accepted for publication. doi: 10.1049/iet-rpg.2012.0036
March 2012	Presentation - Scottish Renewables conference. – 'Keeping the lights on: A Secure and stable supply of renewable energy'
March 2012	Presentation - Scottish Hydrogen and Fuel Cell conference. – 'The case for Energy Storage'
January 2012	Presentation – Aberdeen Renewable Energy Group. – 'The storage challenge'
November 2011	Paper - Barbour, E., Wilson, I.A.G., Bryden, I.G., McGregor, P.G., Mulheran, P.A., & Hall, P.J., - 'Towards an objective method to compare energy storage technologies: Development and validation of a model to determine the revenue available from electrical price arbitrage.' accepted in **Energy and Environmental Science.** doi:10.1039/C2EE02419E
August 2011	Paper - Wilson, I.A.G., McGregor, P.G., Infield, D.G., & Hall, P.J., (2011). – 'Grid-connected renewables, storage and the UK electricity market.' **Renewable Energy**, 36(8), 2166-2170. doi: 10.1016/j.renene.2011.01.007.
February 2011	Presentation – Wilson, I.A.G., Barbour E., – 'A Storage Optimisation Model: What is the maximum revenue available to storage operators using market index price spreads?' **International Conference for Sustainable Energy Storage 2011** – University of Ulster.
November 2010	Poster – Wilson, I.A.G., Barbour, E., – 'A Technical and Economic Model of Tidal Current Energy Conversion coupled with a Storage System.' **5th International Renewable Energy Storage Conference IRES 2010** – Berlin.
August 2010	Paper - Hall, P. J., Mirzaeian, M., Fletcher, S. I., Sillars, F. B., Rennie, A. J. R., Shitta-Bey, G. O., Wilson, G., et al. (2010). – 'Energy storage in electrochemical capacitors: designing functional materials to improve performance.' **Energy Environ. Sci.**, 3(9), 1238-1251. doi:10.1039/C0EE00004C.
August 2010	Paper - Wilson, I.A.G., McGregor, P.G., & Hall, P.J., (2010). – 'Energy storage in the UK electrical network: Estimation of the scale and review of technology options.' **Energy Policy**, 38(8), 4099-4106. doi:16/j.enpol.2010.03.036.

Table of Contents

Abstract ..... **i**

Acknowledgements ..... **ii**

Outputs resulting from this work ..... **ii**

Table of Contents ..... **v**

Acronyms and abbreviations ..... **xiii**

1 Introduction **1**

1.1 Background 1

1.2 Renewable resources 6

2 Objectives **11**

3 What is driving the move to decarbonise the electrical energy supply? – An International, European and UK perspective **12**

3.1 The International Panel on Climate Change Reports 13

3.2 The Kyoto Protocol 20

3.3 European Legislation 29

3.4 European 20-20-20 targets 30

3.5 UK Policy Landscape 33

3.6 Remarks 36

4 The UK's renewable energy resource **37**

4.1 Wind Resource 39

4.2 Tidal Resource 40

4.3 Wave Resource 43

4.4 Solar Resource 44

4.5 Hydro Resource 46

4.6 Bioenergy Resource 46

4.7 Geothermal Resource 47

4.8 Electrical and Gas Infrastructure 47

4.9 Growth of renewable generation in the UK 48

5 The UK's energy landscape **50**

5.1 Background to UK energy systems 50

5.2 UK electrical market framework 57

5.2.1 The Forward Market 57

5.2.2 The Power Exchange Market (Spot Market) 59

5.2.3 The Balancing Mechanism 59
5.2.4 The Ancillary Services Market 60
5.3 Bulk storage operation within the UK electricity market 60
5.4 Storage charging, wind power and spot market price 66
5.5 Is storage counterproductive for fuel saving? 70
6 Bulk Energy Storage in the UK 73
6.1 Background to fuels and networks 76
6.2 Existing storage of the UK electricity network 82
6.2.1 Nuclear fuel stocks 82
6.2.2 Coal Stocks 83
6.2.3 Natural Gas 90
6.2.4 UK Hydro Pumped Storage Schemes 97
6.3 UK Stores of Energy 101
7 Development of the model to determine the upper boundary of revenue available from time-shifting bulk electrical energy 102
7.1 Background 102
7.2 Use of historical data 102
7.3 Accessing UK historical price data 104
7.4 UK electrical energy spot price data analysis 106
7.5 Model development and collaboration 110
7.6 Review of existing optimisation methodologies for energy storage operation 112
7.7 Model assumptions 116
7.8 Principles of the model 118
7.9 Detailed description of the model 121
7.9.1 Variables used in the Fortran code 122
7.9.2 Model Inputs 123
7.9.3 Operation of the algorithm 124
7.10 Algorithm scenarios 127
7.11 Simple example of model iterations 136
7.12 Price files to validate the model 140
7.13 Typical debugging process 145
7.14 Algorithm validation results 150
7.15 Validation of random walk 165
7.16 Automation of different runs 167

8 Results and Discussion8.1 UK market prices - varying power limits in/out and round trip efficiencies 2005 – 2011 **........ 170**

8.2 Discussion of the variation in yearly revenues 172

8.3 UK market prices - varying the power in/out ratio to the device capacity........ 175

8.4 Discussion of varying the power in/out ratio to the device capacity 176

8.5 UK market prices - varying the fixed efficiencies 177

8.6 Discussion of varying the fixed efficiencies 180

8.7 UK market prices - varying the fixed efficiencies versus the time-dependent efficiency 181

8.8 Discussion of varying the fixed efficiency versus the time-dependent efficiency..... 183

8.9 Comparison of grid data and model output for 6th and 7th January 2009 184

8.10 Impact of the diurnal nature of the price file structure........ 187

8.11 How the model can be modified to evaluate the impact of imperfect foresight on the arbitrage revenue 188

9 General Discussion 190

9.1 The requirement for increasing bulk storage 190

10 Conclusions 200

10.1 Conclusions: UK energy stores of energy........ 200

99.9%) available to the UK electrical network........ 200

10.1.2 Distributed storage........ 201

10.1.3 Synthetic fuels 202

10.1.4 Policy direction for energy storage in the UK 202

10.1.5 Storage Research Challenges for the UK 203

10.2 Conclusions: the arbitrage model........ 203

10.2.1 Variation of the power in and out ratio to overall storage capacity........ 204

10.2.2 Non-linear nature of changing the fixed efficiencies in and out........ 204

10.2.3 Self-discharge does not significantly impact revenue for bulk electrical energy storage 205

10.2.4 Annual variation in upper boundary value 206

10.2.5 Future market landscape for storage........ 207

11 Suggestions for future work 209

12 References 212

Appendix 1 - Programming environments 224

Appendix 2 - Matlab file to process and analyse the raw Elexon market index data........ 225

Appendix 3 - Price File Preparation 227
Appendix 4 – Master Input File for Fortran program 233
Appendix 5 – The master_input_shell.sh shell script 236
Appendix 6 – Model Code – Fortran - full_grid_leap.f90 238
Appendix 7 – The UK's natural gas infrastructure 251

175

187

10.1.1 Pre-conversion stores of fuels are the overwhelming stores of energy (over

Acronyms and abbreviations

°C	Degree Celsius
£/MWh	Pounds sterling per Megawatt hour
BaU	Business as Usual
ceteris paribus	all other things being equal
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CH_4	Methane
CHP	Combined Heat and Power
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent according to IPCC definitions (accumulating the effect on climate of all greenhouse gases according to their global warming potentials in a period of 100 years) (IPCC, 2007f)
COP	Coefficient Of Performance
COP	Conferences of the Parties
CSP	Concentrating Solar thermal Power
DG CLIMA	Directorate-General for Climate Action
ECCP	European Climate Change Programme
e.g.	*exempli gratia* – for example
EJ	Exajoule
etc.	*et cetera* - and so forth
ETS	Emissions Trading System
EU	European Union
EUR	Euro
GB	Great Britain
GHG	Greenhouse gas(es)
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt hour
h	hour

H_2	hydrogen
H_2O	water, vapour
HPC	High Performance Computer
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
i.e.	*id est* – that is
IEA	International Energy Agency
IGCC	Internal Gasification Combined Cycle power plant
IPCC	The International Panel on Climate Change
inter alia	among other things
K	Kelvin
kcal	kilocalories
kg	kilogram
kJ	kilojoule
km	kilometre
km^2	square kilometre
kW	Kilowatt
kWh	Kilowatt hour
LDC	Least Developed Countries
LNG	Liquefied Natural Gas
MJ	Megajoule
Mt	Million Tonnes
MW	Megawatt
MWh	Megawatt hour
n.b.	*nota bene* – please note
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
p/kWh	pence sterling per kilowatt hour
per se	through itself
PJ	Petajoule
ppm	parts per million

PV	Photovoltaic
SNG	Substitute Natural Gas
SPM	Summary for Policymakers (IPCC reports)
T	Temperature
th	thermal
TJ	Terajoule
TW	Terawatt
TWh	Terawatt hour
UN	United Nations
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
US, USA	United States of America
WGI	IPCC Working Group I: The Science of Climate Change
WGII	IPCC Working Group II: Impacts, Adaptation and Vulnerability
WGIII	IPCC Working Group III: Mitigation of Climate Change
WMO	World Meteorological Organisation

1 Introduction

1.1 Background

One of the foremost challenges for this and coming generations is to allow for a smooth and orderly transition to radically different energy systems. The challenges in decarbonising energy systems whilst balancing the goals of affordability and security of supply could well have far reaching geopolitical consequences above and beyond the immediate needs of nation states to provide energy for development of, or a continuation in their standards of living. Access to secure energy systems is pursued as a prerequisite to increasing the Gross Domestic Product of nation states. Global primary energy supplies are evolving in order to meet carbon emission reductions and/or provide security of supply or a hedge to increases in fossil fuel prices. The transition to low-carbon energy systems has profound consequences in terms of the cost of energy, the security of energy supply and system operation.

This work is primarily focused on the use of bulk electrical energy storage in the electrical system. Moving to a low-carbon based energy system is one of the greatest technical endeavours facing the world, and it should be acknowledged that a reduction in primary energy is of central importance, as it should logically ease this transition. Heat/cooling services as well as electrical services are a crucially important avenue for research and development in order to meet emission and social wellbeing targets for the use of energy and the services that it provides, however, this study does not cover this area of research in much detail.

The transformation of global energy systems from high-carbon to a low-carbon energy supply over the long-term can be viewed in terms of four major cascading challenges:

1) Applying energy savings and energy efficiency measures to slow the increase and eventually even reduce the overall energy demand *e.g.* electrical demand, heat services and transport. Any reduction in energy use to provide end-use services should have a beneficial effect of making the other challenges incrementally easier.

2) Supplying the energy demand primarily with, low-carbon, and potentially fuelfree renewable energy sources like wind, solar, hydro power, geothermal, wave, tidal and ocean energy.

3) Using carbon-neutral energy vectors such as sustainable bioenergy or synthetic fuels in a strategic way to balance power, heat and transport networks. This may be viewed as stored energy.

4) Supplying any residual demand with low-carbon fossil fuels in combination with carbon capture and storage (CCS).

Different countries face these challenges in different ways, generally dependent on the existing energy infrastructure, potential renewable energy resources, longterm forecast energy demands, existing stakeholders, and the organisational frameworks for energy provision and markets. Energy systems are highly complex engineering systems that have evolved over decades and are tightly regulated in terms of safety and operation. Changes to these systems are therefore generally incremental and conservative in their approach, however it should be acknowledged that great changes can be implemented once the direction of travel has been determined. For example the change of appliances in the UK from town gas to North Sea Gas in the decade from 1967 to 1977 was unprecedented, and was organised by the public utility 'British Gas'. The change of domestic electrical meters to Smart Meters is a planned exercise to be completed in the UK by 2020, and will be undertaken through the market based approach to energy provision that the UK has embraced.

The course of human history is inextricably linked to its ability to exploit available energy resources. Regardless of the future geopolitical disturbances brought about by changes from the current system, it is agreed that existing global energy systems have been built on accessing the historically bountiful resource of fossil fuels, with their superb ability to act as stores of primary energy (originally from solar energy). They have been historically cheap, their local risks are known to a high degree, and access to them is considered a prerequisite of any modern economy. Quite simply – the rate of development of the world would have been significantly slower without the plentiful supply of energy available from fossil fuels. Entire sectors such as the built environment and the food chains of developed nations have been predicated on this availability of cheap and available fossil fuels.

Energy systems are predominantly just-in-time systems (at the point of the final user) that provide the energy service when called upon *i.e.* the conversion of fuels to the useful energy service happens at the time that the energy service is required. There are however many stockpiles and stores of energy throughout the supply chains of energy systems (stockpiles of coal, gas and oil at a bulk level, through to fuel tanks in vehicles at a distributed level) which provide buffers of energy and make the systems more resilient to exogenous shocks. The use of fossil fuels to provide the feedstocks for materials such as plastics and agricultural supplies does provide the ability to stockpile goods after conversion from fossil fuels, whereas the cost of storing electrical energy or heat after conversion from fossil fuels has been much more expensive in comparison to storing the energy in stockpiles of fuel prior to conversion. Electrical systems have developed to facilitate the conversion of fuels to electricity in ever larger, ever more efficient generating plants, and development of larger networks to transmit and distribute this electrical energy to final users. Over many decades electrical systems have adapted to the needs of large centralised dispatchable thermal power stations. This highly complex engineering system requires constant balancing to match electrical supply with demand, and this just-intime paradigm of the conversion of energy to electrical energy has been successful due to the ability of stores of fuels (fossil, nuclear and hydro) to be converted as and when required. In short, the existing model of energy networks and services is predicated to a large degree around the ability to control the time when primary energy inputs to the system are converted. This has meant that the more expensive process of storing energy after it has been converted has not happened on a widespread scale.

Conceptually, post-conversion bulk electrical or thermal storage also allows a decoupling of the supply of primary energy from demand. Post-conversion storage can therefore be viewed as a disruptive technology to change the manner in which energy systems are designed and operated.

A major driver for electrical energy systems to include more post-conversion energy storage is the accommodation of greater levels of renewable forms of primary energy, many of which are simply unable to be stored before conversion *e.g.* wind, wave, solar. Some renewable forms of primary energy however do lend themselves to primary energy storage as they can be considered dispatchable *e.g.* biomass, geothermal, and certain forms of hydro and tidal generation. The move towards ever increasing use of renewable sources for primary energy supply therefore suggests a greater role for post-conversion storage, as systems will have less ability to store energy in fossil fuels before conversion relative to historical precedents. Post conversion storage can therefore also be viewed as a fundamental and critical component of future energy systems.

The size of the technical and economic resource of fossil fuels is an ever-changing value - summed up by the view that *'Geology doesn't create oil; capital creates oil. The more capital you put toward oil, the more of it there will be.'* (Stansberry, 2011). And although this seems a strange way of describing a finite resource, it is felt to be valid, as in general, hydrocarbons that are not economic to currently exploit will be left in the ground until such time as they are economic. It may be best to view the difficulty of hydrocarbon extraction as a trend of increasing difficulty and therefore expense, rather than being driven on volatile short-term price movements. An interesting extension of the train of thought that suggests that the amount of hydrocarbons are created by capital, is that it is indeed feasible that synthetic fuels could be manufactured using renewable sources of energy. These synthetic fuels would not be expected to be competitive with conventional hydrocarbons until such time as the conventional hydrocarbons become increasingly expensive to exploit. If carbon were used in these fuels then the source of the carbon for these synthetic fuels would determine how they were viewed in terms of their carbon neutrality *e.g.* if they were combined with carbon that had been removed from the atmosphere – then they may potentially be considered a carbon neutral type of fuel.

This concept of the size of a finite resource being determined by a man-made construct of 'capital' does seem to succinctly provide the flavour of the difficulty of the nature of energy provision. It is a constantly moving feast of assumptions and forecasts, with many vested interests, some political, some corporate, vying to increase shareholder value, 'keep the lights on', or provide political capital for the next round of elections. The mismatch between political cycles and the planning cycles of large-scale future energy systems, the international nature of energy supply chains, and the highly politicised nature of global warming and nuclear energy provide large political challenges for the provision of future energy systems.

The peak oil view supposes that humanity is not far away from the maximum rate of oil production. The veracity of this view is challenged by the unknown levels of resource in Saudi Arabia, the Barents Sea, the rest of the Artic and the as yet undiscovered oil fields of the world. However, in a dynamically changing oil and gas sector, new significant finds are still occurring (such as the Shaikan field in Kurdistan) and existing fields' lifetimes are being extended with newer technologies. In terms of gas hydrocarbons the resource, the technology improvement and the pace of discovery all seem to be as complex as that for oil *e.g.* the development of Shale gas fracking techniques has recently reduced US dependence on imported international gas (*e.g.* from Canada by pipeline or by Liquefied Natural Gas (LNG) carriers from middle east countries). This has had an impact on gas prices in North America, and a knock on effect of the price of coal in Europe.

No organisation or individual fundamentally knows how much hydrocarbon resource is still left in the ground, because robust data simply does not exist. However, it is possible to suggest that regardless of the level of hydrocarbons still left, that the easily found and easily exploited hydrocarbons are indeed reducing, with the inexorable trend that hydrocarbons will become more expensive in the medium to long-term, especially as the global demand for these hydrocarbons seems expected to inexorably rise too. The balance between hydrocarbon prices and the level of supply and demand is complex, and the lack of clarity of important data must be of benefit to certain players, but does little to help long-term planning for governments around the world when it comes to energy infrastructure. Energy planning requires by its nature a long-term approach, which may seem at odds with the increasingly short-term view taken by many elected officials and financial decision makers in the markets.

The ability of nation states to regain some control over financial markets, the increasing global population, changing demographics in developed countries, the concern with greenhouse gases and the increase in knowledge regarding damage to the environment in general – all point to a very challenging time ahead, but maybe it has always been so. The European Project, democracy, and peoples' acceptance of the laissez-faire form of capitalism that has become dominant over the last two to three decades is being re-evaluated. These are geopolitical changes that will play out throughout the world, and one wonders how this will influence the move to decarbonise energy systems. If, for example, a global recession keeps the price of hydrocarbons lower, and communities have other more pressing issues to resolve, will the decarbonisation programme be slowed, halted or reversed?

1.2 Renewable resources

The UK, and Scotland in particular have raw renewable energy resources that other countries would dearly welcome, and a political commitment by the UK coalition government to rebalance the economy away from financial services. Due to the geographical position in relation to the North Atlantic Current and prevailing wind patterns, Scotland is often reported to have one quarter of Europe's offshore wind and tidal resource, and one tenth of Europe's wave power (Scottish Government, 2011).

The ability of the UK to maximise its use of this raw renewable resource itself presents many complex challenges that can be conceptually viewed as three grouped themes:

1) capturing the resource
2) transmitting the energy to system loads
3) providing the stability within this system *e.g.* matching supply and demand on different timescales.

The growth in exploitation of the raw renewable energy resource in the UK has to function with the existing paradigm of large central power plants that use nonrenewable energy carriers, and will likely be attempted in an incremental rather than a revolutionary or parallel approach. These three themes are highly interlinked – with decisions taken in one theme having effects on others, with the choice of energy vector determining the technologies and therefore the impacts on the system as a whole.

If the energy vector is electricity, then this immensely useful form of energy has a major disadvantage of being difficult and expensive to store. In current and historical systems, with dispatchable generators that could be turned on/off or ramped up/down, the electrical energy has not tended to be stored after it was converted, it was 'stored' in the energy contained within the fuels of the dispatchable plants before it was converted. This dispatchable plant hegemony has served developed nations well. Large centralised plant with higher and higher efficiencies have continued to transform more electrical energy from the available fuels, whilst increasing the size of electrically connected markets has also contributed to a smoothing of the demand profile, thus providing a system benefit that helps to balance larger networks.

The increase in technical maturity of renewable energy technologies and markets over the last 20 years has allowed the energy sector to deploy greater of amounts of wind and solar generation. The weather input resource and therefore the generated outputs fluctuate and are not dispatchable. Accuracy in forecasting the input resource is increasing, dependent on the technology and the forecast window (*e.g.* tidal is known for decades to come), and so there is a better understanding of how much generation will be coming onto a particular network over a given period. This is obviously of great interest to network operators to be able to balance systems in real time, as the more notice they have, the more ability they have to take measures to balance the shortfall or potentially the oversupply of generation. Overall it seems that the global increase in renewable generation investment is guided by the subsidy regimes in place, but this is just one of many financial considerations taken when investing in any large generation plant (albeit with a different set of risks).

This increase in the capture of renewable energy (Theme 1) has a direct impact on the transmission of the captured resource to centres of loads (Theme 2) and on the provision of stability within the system (Theme 3). In the UK the largest renewable resources are located on the periphery and offshore, whereas the demand is concentrated in the South East of England. Energy storage is thought to fit well into Theme 3, but due to the interlinked nature of the different Themes, will be influenced by and will itself influence Themes 1 and 2 too. Whereas capturing the energy (when it is available) and transmitting the energy to demands can be thought of as instantaneous conversion to and movement of electrical energy over distances to users, energy storage can be conceptually viewed as providing a temporal as well as a spatial dimension. In short – it can store the energy until needed – it can offer the potential to decouple the supply from the demand in the time domain. Energy storage can therefore often be seen as a potential solution for the integration of greater fluctuating renewable energy due to the flexibility and resilience it creates, but its increased deployment is hampered by the technical maturity and cost of various technologies, and the roles and revenue streams that storage operators may seek to capture within the existing energy landscape. One main research question therefore is how to match future energy supply with energy demand within controlled limits at increasingly higher shares of non-dispatchable energy sources, *i.e.* how to balance and integrate wind and solar energy at increasingly higher levels of deployment. This is a challenge for all future networks that seek to incorporate greater levels of nondispatchable energy sources, not just the UK.

In order to encourage a greater amount of post conversion energy storage on electrical networks in a market based system, the potential revenues available to developers and investors have to be better understood and quantified for policy makers and market participants.

This work seeks to understand better, and clarify a particular revenue stream available to energy storage operators from the time shifting of bulk electrical energy. The changing spot-price of electrical energy provides potential revenue from buying from the market at periods of low prices and selling back to the market at times of higher prices. The amount of revenue available over a year is an interesting problem to be analysed. This revenue stream is widely known as electrical energy ‘arbitrage’ (although not strictly true in the normal definition as it is trading within the same market but at a different time). This work will use also use this common use of ‘arbitrage’ as the term to describe the time-shifting of electrical energy.

It is hoped that this research will add to the developing body of knowledge for bulk electrical energy storage.

Electrical energy storage offers a tool to allow fluctuating renewable energy generation to be more effectively matched to demand patterns, and as such can play a crucial role in the grand challenge of moving towards a low-carbon energy system. The effort involved in capturing a renewable resource and transmitting it to centres of demand should not be underestimated – but the progress that has been made on these two fronts is likely to continue to be impressive. The challenge in keeping energy systems balanced with the expected increase of fluctuating renewable energy seems the biggest challenge of all, and progress on this is beginning to accelerate.

The author believes that at some stage in the move towards a low-carbon energy future, that an increase in post-conversion storage is inevitable. The scale, location, overall amount, and timing of this increase is unknown, but it would be judicious for policy makers to allow for a greater market to develop for post-conversion energy storage before the need for increased storage becomes a critical necessity. In this manner, the UK will have gained knowledge in the use and ability of storage to provide wider system benefits in a timely manner before it becomes a major problem. Whether there is a potential first mover advantage to having this experience in the UK depends upon the manner of ownership of companies involved in gaining this experience. If UK based companies can develop the skills and knowledge involved in the integration of storage, and are then able to build upon this into international markets (which will themselves undoubtedly have to gain the same experience at some stage), then this should be seen as a positive outcome.

The existing paradigm of using the stores of energy in fuels to provide system storage for balancing seems set to continue for the medium term. Although, if at some point future energy systems move away from fossil fuels, then they will also have moved away from their intrinsic ability to store energy. The replacement of the flexibility and resilience provided by this storage property of fuels prior to conversion is one of the greatest challenges to allow for an orderly transition to secure and affordable low-carbon energy systems of the future.

2 Objectives

The objectives of this work were to investigate the drivers behind the growing importance given to electrical energy storage, with a study of the historical levels of the stores of energy available to the electrical network in Great Britain and the UK, and to create an algorithm that could provide some insight into the maximum available theoretical revenue that could be captured from the arbitrage of electrical energy through the use of electrical spot markets.

The ability to calculate values of the potential revenue a storage operator could derive from this arbitrage revenue stream was thought to be of interest. An assessment of these revenues could be useful in allowing stakeholders with an interest in the provision of bulk electrical energy storage to determine how attractive this revenue stream was in terms of investment. The UK has embraced the ownership and operation of energy systems through regulated markets, and therefore any change in the level of bulk electrical energy storage would have to be viewed in this context. Through this regulated market prism, interesting questions arise regarding the level of revenue from arbitrage, and the variability of this revenue stream. In simple terms, how attractive is the revenue stream from electrical energy arbitrage to allow for investment in bulk electrical energy storage?

The review of historical stores of energy in the UK was considered to be important to provide the background and comparison between the levels of postconversion electrical energy storage and the pre-conversion stockpiles of fuels. Research into this area also helped to crystallise the view that stores of energy have always been a critical part of the UK's energy systems, it is just that they have been overwhelmingly pre-conversion stores of fossil fuel and nuclear energy. This is undoubtedly true for most other nation states too.

Although the work has focussed primarily on bulk electrical energy storage, it is clear that distributed forms of electrical and heat storage are likely to provide a benefit in terms of network resilience and balancing too. It raises the question that if there is a limited amount of capital to spend on storage devices, should these be focussed on distributed storage or on centralised bulk energy storage devices? Although the answer is unknown, it is conceivable that storage at different scales and geographical location would be complementary.

Throughout the duration of this work, storage in general has attracted more interest at a political and research level. There is also a growing consensus that postconversion storage has not hitherto been adequately included in many forecasting models (at a UK and international level), and therefore has been largely omitted from decisions taken on the basis of outputs from these models. The benefit of storage has historically not been widely appreciated in an objective manner to allow decision makers to compare various scenarios, which is thought to be due in part to the difficulty of including storage in energy forecasting techno-economic models such as the widely used Markal (IEA, 2012). The difficulty seems to stem from the mismatch in timeframes required by modelling storage and the timeframes used by Markal, with storage modelling requiring evaluation on windows with much shorter timeframes. The lack of objective data provides the backdrop to the lack of assessment and potential incentivisation of storage through a regulated market framework.

Five papers and a communication were produced and published using knowledge gained throughout development of the study. The work ultimately provides an objective model to assess the upper boundary of the arbitrage revenue stream available to operators with access to electrical spot markets.

3 What is driving the move to decarbonise the electrical energy supply? – An International, European and UK perspective

The drive to decarbonise the electrical energy supply system in Great Britain is shaped by the international framework of agreements to tackle anthropogenic causation of climate change. Important legislation and information has been chosen to detail and consider in this section, but it is only a flavour of the work carried out to help move the world towards a low-carbon future.

International negotiations and national targets seek to reduce greenhouse gas (GHG) emissions significantly in order to limit the risks associated with climate change. In the UK, the Climate Change Act (2008) requires a reduction in emissions of 80% by 2050 compared with 1990 levels. It also expects Parliament to set successive five-year carbon budgets that limit emissions in order for the eventual target to be met. The fourth budget equates to a reduction in annual emissions of 50% from 1990 levels for the period 2023-27.

3.1 The International Panel on Climate Change Reports

The International Panel on Climate Change (IPCC) is a scientific body established in 1988 by two United Nations organisations – the World Meteorological Organisation (WMO) and the United Nations Environment Program (UNEP). Its mission is '*to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts*.' (IPCC, 2011) The IPCC collates, reviews and assesses the most up to date scientific, technical and socio-economic global knowledge relating to the area of climate change. However, it does not undertake any research or monitor climate related data in and of itself. It is open to all member countries of the United Nations and the WMO and has a current membership of 194. On the IPCC website it also states that *'Because of its scientific and intergovernmental nature, the IPCC embodies a unique opportunity to provide rigorous and balanced scientific information to decision makers. By endorsing the IPCC reports, governments acknowledge the authority of their scientific content. The work of the organization is therefore policy-relevant and yet policy-neutral, never policy-prescriptive'*. (IPCC, 2011). It is therefore critical that the organisation is viewed as apolitical, neutral and representative of a scientific viewpoint in order to provide evidence based, balanced, and unbiased scientific reports. The decision makers who subsequently use this information are not bound by the same criteria – and can form their own opinions of the data presented to align with their own agendas. This is not to say that facts and data input into the IPCC could not themselves be subject to bias, but only to recognise that the IPCC is acutely aware of the priority to be perceived to be objective, in order to retain its credibility, and therefore its influence as an honest broker in terms of climate related information. Transparency and a rigorous process that prevents undue influence by individuals or small groups are paramount to the IPCC's ongoing credibility. An example of how quickly the reputation of the IPCC can be damaged by adverse public relations can be seen in two examples of the release of hacked emails from the University of East Anglia between four scientists involved in writing high-profile scientific papers that have been cited by the IPCC reports (WKP, 2011a), and the inclusion of erroneous information regarding the rate of retreat of Himalayan glaciers into the 4th Assessment report (WKP, 2011c). The IPCC has aimed to be transparent in dealing with these and other issues.

One of the major activities and output from the IPCC are regular publication of assessment reports. The IPCC has published these in the years 1990, 1995, 2001, 2007 and is in the process of preparing the 5th Assessment report: Climate Change 2014. The unique nature of these reports, produced from thousands of experts throughout the world who volunteer as authors, contributors and reviewers, provides the most comprehensive assessment of the changing climate, and is widely regarded as the ultimate authority on the subject. However, due to the discrete timeframes of the report publications, and the constantly evolving nature of the science knowledgebase, it is not uncommon that empirical evidence compiled to produce the reports is superseded by more recent evidence. This could be regarded as part of the nature of all science, and therefore a main factor for the continued development of the IPCC and the production of subsequent reports. This is especially important as the timeframes over which climate change acts mean that it can only be suitably analysed and understood over prolonged periods of measurement and study.

As knowledge has increased in the area of climate change, so have the perceived accuracy of the report findings, and therefore the strength of the probabilities of the assessments and findings being valid. In the Synthesis report (a summary report) for Policy Makers (IPCC, 2007a) of the 4th assessment report published in 2007 (IPCC, 2007b), the final section (section 6) titled *'Robust findings, key uncertainties'* contains a summary of these findings and uncertainties, which are detailed in Table 1 and Table

2 below. All parts of the IPCC's 4th assessment report can be downloaded from (IPCC, 2007b).

Robust findings
Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. *{WGI 3.9, SPM}*
Many natural systems, on all continents and in some oceans, are being affected by regional climate changes. Observed changes in many physical and biological systems are consistent with warming. As a result of the uptake of anthropogenic CO2 since 1750, the acidity of the surface ocean has increased. *{WGI 5.4, WGII 1.3}*
Global total annual anthropogenic GHG emissions, weighted by their 100-year GWPs, have grown by 70% between 1970 and 2004. As a result of anthropogenic emissions, atmospheric concentrations of N2O now far exceed pre-industrial values spanning many thousands of years, and those of CH4 and CO2 now far exceed the natural range over the last 650,000 years. *{WGI SPM; WGIII 1.3}*
Most of the global average warming over the past 50 years is *very likely* due to anthropogenic GHG increases and it is *likely* that there is a discernible human-induced warming averaged over each continent (except Antarctica). *{WGI 9.4, SPM}*
Anthropogenic warming over the last three decades has *likely* had a discernible influence at the global scale on observed changes in many physical and biological systems. *{WGII 1.4, SPM}*

Table 1 - Robust Findings from IPCC 4th Report Summary for Policymakers (SPM)

Key uncertainties
Climate data coverage remains limited in some regions and there is a notable lack of geographic balance in data and literature on observed changes in natural and managed systems, with marked scarcity in developing countries. {WGI SPM; WGII 1.3, SPM}
Analysing and monitoring changes in extreme events, including drought, tropical cyclones, extreme temperatures and the frequency and intensity of precipitation, is more difficult than for climatic averages as longer data time-series of higher spatial and temporal resolutions are required. {WGI 3.8, SPM}
Effects of climate changes on human and some natural systems are difficult to detect due to adaptation and non-climatic drivers. {WGII 1.3}
Difficulties remain in reliably simulating and attributing observed temperature changes to natural or human causes at smaller than continental scales. At these smaller scales, factors such as land- use change and pollution also complicate the detection of anthropogenic warming influence on physical and biological systems. {WGI 8.3, 9.4, SPM; WGII 1.4, SPM}
The magnitude of CO2 emissions from land-use change and CH4 emissions from individual sources remain as key uncertainties. {WGI 2.3, 7.3, 7.4; WGIII 1.3, TS.14}

Table 2 - Key Uncertainties from IPCC 4th Report Summary for Policymakers (SPM)

This 4th assessment report is seen by many as being a seminal moment in the area of climate change, as although subject to the key uncertainties, it is stated that *Warming of the climate system is unequivocal*, and is *very likely* to be happening because of the changes that man has, and continues to make to the environment. The choice of the phrase *very likely* was chosen to convey the message that it was felt that this is statistically greater than 90% probability or ‘beyond all reasonable doubt’. The publication of the 4th assessment report (on the 2nd of February 2007) was recognised by a joint award of the 2007 Nobel Peace prize between the IPCC and Al Gore, for *‘their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change.’* (NPP, 2007).

The reports from the IPCC are widely regarded as the mainstream view of climate scientists, but there are a range of dissenting views amongst some climate scientists, climate sceptics, and climate change deniers - for a flavour of this see the Wikipedia page of scientists opposing the mainstream scientific assessment of global warming (WKP, 2011d). The political and cultural issues regarding global warming are presented at length in (Oreskes & Conway, 2010; Hulme, 2009; Perrow, 2010). Also in the 2010 paper by Anderegg et al. (2010) they analysed a dataset of 1372 climate researchers and their publication and citation data, and found that 97-98% of the most active researchers supported the knowledge regarding anthropogenic climate change expressed by the IPCC, and that the expertise and prominence of the climate researchers that do not support the views of the IPCC on anthropogenic climate change are *‘substantially below’* those that do. These documents suggest that a range of opinions should be an indicator of a healthy branch of scientific research, but there continues to be a difficulty in translating this science into increased knowledge within the general public – without whose support politicians find it difficult to implement policies required to address climate change.

With such an overwhelming challenge to the business as usual approach to the use of fossil fuels and other processes that contribute to climate change, it is no surprise that the nature of the global warming or climate change debate has become highly politicised, and subject to the vagaries of misinformation, lobbying and spin by vested interest groups. It is more than unfortunate that such a critical challenge for the world as a whole has become seemingly more and more polarised over the course of its debate. It is not uncommon to find views of the general public (especially in the United States of America (Leiserowitz et al., 2011)) that wonder if climate change is actually happening, and if it is, then what are the anthropogenic contributions to this change. Two highlights from this ongoing study reveal that 65% of respondents said that they thought that global warming is affecting weather in the United States, but only 14% had heard of the IPCC. The dissemination of beliefs in conspiracies, and faith in ones own views are interesting areas of research, as are the evolution of the information and ebbs and flows of pubic opinion regarding climate change. An excellent paper on the discrepancy over time between scientific and public opinion on climate change, is by Weber & Stern, (2011) .

The IPCC has a herculean task to prepare the ongoing reports without undue interference from political or vested interest groups, and also to defend itself against attacks that question the very nature of the information or the organisation's impartiality. Climate change seems to be one of the thorniest political areas of the modern era and the continued challenge for the IPCC is to report on the best available knowledge in a transparent manner.

The 5th assessment report is now underway and similar to previous work will consist of three Working Group (WG) Reports and a Synthesis Report, all to be completed in 2013/2014.

The IPCC reports form a comprehensive ongoing knowledgebase for the United Nations Framework Convention on Climate Change (UNFCCC), which itself is an international treaty produced at the United Nations Conference on Environment and Development at the Earth Summit in Rio de Janeiro in June 1992 (but entered into force in 1994). Although this treaty contains no mandatory limits and contains no mechanisms for enforcement (and is thus considered non-legally binding) it provides for updates or protocols (such as the Kyoto Protocol) that can provide legally binding limits to greenhouse gas emissions. A priority task of the UNFCCC was to establish a baseline of national emission levels and to create a framework for regular reporting of these data. Without these regular reportable assessments of national emissions levels – very little concrete progress could be achieved to limit future emissions. The initial data thus provided 1990 benchmarks that subsequent future targets from the Kyoto Protocol would use as a comparator.

In 2002 the UNFCCC adopted a convention policy objective under Article 2, which states that *'The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.'* The objective seems fairly concise and clear in terms of its focus.

The UNFCCC recognised that there is a growing global risk from climate change, established a specific and clear goal to reduce the risk of climate change from happening, established the onus on developed countries to lead the way, allowed funds to be directed to developing countries to mitigate the growth of global emissions, provided a framework of reporting mechanisms to provide ongoing data, and started the formal consideration of the adaption to climate change. The IPCC assessment reports have provided a critical body of knowledge that enables further actions to be undertaken. Many policies have and continue to be enacted around the world with the primary aim of reducing man-made release of green house gases.

The convention divides members into parties (countries or groups of countries) or observer organisations (*e.g.* non-governmental organisations). Parties that are countries are further categorised into three main groups depending on the level of economic development and commitments; Annex 1, Annex 2, and Non-Annex 1 countries. The different categories are described in Table 3 below (UNFCCC - Parties & Observers, 2013).

Annex I Parties include the industrialized countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States.

Annex II Parties consist of the OECD members of Annex I, but not the EIT Parties. They are required to provide financial resources to enable developing countries to undertake emissions reduction activities under the Convention and to help them adapt to adverse effects of climate change. In addition, they have to "take all practicable steps" to promote the development and transfer of environmentally friendly technologies to EIT Parties and developing countries. Funding provided by Annex II Parties is channelled mostly through the Convention's financial mechanism.
Non-Annex I Parties are mostly developing countries. Certain groups of developing countries are recognized by the Convention as being especially vulnerable to the adverse impacts of climate change, including countries with low-lying coastal areas and those prone to desertification and drought. Others (such as countries that rely heavily on income from fossil fuel production and commerce) feel more vulnerable to the potential economic impacts of climate change response measures. The Convention emphasizes activities that promise to answer the special needs and concerns of these vulnerable countries, such as investment, insurance and technology transfer.
The 49 Parties classified as least developed countries (LDCs) by the United Nations are given special consideration under the Convention on account of their limited capacity to respond to climate change and adapt to its adverse effects. Parties are urged to take full account of the special situation of LDCs when considering funding and technology-transfer activities.

Table 3 - UNFCCC Party categories from: (UNFCCC - Parties & Observers, 2013)

The UNFCCC also detailed several key principles in facing the challenge of how to distribute the burden of reducing global GHGs. In Article 3 of the convention the following principles are detailed (UNFCCC - Article 3: Principles, 2013).

In their actions to achieve the objective of the Convention and to implement its provisions, the Parties shall be guided, INTER ALIA, by the following:
1. The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.
2. The specific needs and special circumstances of developing country Parties, especially those that are particularly vulnerable to the adverse effects of climate change, and of those Parties, especially developing country Parties, that would have to bear a disproportionate or abnormal burden under the Convention, should be given full consideration.
3. The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost. To achieve this, such policies and measures should take into account different socio-economic contexts, be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors. Efforts to address climate change may be carried out cooperatively by interested Parties.
4. The Parties have a right to, and should, promote sustainable development. Policies and measures to protect the climate system against human-induced change should be appropriate for the specific conditions of each Party and should be integrated with national development programmes, taking into account that economic development is essential for adopting measures to address climate change.

5. The Parties should cooperate to promote a supportive and open international economic system that would lead to sustainable economic growth and development in all Parties, particularly developing country Parties, thus enabling them better to address the problems of climate change. Measures taken to combat climate change, including unilateral ones, should not constitute a means of arbitrary or unjustifiable discrimination or a disguised restriction on international trade.

Table 4 - Article 3 principles from UNFCCC

Since the UNFCCC entered into force in 1994 the parties have met at least annually at the Conferences of the Parties (COPs) at different cities around the world. The last (COP 18) was held in Doha in Qatar in late 2012. The COPs are the convention's supreme body, and provide the mechanism for review of the convention's progress and a platform for further negotiations.

The major protocol of the UNFCCC COPs so far has been the agreement and enactment of the Kyoto Protocol.

3.2 The Kyoto Protocol

The first protocol of the UNFCCC - The Kyoto Protocol is an international environmental treaty that aims to '*stabilise the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*' (UNFCCC, 2005d) and is arguably more well known by members of the general public than the UNFCCC framework that produced it.

In essence, the Protocol imposes reduction targets on a basket of greenhouse gas emissions for Annex 1 countries (industrialised or transitional countries). At December 2011, 191 nations have signed and ratified the Protocol, with Canada announcing its withdrawal on the 13th of December 2011, and the United States having signed the Protocol on the 12th of November 1998, but not intending to ratify.

The Protocol was adopted in Kyoto in 1997, finally ratified and entered into force on the 16th of February 2005 (after Russia's ratification triggered a combined threshold) and has a first commitment period running from 2008-2012.

At the Copenhagen summit (COP15) in 2009 non-binding pledges were made by major economies. COP15 was widely regarded as a failure to achieve a legally binding successor to the first round of commitments, but did achieve the Copenhagen Accord, which was *'taken note'* of rather than adopted by the COP delegates. The Accord put a figure on the ambition of climate change control – in order to limit the increase in global temperature rise below 2 degrees Celsius. There are several other aims of the accord which can be read at (UNFCCC, 2009; WKP, 2011b). A United Nations Environment Programme (UNEP) assessment of the pledges of the Accord (UNEP, 2010) concluded that *'In order to bring emissions in line with integrated assessment models (IAM) pathways that meet a 2° C limit, there is a need to not only implement current pledges fully, but also to raise the ambition of those pledges and lay the groundwork for faster and deeper reductions of post 2020 emissions. Going further in the short term and achieving stronger cuts to lower levels in 2020 would leave open more possibilities to meet temperature limits and would allow more flexibility in choosing a post 2020 pathway for global emissions.'*

At the Doha summit (COP18) in November 2012 a second commitment period of emissions reductions was agreed to run from January 1st 2013 to the 31st of December 2020. This takes the form of an amendment to the Kyoto Protocol. The Annex 1 signatories to this second commitment period have agreed to collectively reduce their emissions 18% below 1990 levels. Several Annex 1 countries have not agreed to commitment targets, including America, Canada and Russia as previously mentioned, but also Japan, New Zealand, and potentially Ukraine, Belarus and Kazakhstan.

The Kyoto Protocol allows countries to use various, specifically created, flexible market mechanisms in meeting their emissions reduction commitments, which are the Clean Development Mechanism (UNFCCC, 2005a), Emissions Trading (UNFCCC, 2005b), and Joint Implementation (UNFCCC, 2005c). The theory is to allow abatement mechanisms to take place in the most cost effective manner *i.e.* where it is cheapest, and also allow for the transfer of low-carbon technologies to developing countries. Kyoto Protocol emission limits do not include emissions by international aviation and shipping.

An excellent paper by Michael Grubb in 2004 (Grubb, 2004) makes several important points in a clear and concise manner, it was published before Russia ratified and the Protocol entered into force. Namely: The Kyoto Protocol's basic role is to provide a structure for long-term evolving policies to effectively tackle climate change over the course of the century. The first round commitment period targets from 2008-2012 are only a first step in a long-term journey. Targets in subsequent periods will have to be widened to encompass developing countries' commitments in order to be effective, there is simply no way to stabilise GHGs without including reductions from developing nations. There is an implicit need for developed countries to lead by example and stabilise and reduce emissions, before developing countries will accept that they have to do the same. The rejection of the Kyoto Protocol by the Bush administration in 2002 is seen as being positive for the development of the Protocol in the short term, but unknown in the longer term (Grubb, 2004). The Bush rejection was seen as a political rejection of the Clinton administration's development of the Protocol previously, and also a rejection of the United Nations' process in general (one country one vote). Grubb finds it hard to accept that bilateral agreements between countries could ever be as effective as the Kyoto framework, and that the faith put in technology transfer as a bilateral solution to climate change is fraught with complexity and would not deliver reductions on its own. He also believes that absolute national emissions caps are simple to understand and therefore have advantages over other indicators using ratios that involve gross domestic product or per capita, but that other indicators could be used if demonstrated to be useful. A highly illuminating paragraph from the paper states *'It is easy, however, to mis-specify the nature of the US problem, or rather, problems. There are, at root, two fundamental issues. The first concerns the climate issue itself, where a combination of doubts about the seriousness of the problem and fears about the costs of emission limitations provide fertile ground for the political machinery in Washington to resist any serious emission reduction commitments. The second is the fundamental disconnect between US domestic debates and global realities, as manifest in the overall hostility of much of the Republican right to the United Nations, for example. It was the master strategy of lobbying by US industry groups in the early 1990s that connected the two and persuaded the US body politic* *that it should not adopt commitments without concurrent action by developing countries, whilst simultaneously lobbying developing countries to perceive any commitments as a threat to their economic growth. This twin-track strategy must rank as one of the most cynical, and successful, international lobbying campaigns in history.'*

Overall, Grubb views the Protocol as a phenomenal international effort to bring into force – it is not by any means perfect, and requires continued and committed development – but he feels that it is the only credible framework to allow for the stabilisation of greenhouse gases over the long-term. In the timeframes for action required by the advice from the IPCC - it does seem to be the only advanced mechanism at a global level.

Kyoto is felt to contain the critical basic architecture needed for an effective global climate protecting process. The necessary elements include systems for monitoring, compliance, finance, technical cooperation and economic efficiency, and even this seemingly basic architecture took years to negotiate, refine and ratify. If there was to be a completely different replacement for the Kyoto Protocol (not a successor) - then it is difficult to see which body it would chose as a framework to provide agreements on a global scale *i.e.* what global organisations (other than the UN) are ready to take on this challenge and provide an alternative framework. It may be that the problems many countries have with the Protocol stems not from its flaws, but the fact it holds them to account in delivering real GHG emission reductions. One can also wonder whether the talks of different methods of climate control are actually delaying the requirement for countries to adopt different strategies to Business as Usual (BaU).

Canada for example announced its intention to withdraw from the Protocol (13/12/12) the day after the COP 17 finished in Durban. This has been blamed by the Canadian government on the level of reductions that would now be needed to meet their Kyoto commitments (a 6% reduction from 1990) when they are actually on target to increase their emissions by 16%. The lack of reductions and inaction by proceeding Canadian governments is suggested as the root cause of this problem, and the solution to severely curb emissions or buy (trade) carbon emission permits from other countries would be prohibitive (and could be better spent) – especially with the continued economic backdrop of uncertainty in financial markets and potential recession of their biggest trading partner – the USA. It is not surprising that Canada took this decision for economically rational reasons (for Canada) to move in step with the USA *i.e.* be outwith the Kyoto Protocol altogether (but still a signatory to the UNFCCC) – but it rather brings into focus the difficulties of having concerted agreement and effort on a global scale to control emissions. One of the crucial features of the disagreement between parties to the UNFCCC of the first round of the Protocol is its exemption of the developing world from emissions reduction obligations. Without this initial concession, the developing world is not thought likely to have accepted the treaty—but with it, the treaty was very weak in reducing overall emissions in the first round timeframe (particularly since, in a political sense, this concession precluded American participation). This is one of the fatal flaws of Kyoto as seen by the American and now the Canadian governments. However, the exemption of developing countries from the first round of targets should not be taken to mean that they would always be exempted. Indeed, they cannot, as it is not credible to stabilise the GHG concentration at a particular level without the stabilisation and reduction of GHG from developing countries. The USA and Canada are therefore correct to argue that developing countries are required to participate at a greater level, but developing countries in turn assert that developed countries (who have caused the historical levels of GHG emissions, and have economies that have benefitted from these emissions) should lead by example, and should allow some room for growth of developing countries economies. This is one (albeit probably the major one) area of difficulty in agreeing global commitments from diverse economies. However, it can also be argued that countries that are more profligate with energy (linked to the cost of energy to end-users as well as the overall need for energy services) should have more flexibility to decrease their use of energy through efficiency and fiscal measures. For example why has the USA not increased taxes on fuel, and not increased the emission targets for vehicles to keep pace with other areas of the world in order to reduce the per capita use of fossil fuels? It seems entirely logical to suggest that a similar level of service (e.g. transport, heat) could be expected from a given amount of energy (fuel) by using more efficient technologies, and furthermore that this would be in most stakeholders' interest (other than the entities selling the energy). As the USA is a net importer of oil – one wonders why a reduction in the need for oil is not more obvious to an oil net importing country, even in terms of energy security.

The decision by Canada to withdraw from the Kyoto Protocol (after a year's notice period) also brings into focus the lack of ability of the Protocol to force members to comply with their commitments or even the penalties or sanctions available if they do not. Other than diplomatically naming and shaming countries that are lagging behind their stated commitments – the Kyoto Protocol is effectively a voluntary scheme – countries have to want to take part and also have to want to put policies in place to reduce their emissions. If there is a lack of political imperative to undertake this – it is no surprise that countries subsequently seek to renegotiate the terms of the agreement – even by withdrawing.

The following 4 graphs provide some indication of the relative historical amounts of CO_2 emissions between some nations with major emissions. The graphs only show CO_2 rather than other greenhouse gases and are annual values. The data sets are from the Carbon Dioxide Information Analysis Centre (CDAIC) in Tennessee, and the World Bank. The visualisation platform from Google provides an interactive method to compare data from different countries (Google Public Data Explorer, 2013).

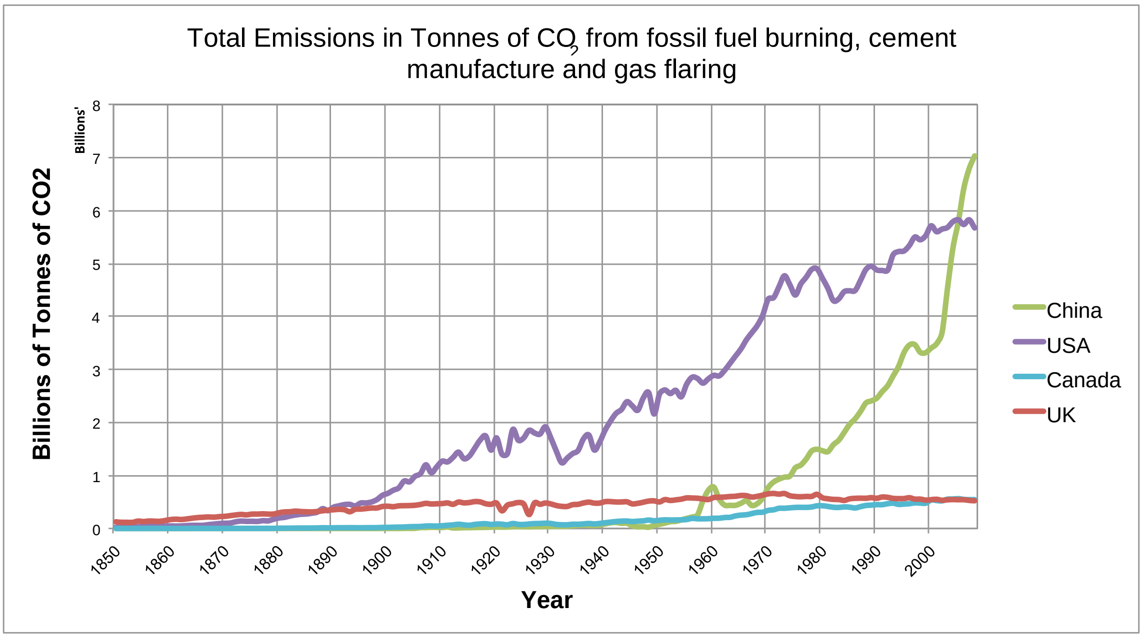


Figure 1 - Historical CO2 emissions for China, USA, UK and Canada 1850 – 2008 data from (CDIAC, 2011)

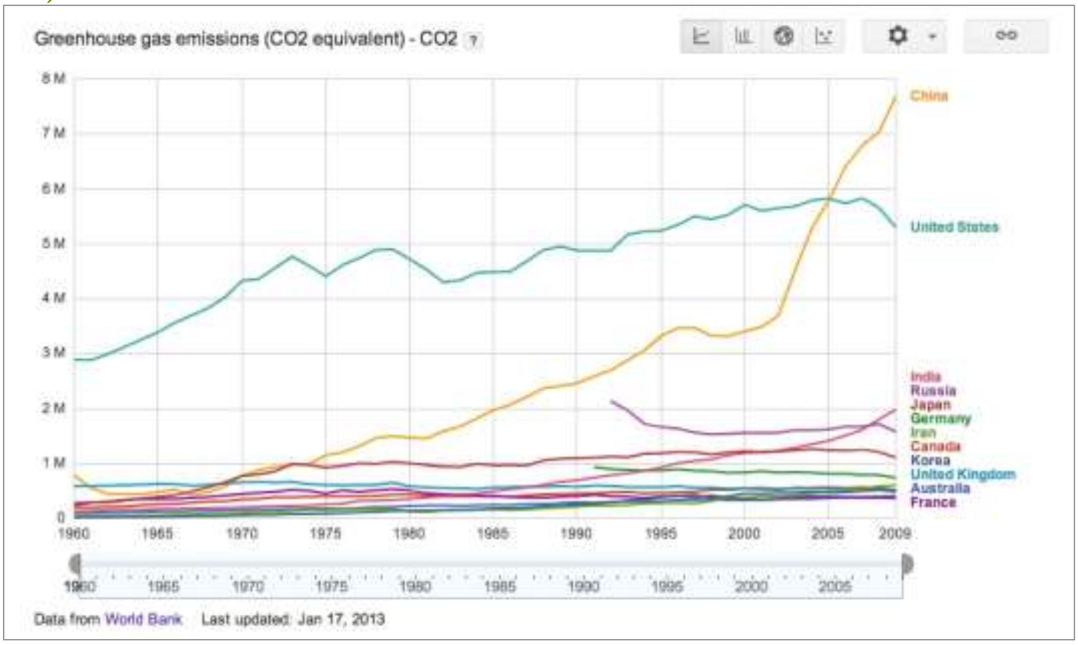


Figure 2 – CO_2 emissions (in Thousand of Tonnes) – 1960 -2009 (WB-WDIa, 2013)

Figures 1 and 2 above clearly show that the increase in absolute terms from China has been the largest over the period since 1990 but the cumulative amount of emissions (the area under each line) is greater from the USA. The historical emissions are one of the main reasons behind the principle that developed countries should take the leadership role in reducing GHG. This graph also lends credence to a view of futility by some in the UK, that regardless of the amount of emission reductions carried out by the UK – it is dwarfed by the increases in GHG emissions by China and other developing nations.

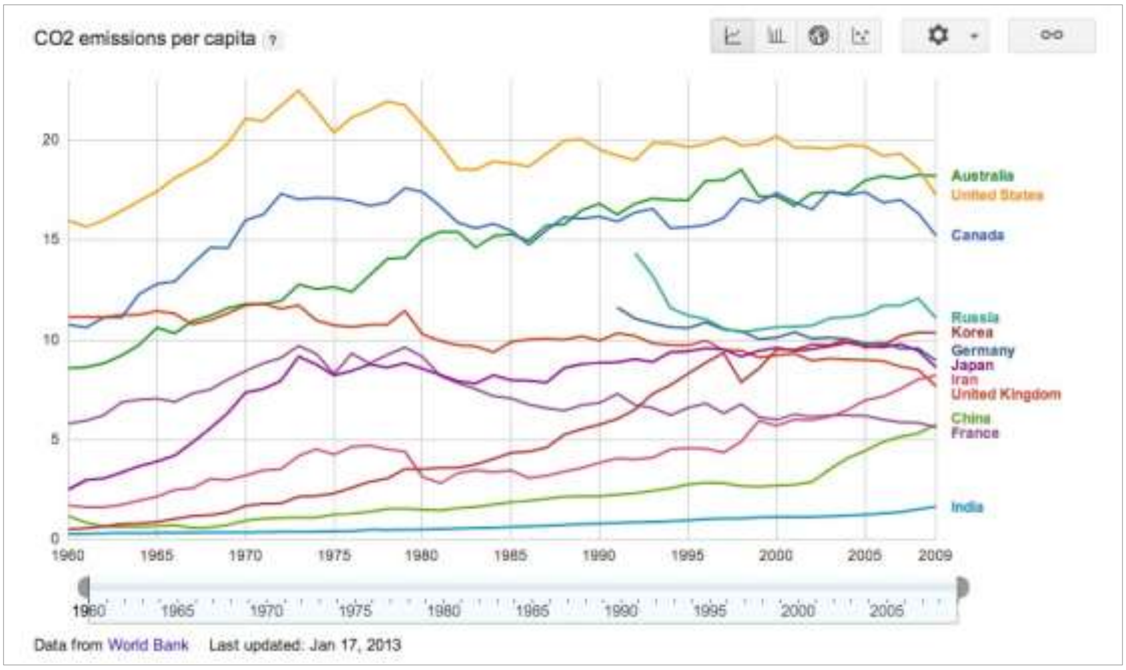


Figure 3 – CO_2 emissions per capita (Tonnes) – 1960 – 2009 (WB-WDIb, 2013)

Figure 3 shows the CO_2 emissions per capita for different countries – it can be seen that the high comparative level of the USA, Australia and Canada leads to political difficulties in these countries in order to reduce the per capita emissions, for many different reasons, the populations of these countries have become used to many years of the higher standards of living predicated on these high levels of emissions. The figure also shows that it is possible to reduce emissions (Russia, Germany and the UK), but this aggregated data needs careful consideration and explanation. For example, in the case of the UK, the move to a competitive electricity market provided a market driver to move away from coal fired power stations to gas fired power stations throughout the 1990s – the 'Dash for Gas', which had a beneficial impact on reducing emissions throughout this time. The figure also clearly shows the argument by developing countries that their emissions on a per capita metric are well below developed countries. The use of emissions on a per capita metric brings the question of equitability very much to the fore, certainly in terms of convergence around a band of emissions levels. If standards of living are intimately correlated with per capita emissions – then different levels of emissions would therefore equate to broadly different levels of standards of living – and is it fair and equitable that certain countries should be constrained in terms of their development potential? This is a complex and emotive issue and considers the notion of climate justice, where the effects of climate change may disproportionally fall on those countries least able to cope with these effects.

Overall though, it should always be remembered as far as global gas emissions are concerned (and therefore stabilisation of emissions) – it is the absolute amount of emissions that is the important issue, rather than a metric that uses a ratio of per capita or per Gross Domestic Product (GDP) as a measurement. The overall global emissions need to be stabilised and reduced – but the obvious difficulty shown in Figures such as 3 & 4, is how to do this on an equitable manner such that countries actually start to reduce emissions.

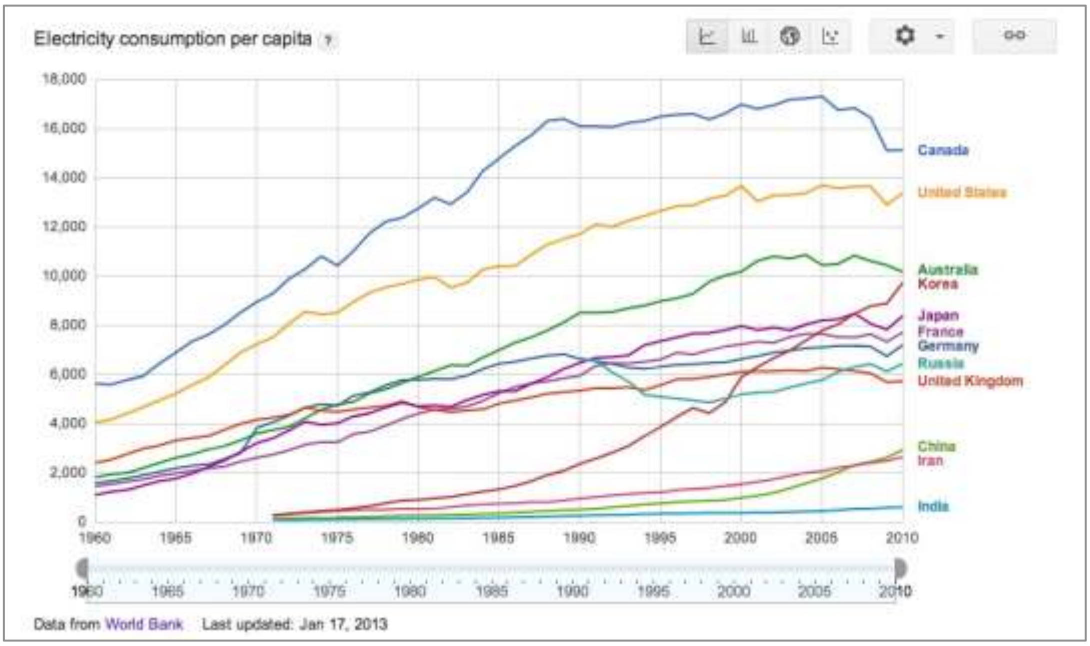


Figure 4 - Electricity consumption per capita 1960 – 2010 in kWh (WB-WDIc, 2013)

In contrast to Figures 2 & 3 that show several countries with a stabilising or reducing level of CO_2 emissions (absolute or per capita), Figure 4 shows that the level of electricity consumption on a per capita basis has an increasing trend for most countries. These trends have longer-term structural dips (Russia and Germany after the fall of the Berlin Wall), and smaller dips that are thought to be linked to economic downturns (USA 2000, Japan 2008, Korea 1997). It can also be seen that the UK has stabilised its per capita electricity consumption – which may be partially explained by the reduction in heavy industry, and move from manufacturing and primary sector towards a service sector biased economy, *i.e.* an offshoring of electricity intensive industries. However, if other loads start to move over to use electricity as an energy vector – such as heating and transport – then it will be interesting to note the difference in these per capita values in future years, as undoubtedly there will be an increase in these levels.

The process of reducing levels of GHG can be seen to be framed in the language and knowledge of climate change control at a global level. This has a drawback in terms of all parties moving at once, and parties not wishing to commit until others have done so – an interesting exercise in terms of game theory. There are however, different drivers that have a similar direction in order to reduce GHG emissions but are able to be argued at a national level and in the national interest – namely a reduction in the importation of fuels, with a possible benefit in terms of balance of payments and possible benefits to energy security. However, offsetting imported energy needs with the use of national resources has to be carefully considered in terms of the overall cost and benefits to a nation.

3.3 European Legislation

The European Commission launched the European Union’s European Climate Change Programme (ECCP) in 2000, which was changed to the Directorate-General for Climate Action (DG CLIMA) in February 2010. Its aims are: to lead international negotiations on climate; help the EU to deal with the consequences of climate change and to meet its targets for 2020; develop and implement the EU Emissions Trading System. The history and developments at a European level have changed over several years, and rather than present the historical parts of the process in detail – the existing and future plans and legislation will be presented. It should however be noted that the process of recognising climate change and legislating for solutions started around the same time as the birth of the UNFCCC in the early 1990s. The European Union as a whole and certain member states have chosen to lead on several initiatives, which build upon and complement the Kyoto Protocol commitments.

The major elements of European policy that frame national policies include the Climate and Energy Package, which became European law in June 2009. The policy has target dates to 2020 and is in place regardless of wider progress made under second round commitments of the Kyoto Protocol. The core principles of the package are reduction in overall emissions, promotion of energy efficiency measures, and an increase in the energy derived from renewable sources. Table 5 gives an overview of the core legislation (EC, 2009b).

The core of the Climate and Energy Package comprises four pieces of complementary legislation:
A revision and strengthening of the Emissions Trading System (ETS), the EU's key tool for cutting emissions cost-effectively. A single EU-wide cap on emission allowances will apply from 2013 and will be cut annually, reducing the number of allowances available to businesses to 21% below the 2005 level in 2020. The free allocation of allowances will be progressively replaced by auctioning, and the sectors and gases covered by the system will be somewhat expanded.
An 'Effort Sharing Decision' governing emissions from sectors not covered by the EU ETS, such as transport, housing, agriculture and waste. Under the Decision each Member State has agreed to a binding national emissions limitation target for 2020, which reflects its relative wealth. The targets range from an emissions reduction of 20% by the richest Member States to an increase in emissions of 20% by the poorest. These national targets will cut the EU's overall emissions from the non-ETS sectors by 10% by 2020 compared with 2005 levels.
Binding national targets for renewable energy, which collectively will lift the average renewable share across the EU to 20% by 2020 (more than double the 2006 level of 9.2%). The national targets range from a renewables share of 10% in Malta to 49% in Sweden. The targets will contribute to decreasing the EU's dependence on imported energy and to reducing greenhouse gas emissions.
A legal framework to promote the development and safe use of carbon capture and storage (CCS). CCS is a promising family of technologies that capture the carbon dioxide emitted by industrial processes and store it in underground geological formations where it cannot contribute to global warming. Although the different components of CCS are already deployed at commercial scale, the technical and economic viability of its use as an integrated system has yet to be shown. The EU therefore plans to set up a network of CCS demonstration plants by 2015 to test its viability, with the aim of commercial update of CCS by around 2020. Revised EU guidelines on state aid for environmental protection, issued at the same time as the legislative package was proposed, enable governments to provide financial support for CCS pilot plants.

Table 5 - EU Climate and Energy Package (EC, 2009b)

The overall aim of the package is to meet its 2020 targets by sharing out the burden of emissions reductions to members within the EU framework.

3.4 European 20-20-20 targets

The targets set by the Climate and Energy Package are known as the 20-20-20 targets, which are to be met by the end of the year 2020 and are composed of:

- A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels.

- 20% of EU energy consumption to come from renewable sources.
- 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

The UK is a signatory to this European Union burden sharing agreement, which binds the UK to a target of 15% of energy supply from renewables by 2020. The European Renewable Energy Directive (2009/28/EC) (EC, 2009a) was passed on 23rd April 2009 with the aim of establishing a '*common framework for the use of energy from renewable sources in order to limit greenhouse gas emissions and to promote cleaner transport'*. It sets mandatory national targets for each Member State (Annex 1) with the aim of achieving a 20% share of renewable energy of Europe's final energy consumption by 2020.

Member state's targets can be seen in Table 6 and Figure 5. It should be noted that under this particular legislation ALL member states have an increased target from 2005.

Member State	2005 % from Renewables	2020 target % from Renewables	Member State	2005 % from Renewables	2020 target % from Renewables
Belgium	2.2%	13%	**Luxembourg**	0.9%	11%
Bulgaria	9.4%	16%	**Hungary**	4.3%	13%
Czech Republic	6.1%	13%	**Malta**	0.0%	10%
Denmark	17.0%	30%	**Netherlands**	2.4%	14%
Germany	5.8%	18%	**Austria**	23.3%	34%
Estonia	18.0%	25%	**Poland**	7.2%	15%
Ireland	3.1%	16%	**Portugal**	20.5%	31%
Greece	6.9%	18%	**Romania**	17.8%	24%
Spain	8.7%	20%	**Slovenia**	16.0%	25%
France	10.3%	23%	**Slovak Republic**	6.7%	14%
Italy	5.2%	17%	**Finland**	28.5%	38%
Cyprus	2.9%	13%	**Sweden**	39.8%	49%
Latvia	32.6%	40%	**United Kingdom**	1.3%	15%
Lithuania	15.0%	23%	**Scotland**	21% (2008)	30%

Table 6 - National overall targets for the share of energy from renewable sources in gross final consumption of energy in 2020. European Renewable Energy Directive (2009/28/EC) Annex 1 + Scotland

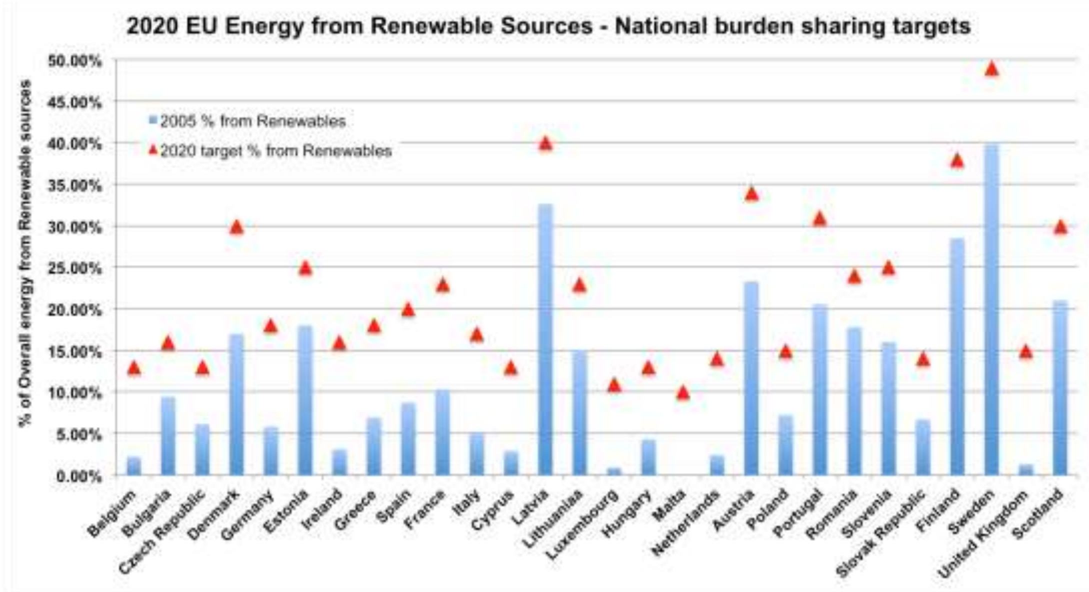


Figure 5 - National overall targets for the share of energy from renewable sources in gross final consumption of energy in 2020. European Renewable Energy Directive (2009/28/EC) Annex 1 + Scotland

Under Article 4 of the European Renewable Energy Directive (2009/28/EC) each Member State was required to submit a National Renewable Energy Action Plan (NREAP). The UK's plan (NREAP, 2009) describes the background to the 15% agreed target of the UK's energy consumption from renewable sources by 2020.

Other EU legislation includes the EU Emission Trading Scheme and the EU Energy Performance of Buildings Directive, which both set targets and reporting procedures for GHG emissions.

3.5 UK Policy Landscape

The UK is within the scope of the European level targets of the Kyoto Protocol (an 8% reduction in GHG over the first commitment period to 31st December 2012) that has provided the framework for Member State legislatures to enact primary legislation that commits member states to a reduction in greenhouse gas emissions. As part of the 'Burden Sharing' agreements the UK was committed to a 12.5% reduction in GHG by the end of the first commitment period.

The EU ETS caps emissions from industrial facilities within the EU and forms the core instrument for the EU to meet its obligations under the Kyoto Protocol.

At a UK level – the major legislation was the enactment of the Climate Change Act in November 2008 (CCA, 2008) that introduced the framework to set 5 year carbon budgets with legally binding emission reduction targets, and also created the independent Climate Change Committee (CCC) that advises on these budgets, advises on paths to meet these targets, and reports to the UK parliament on the progress being made. In the following UK budget in April 2009, the UK parliament presented the first three carbon budgets under the Climate Change Act (2008-2012, 2013-2017, 2018-2022), which aim to set the UK on a path to achieve the 80% reduction on 1990 emissions by 2050. The CCC advised on the level of the 4th carbon budget (2023-2027) in December 2010 (CCC, 2010), and proposed a tightening to the second and third carbon budgets. '*In May 2011 the Government accepted the Committee's recommendation for the level of the 4th budget - a limit of 1950 MtCO2e over the years 2023-2027, amounting to an emissions cut of 50% on 1990. The Government has accepted that the aim should be to deliver this through domestic action, though the use of credits has not been ruled out. It legislated the level of the fourth carbon budget by the end of June 2011.*' (CCC, 2013)

In late 2012, the Energy Bill was introduced to the House of Commons alongside the Annual Energy Statement. This bill aims to introduce a range of measures to provide greater certainty to investors to invest in the energy system in the UK. The Bill (UK_Energy_Bill, 2012) aims to *'attract investment, reduce the impact on consumer bills, and create a secure mix of electricity sources including gas, new nuclear, renewables, and carbon capture and storage*' by the introduction of a carbon price floor, 'contracts for difference' long-term contracts, an emissions performance standard set at 450g CO_2/kWh, and a payment for capacity mechanism.

The bill *'will establish a legislative framework for delivering secure, affordable and low-carbon energy and includes provisions on'*:

Electricity Market Reform (EMR)
This bill puts in place measures to attract the £110 billion investment, which is needed to replace current generating capacity and upgrade the grid by 2020, and to cope with a rising demand for electricity. This includes provisions for:
• **Contracts for Difference (CFD): long-term contracts to provide stable and predictable incentives for companies to invest in low-carbon generation;** • **Capacity Market: to ensure the security of electricity supply;** • **Conflicts of Interest and Contingency Arrangements: to ensure the institution which will deliver these schemes is fit for purpose;** • **Investment Contracts: long-term contracts to enable early investment in advance of the CFD regime coming into force in 2014;** • **Access to Markets: This includes Power Purchase Agreements (PPAs), to ensure the availability of long-term contracts for independent renewable generators, and liquidity measures to enable the Government to take action to improve the liquidity of the electricity market, should it prove necessary;** • **Renewables Transitional: transition arrangements for investments under the Renewables Obligation scheme; and** • **Emissions Performance Standard (EPS): to limit carbon dioxide emissions from new fossil fuel power stations.**
Nuclear regulation
The Bill places the interim Office for Nuclear Regulation (ONR) on a statutory footing as the body to regulate the safety and security of the next generation of nuclear power plants. This includes setting out the ONR's purposes and functions.
Government pipe-line and storage system
The Bill includes provisions to enable the sale of the Government Pipe-line and Storage System (GPSS). This includes providing for the rights of the Secretary of State in relation to the GPSS, registration of those rights, compensation in respect of the creation of new rights or their exercise, and for transferral of ownership, as well as powers to dissolve the Oil and Pipelines Agency by order.
Strategy and policy statement
The Bill improves regulatory certainty by ensuring that Government and Ofgem are aligned at a strategic level through a Strategy and Policy Statement (SPS), as recommended in the Ofgem Review of July 2011.
Cheaper tariffs
The Bill (as amended) includes provisions that enable the Government to: set a limit on the number of energy tariffs offered to domestic consumers; require the automatic move of customers from poor value closed tariffs to cheaper deals; require the provision of information by suppliers to consumers on the best alternative deals available to them from them. It also allows for Ofgem to extend its licence regime to third-party intermediaries, such as switching websites.

Table 7 – Overview of 2012 Energy Bill (UK_Energy_Bill, 2012)

The bill is passing through the UK parliament in early 2013 – and will be the foundation of the UK's legislative framework to provide energy for the UK going forward. There is some concern in the nascent storage sector that the bill may not take full account of the benefits that storage has to offer, and that the market may choose to opt for open cycle gas turbine technology as a method to balance an increase in renewables. It is not the aim of this work to discuss this bill in detail, but there seems little to provide a distinct market for electrical energy storage as opposed to other forms of capacity or balancing services. It will be most interesting to look back in a decade to see what the bill has achieved in terms of the cost of energy to consumers and to the reduction in the overall GHG emissions of the UK.

3.6 Remarks

As an overview of the policy landscape, there is a constant cascade of changing knowledge and objectives aimed at mitigating the threat of anthropogenic climate change, increasing system resilience or 'keeping the lights on', and possibly reducing energy dependency on imported fuels or electricity. As a global problem – climate change requires a global agreement on policy, which then proceeds down the global action chain and is adapted to regional and then national constraints and conditions. It is a complex and ever changing area that provides many opportunities and threats to business as usual in an economic and a social sense. The challenge of equitability in global development over historical timeframes seems to be the Achilles heel of a combined approach (especially in the US and now Canada) where policy makers find it electorally difficult to promote the view that changes of living standards are required in order to allow other developing countries to proceed to a rising standard of living closer to that of their electorates. Unknown unknowns are also able to impact the course of actions to be taken *e.g.* the accident at Fukushima has had an impact not only on Japan's future energy policies, but also that of Germany. The fact that the majority of historical emissions have come from developed countries and that the majority of future emissions are expected to come from developing countries is a simple view to understand, but can be politically toxic on a national level to explain. Regardless of the increasing threat – national policies will continue to be couched in terms of national electorates, and this, above all, defines the difficulties in translating the knowledge from science (which can work well on an international level) with the actions that require political capital at a national level.

In the medium to long term, regardless of the point of view expressed by Stansberry that fossil fuels are created by capital, existing fossil fuels (and therefore the energy that they contain) are a finite resource. The primary solar energy that was transformed into chemical energy over geological timeframes is now being used up by the global demand of fossil fuels in human generational timeframes. In these existing fossil fuel forms – they are a one off bargain – once they have been oxidised their useful form has been changed, their exergy has been reduced, and they cannot be reused. So the total amount of fossil fuels on earth is finite (but unknown) and is currently being depleted at rates that are fairly well understood through international trade data. Humans will have to adapt to radically changed energy systems with differing primary energy sources and possibly different energy vectors. Eventually low-carbon and sustainable forms of primary energy supply will overtake fossil fuel use, which strongly points towards renewable energy resources unless fusion or another form of low-carbon and sustainable form of primary energy harnessing is found. This shift would suggest that greenhouse gas emissions could indeed be eventually stabilised. Whether this happens on a timeframe that stabilises at concentrations that prevents dangerous anthropogenic interference with the climate system depends on a multitude of factors literally on a global scale, and potentially a transition away from the hegemony that has developed over the last century in energy systems, nation development, international trade, and finance. It is an overwhelming challenge to change the grip of powerful interests in order to promote the wellbeing of humankind, and history is not encouraging in this regard.

4 The UK's renewable energy resource

Rather than considering the future energy requirements of the UK electrical network (as there is considerable uncertainty in the trade off between energy efficiency measures and increasing electrical energy use due to the transfer of heat and transport to the electrical network), this section looks at the renewable energy resource available to the UK for conversion to electrical energy.

The renewable energy resources for the UK have undergone considerable revisions over a number of years, as the resources have been better understood. Three source documents that provide estimated values for the different renewable resources include the Committee on Climate Change's Renewable Energy Review (CCC, 2011), the Offshore Valuation Group's report (OVG, 2010), and DECC's 2050 Pathways Analysis report (HMG PA, 2010).

Table 8 provides an overview of the results from the Offshore Valuation Group report, where it can be seen that overall, the UK has a significant practical resource which it could choose to exploit, which is in marked difference to many other European countries with much smaller national practical renewable energy resources. However, to put the values of the resource in some sort of context, the forecast electrical energy demand for the UK was estimated by the Offshore Valuation Report to be 610 TWh in 2050 in a low case scenario and 800 TWh in a high case scenario, compared to a current annual electrical demand of around 350 TWh.

Technology	Capacity	Annual Output
Onshore Wind	50 GW	132 TWh
Fixed Wind	116 GW	406 TWh
Floating Wind	350 GW	1533 TWh
Tidal Stream	33 GW	116 TWh
Tidal Range	14 GW	36 TWh
Wave	18 GW	40 TWh
Solar	4000km^2	140 TWh
Small Scale Hydro	0.8-0.9 GW	~3.5 TWh
Bioenergy	?	?
Geothermal	9.5 GW	35 TWh
Total	-	2441.5 TWh

Table 8 – Estimated Practical Resource by technology sources: data from Offshore Valuation Group, CCC Renewable Energy Review and DECC 2050 Pathways Analysis Report.

4.1 Wind Resource

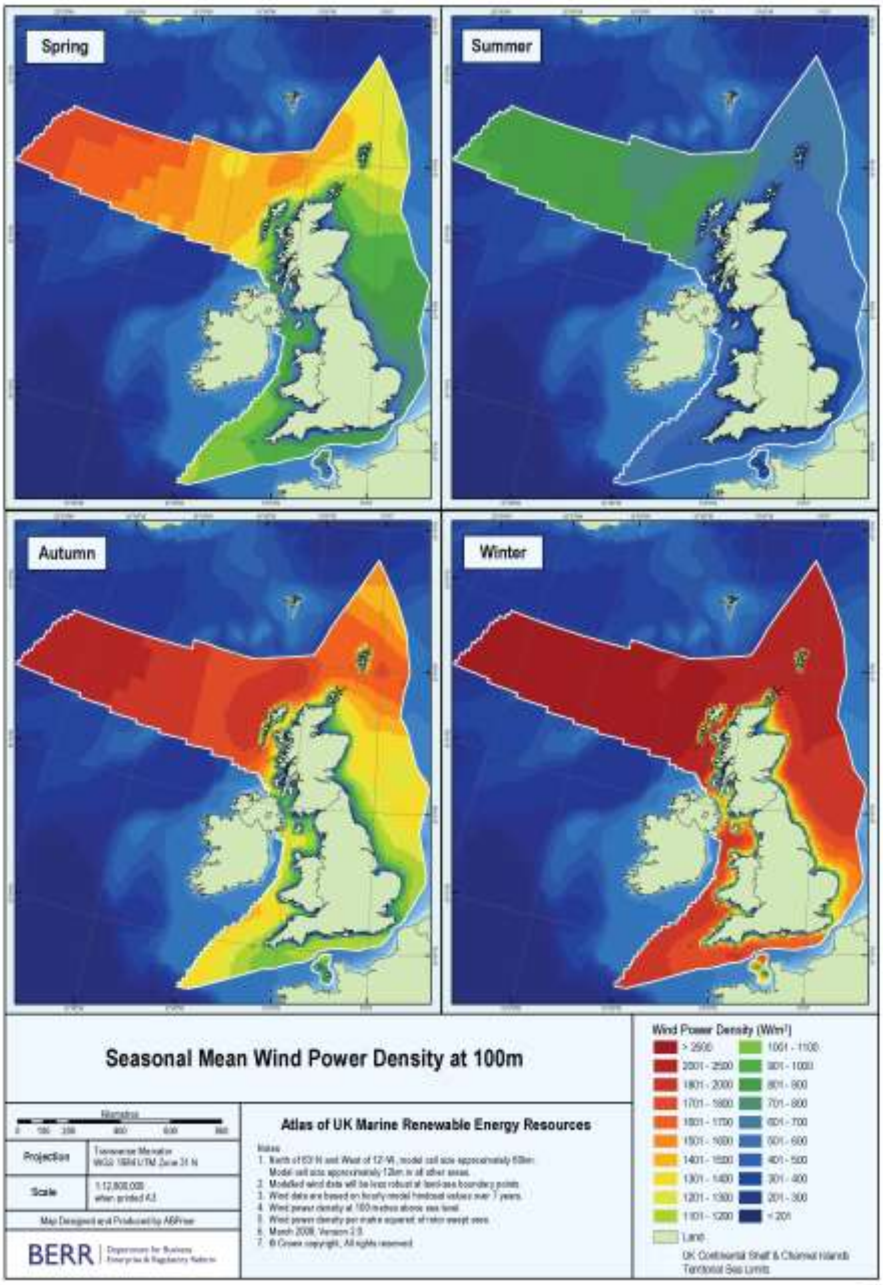


Figure 6 – Seasonal Mean Wind Power Density at 100m, source: Atlas of UK Marine Renewable Energy Resources

The total practical resource estimated by the Offshore group for fixed wind is 116 GW / 406 TWh per annum (40% load factor). Floating wind is 350 GW / 1533 TWh per annum (50% load factor). Onshore wind's practical potential is estimated as 50 GW / 132 TWh per annum (30% load factor).

4.2 Tidal Resource

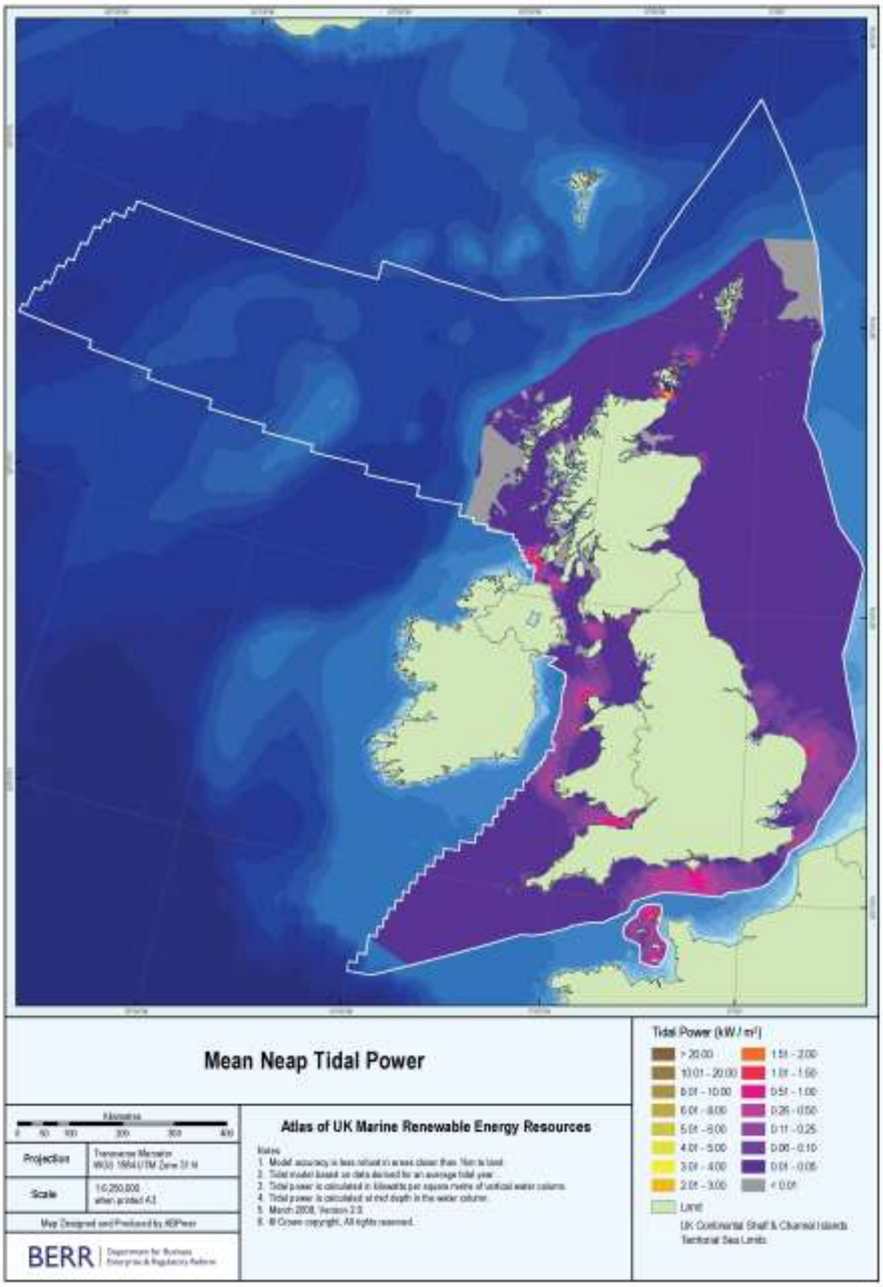


Figure 7 - Mean Neap Tidal Power, source: Atlas of UK Marine Renewable Energy Resources

The total practical resource estimated by the Offshore group for tidal stream is 33 GW / 116 TWh per annum (40% load factor). Tidal range is 14 GW / 36 TWh per annum (30% load factor).

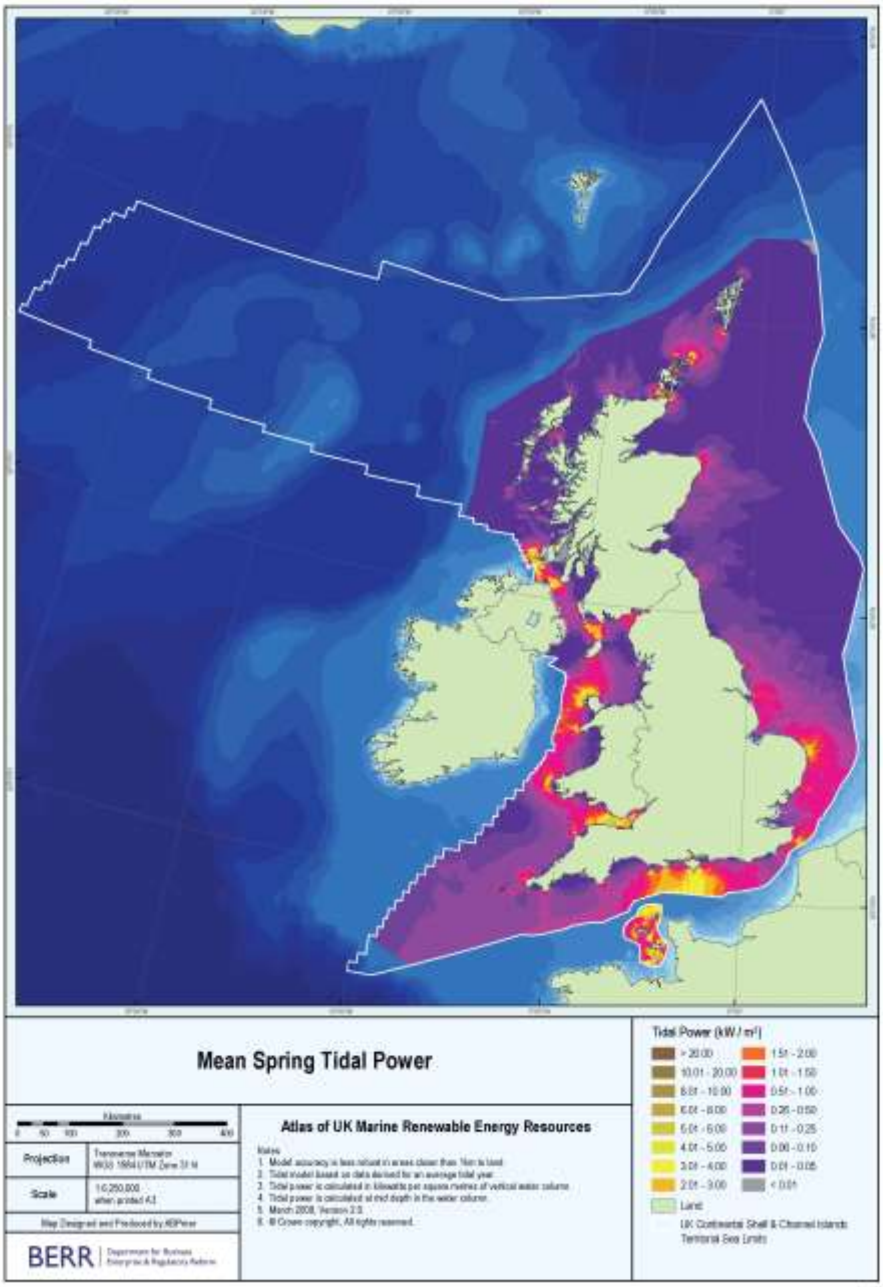


Figure 8 - Mean Spring Tidal Power, source: Atlas of UK Marine Renewable Energy Resources

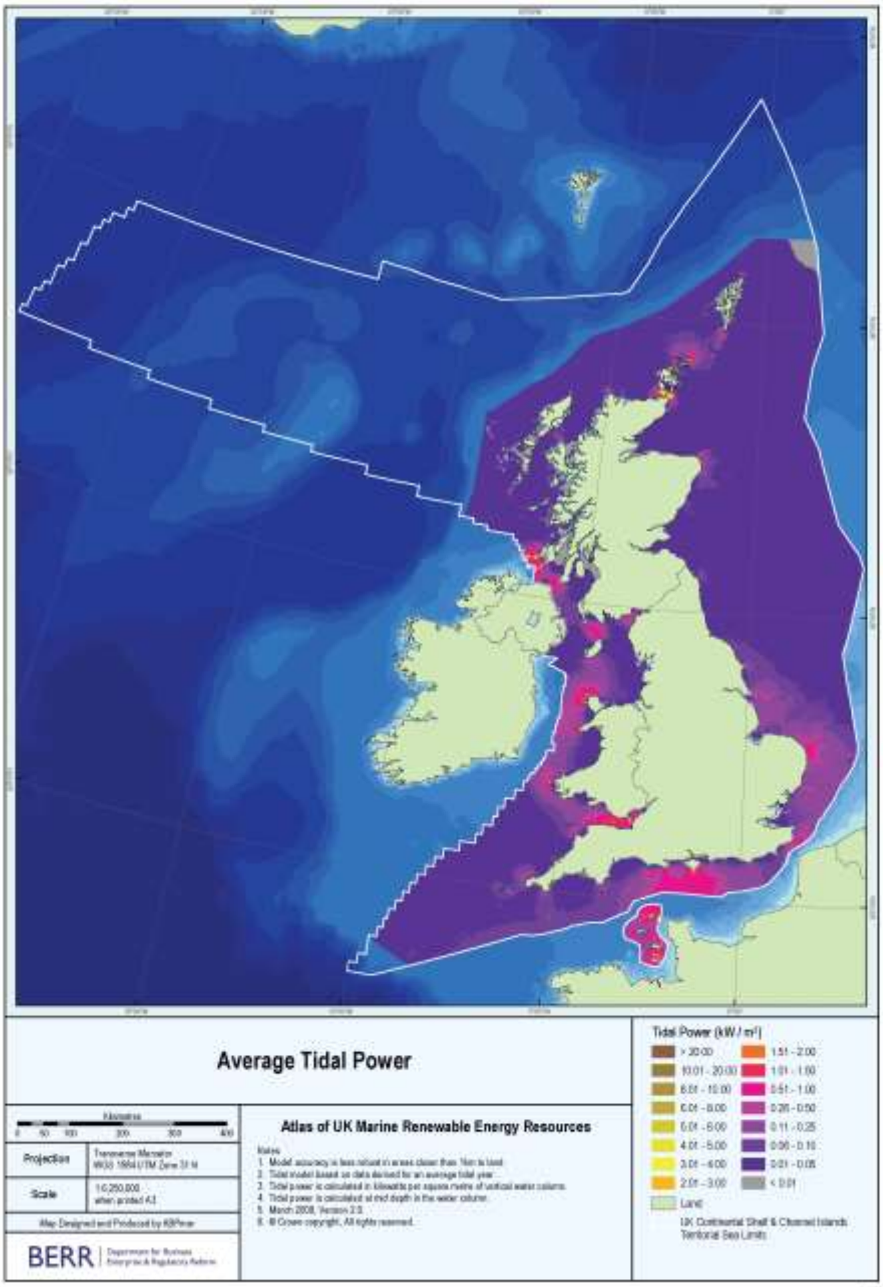


Figure 9 - Average Tidal Power, source: Atlas of UK Marine Renewable Energy Resources

4.3 Wave Resource

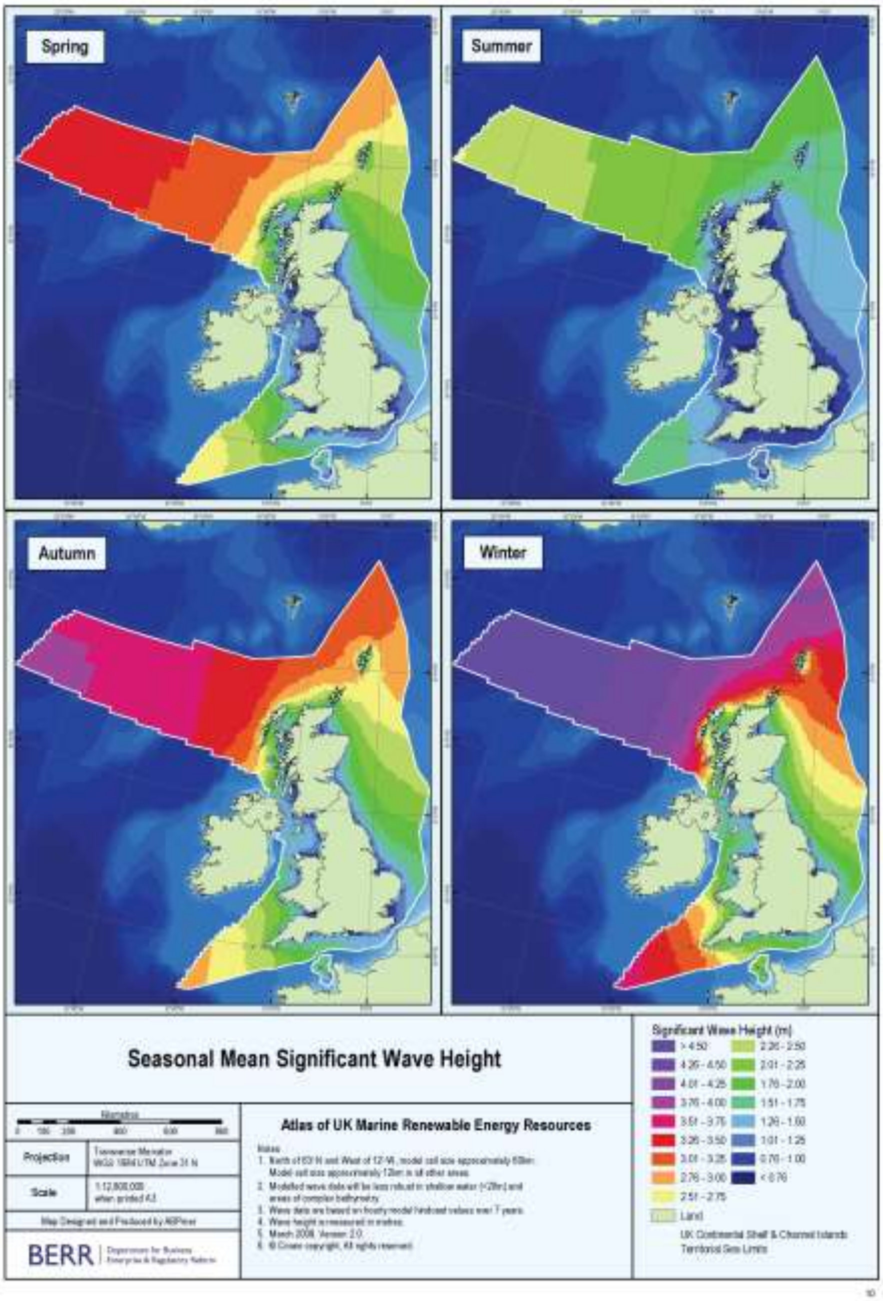


Figure 10 - Seasonal Mean Significant Wave Height, source: Atlas of UK Marine Renewable Energy Resources

The total practical resource estimated by the Offshore group for wave is 18 GW / 40 TWh per annum. (25% load factor).

4.4 Solar Resource

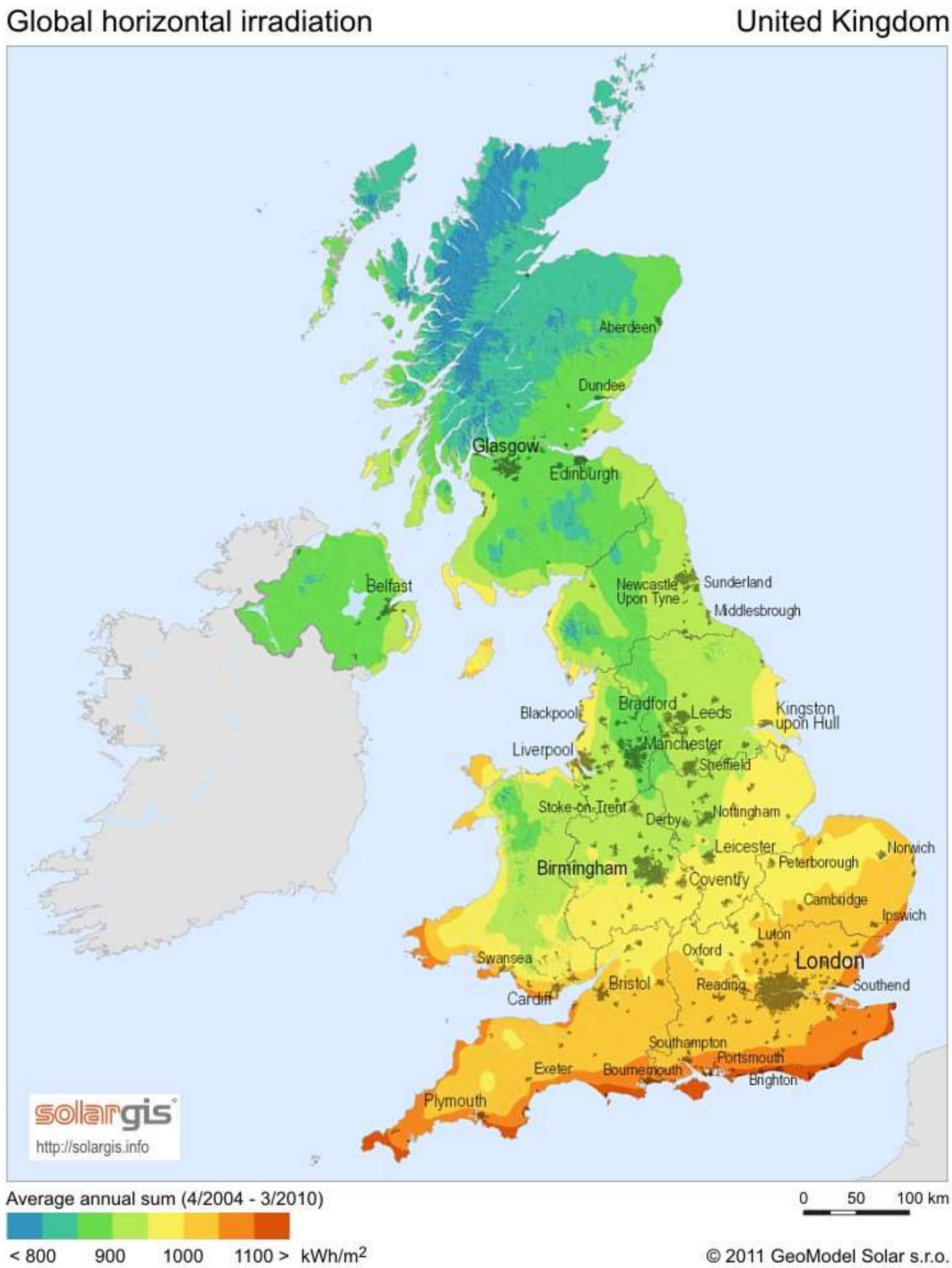


Figure 11 – Solar Irradiation Levels UK. source: SolarGIS © 2012 GeoModel Solar s.r.o.

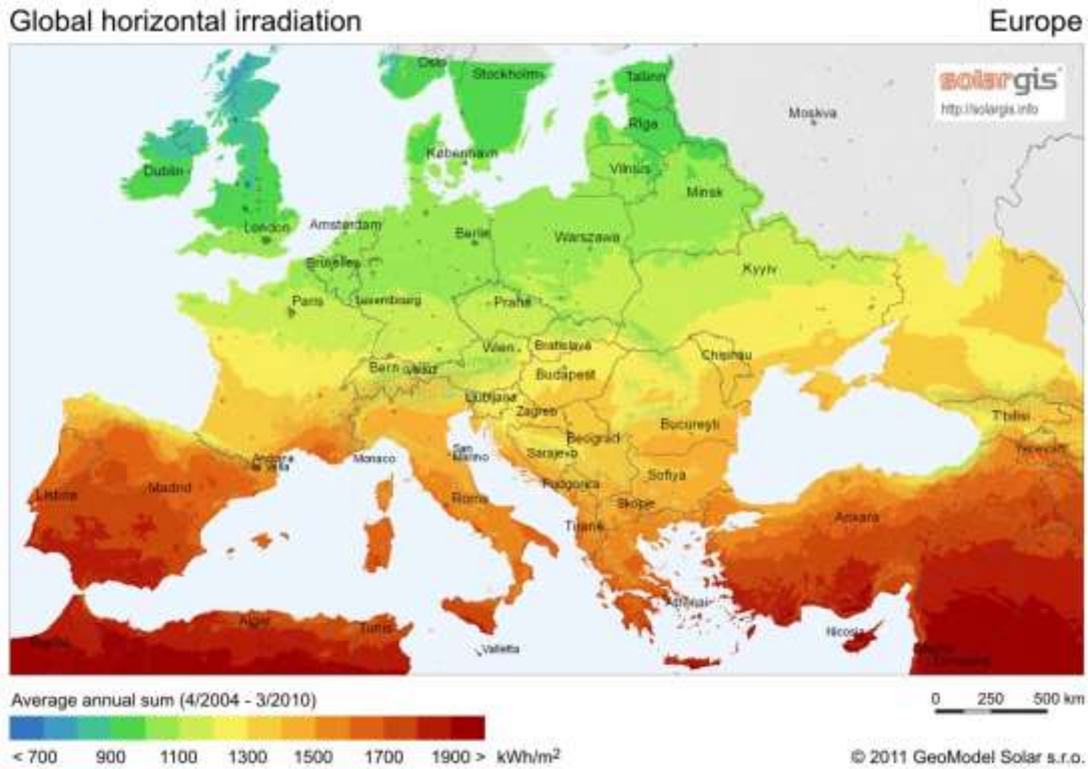


Figure 12 – Solar Irradiation Levels Europe. source: SolarGIS © 2012 GeoModel Solar s.r.o.

The area of the country and the location of the UK as a Northern European Country limit the UK's technical solar resource. The practical solar resource is difficult to establish, due to factors such as whether the solar resource is captured for heat purposes (Solar Thermal) or captured for electrical conversion (Photo Voltaic). The costs of the technology and installation are ever changing and the available space for installation (nationwide) is not known with a high degree of certainty, however, the figure from page 217 of the DECC 2050 Pathways report of 140 TWh is presented (HMG PA, 2010). This is viewed as a significant, although long-term in potential.

The installed capacity of Solar PV in the UK at the end of August 2012 is ~1300MW = 1.3 GW. At a conversion rate of 850 kWh per installed kW of PV per annum, equates to ~1.1 TWh per annum. Figure 13 shows the installed capacity of Solar PV under the Feed In Tariff mechanism – the four peaks of weekly installation clearly show the difference that changes in policy (*i.e.* feed in tariffs) can produce. The figure also shows that the supply chain for PV installation in the UK coped with a level of 120

MW in one week in December 2011, and although this value should be treated with some caution – it is still impressive considering the level of installation in 2010.

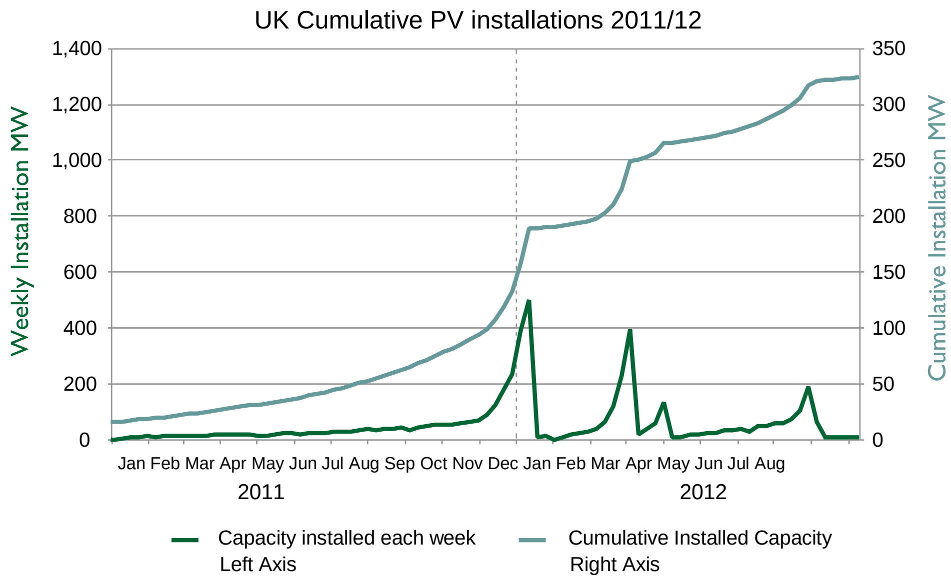


Figure 13 – PV installations under the UK Feed In Tariff. Data from (DECC PV, 2013)

4.5 Hydro Resource

Studies were carried out into the hydro resource of England and Wales (DECC Hydro, 2010) and separately for Scotland (NFA, 2008). These gave estimates of the practical small-scale hydro resource to be a practical resource of between 146 MW – 248 MW in England and Wales, and 657 MW that could deliver 2.77 TWh of electricity annually for Scotland.

4.6 Bioenergy Resource

The AEA report for DECC in 2011 (AEA, 2011) suggests that the UK could have access to a significant bioenergy supply of 1800 PetaJoules (PJ) which is roughly equivalent to 20% of 2011 UK energy demand. This figure, although subject to major assumptions on price, land use and availability, still points to a potentially large source of primary energy for the UK. However, the amount of resource available to the electrical generating sector is dependent on competing pressures for the resource from other sectors. It should also be noted that the bioenergy resource is also set to become more international in nature, with the distinct possibility of an increase in bioenergy imports.

4.7 Geothermal Resource

A recent assessment of the UK's geothermal resource was carried out by SKM for the Renewable Energy Association. It concludes that there is potential for 9.5 GW of electrical power and 100 GW of heat (GWth). The report considers these values as baseload, and is thought to be more than the resource estimated by the earlier report from the Committee for Climate Change at 35 TWh per annum (35 TWh with an installed capacity of 9.5 GW equates to a load factor of ~40%, which must be less than that assumed for baseload).

4.8 Electrical and Gas Infrastructure

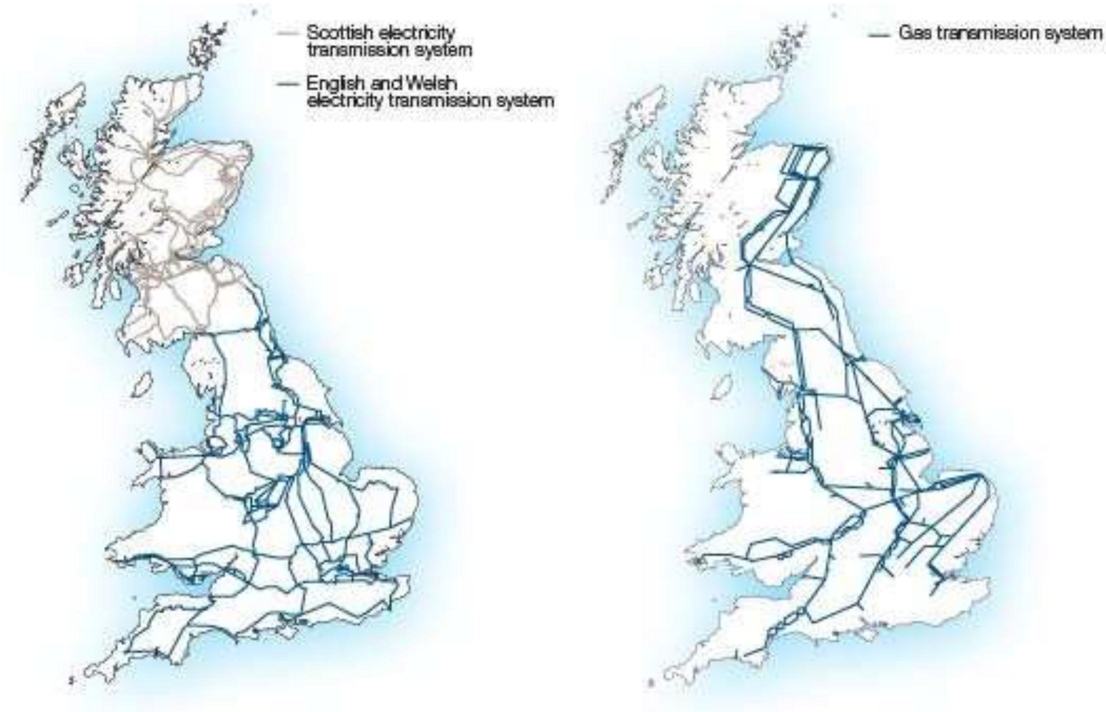


Figure 14 - UK electrical and gas transmission networks source: National Grid

The high voltage transmission network in the UK has grown over many decades to connect large centralised power plants to the centres of demand. This has largely been a North to South flow of electrical energy. The transmission network operator is now challenged with the connection of flows from the East of the country (from offshore wind) and from further North in Scotland. Equally transmission level gas infrastructure has also had to accommodate the construction of several LNG import terminals, which now provide a significant amount of natural gas to the UK market (see Figure 17).

4.9 Growth of renewable generation in the UK

As suggested by the values earlier in this section, the UK has significant technical and practical renewable energy resources that could be exploited depending on the continued political will (and thus the market incentives) to do so. However, the connection of the resource to centres of demand in a geographical as well as a temporal sense is challenging and is heavily influenced by the type of generation technologies chosen and their location.

The amount of electricity generated from renewables sources in 2011 was 34,410 GWh. This is ~9% of annual UK electrical demand in 2011 (DECC ET, 2012), and a 33 per cent increase on 2010.

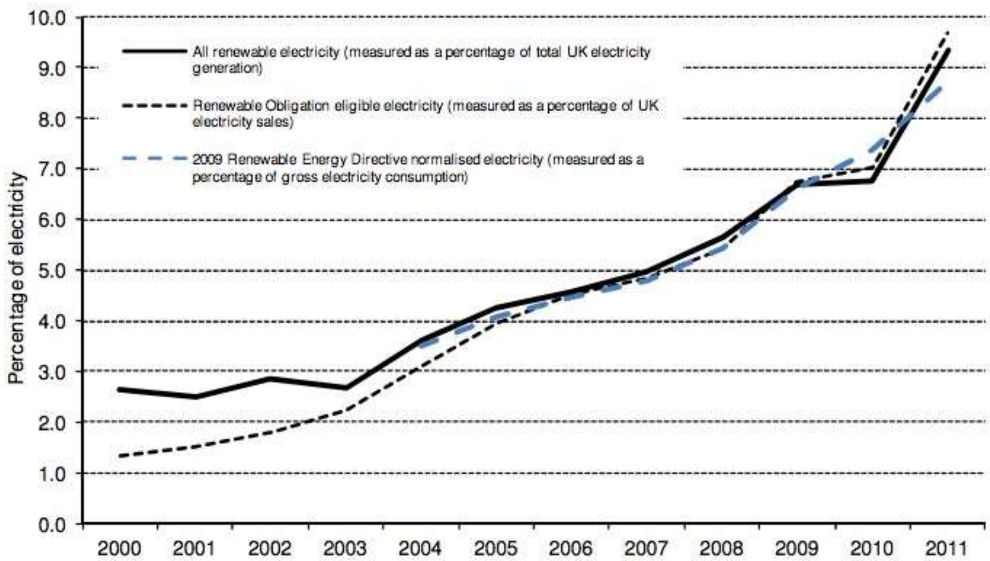


Figure 15 – UK Growth in renewables 2000 – 2011. source: pp52 (DECC ET, 2012)

Over the last decade there has been a significant increase in the capacity and therefore the renewable energy supplied to the UK market, as can be seen from Figure 15. The growth has been primarily incentivised by the Renewables Obligation, which has led to the deployment of primarily onshore wind but going forward an expected large increase in offshore wind.

There is little doubt that the UK benefits from a significant renewable energy resource, but the challenges of harvesting this energy, transmitting it to demand centres and balancing the network all have costs and challenges. The benefit of using these natural resources eventually points to a reduction in the balance of payments of the UK as a whole (rather than importing an ever greater percentage of its energy needs). In a globalised world with an increasing population and expected increase in the per capita energy needs of this increasing population, it would seem to make long-term sense to hedge the costs at a national level by using the natural resources that exist within national borders. This could be regarded as a separate but complimentary driver to reduce the CO_2 footprint of the UK in the long-term.

5 The UK's energy landscape

5.1 Background to UK energy systems

The UK has been a major producer of oil and natural gas from the continental shelf in the North Sea since the 1980s, however, since 2000, UK Continental Shelf gas production has been declining (Figure 16). In 2004, although with production still at historically significant levels, the UK became a net importer of gas for the first time since 1996 (it imported more than it exported). Furthermore, in November 2009 it imported more gas than it produced (UPO, 2009). The trend seems to leave little doubt that the UK's indigenous production of natural gas has peaked (from the continental shelf at least), and therefore continuation of or further increases in natural gas demand will have to be supplied by imports or non-conventional gas supplies.

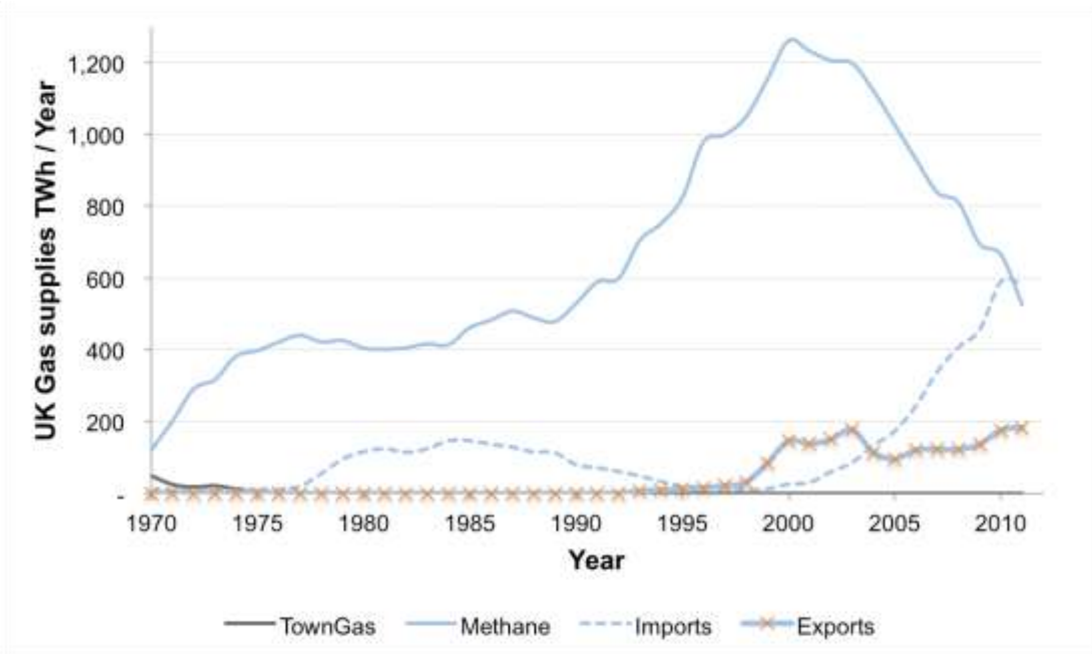


Figure 16 – UK Gas supply 1970 – 2011 data from (DUKES 4.1.1, 2011)

The change of source of natural gas imports from 2006 – 2011 can be seen in Figure 17. This shows that the majority of the imports come from Norway, and in recent years there has been an increasing supply from Liquefied Natural Gas (LNG) through the LNG terminals including Milford Haven and the Isle of Grain. It can also be seen that imports from mainland Europe (Zeebrugge and Balgzand pipelines), and therefore potentially Russian gas supplies are a smaller component of UK gas supplies than sometimes portrayed by parts of the UK media.

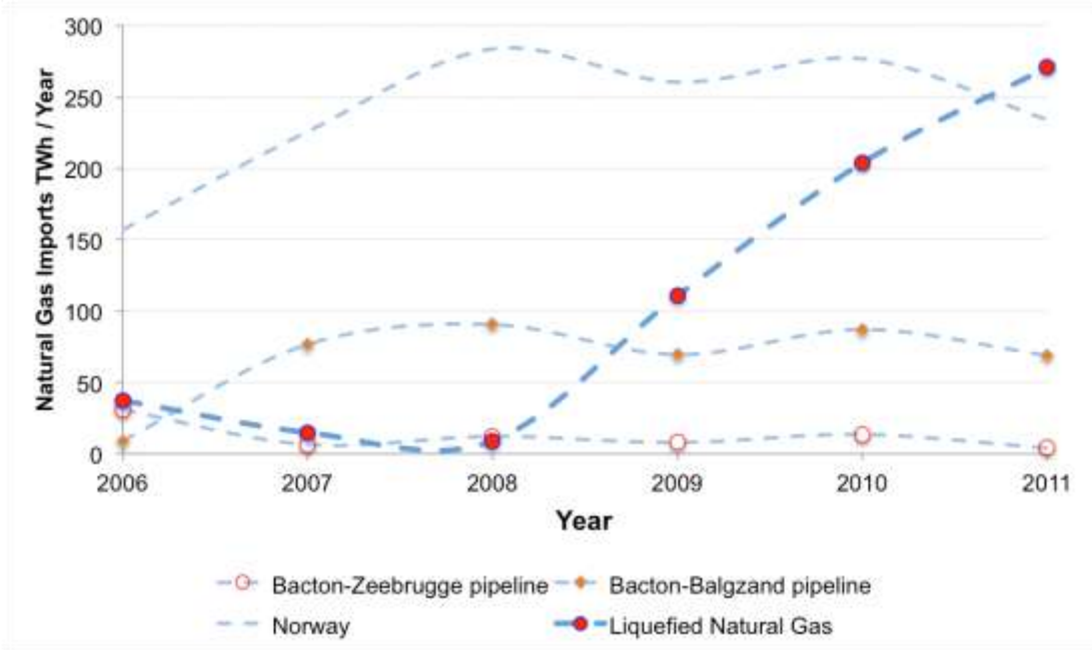


Figure 17 – UK Natural Gas imports 2006 – 2011 data from (DUKES 4.5, 2011)

Historically, the UK was a significant coal producer, but high costs have rendered most production uneconomic and output is now a historically modest 20,000,000 Tonnes per year.

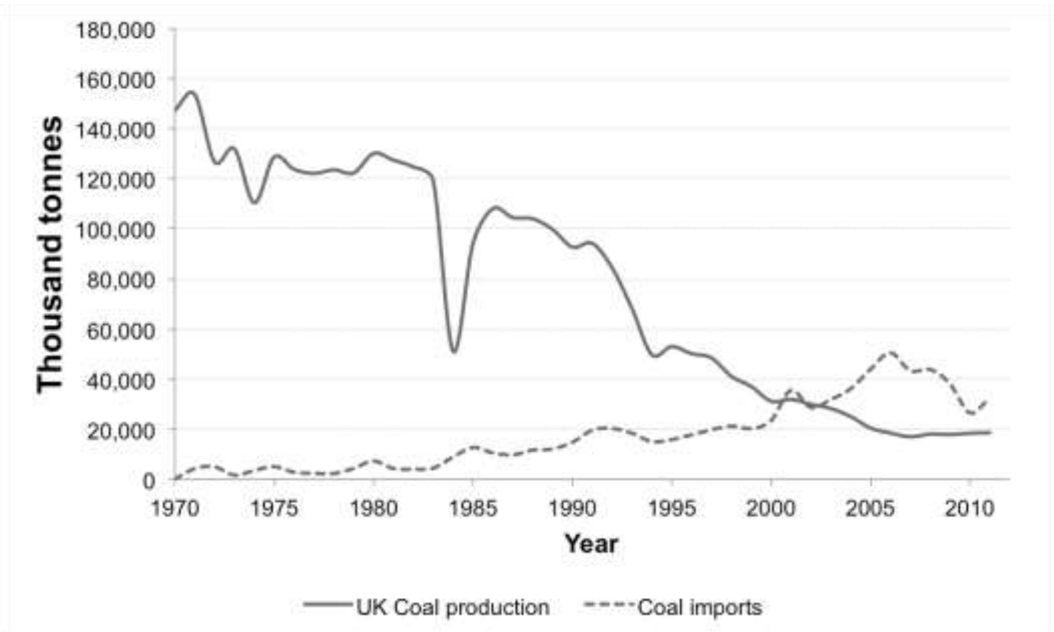


Figure 18 – UK Coal production and imports 1970 – 2010 data from (DECC Coal, 2011b)

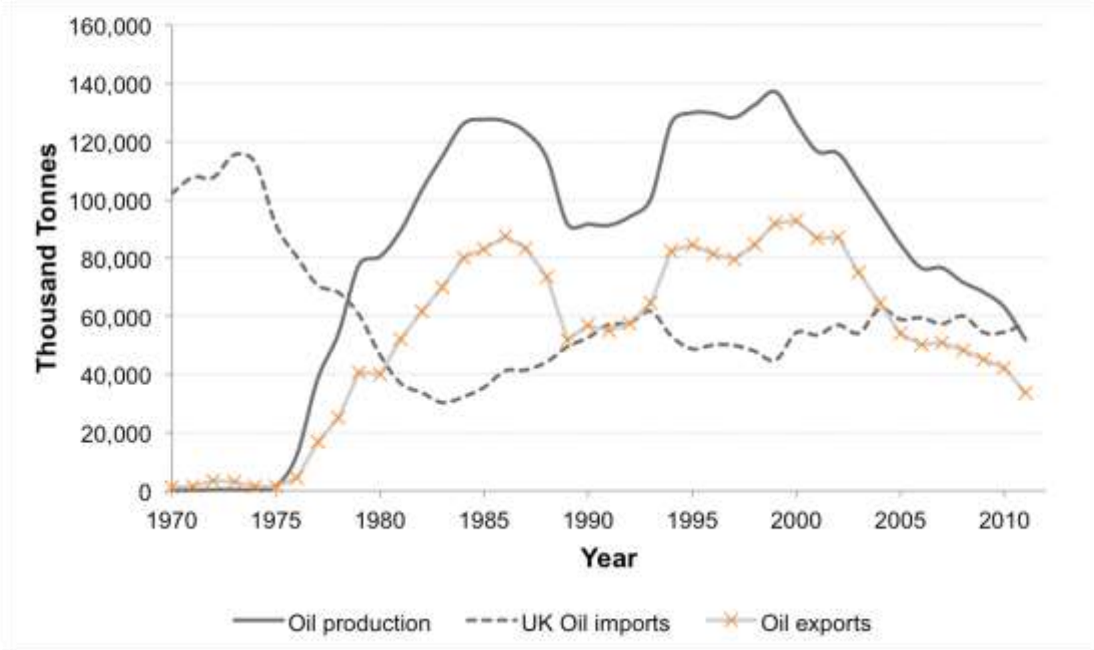


Figure 19 – UK Crude Oil production and imports 1970 – 2011 data from (DUKES 3.1.1, 2011)

Over the same timeframe of 1970 – 2011 Figure 17 shows a similar trend of declining indigenous production for crude oil. Oil imports have been fairly static since 2000, which is very different compared to the growth in imports of natural gas over this timeframe.

Figure 16, Figure 18 and Figure 19 show indigenous gas, coal and oil production and imports and provide a clear indication that the UK is exhausting its easily won fossil fuel resources from the continental shelf of the North Sea. As a nation, the UK has moved from a position of indigenous fossil fuel energy security to a position of import dependence. There are many who argue that this is a perfectly normal position for a modern economy, and this may be true when one looks at Singapore, Hong Kong, Japan and Korea. However, the UK is highly fortunate to have the scale of renewable resources and at least has a choice whether to develop and exploit these in comparison to the decision to import ever-increasing amounts of energy. This is a choice that many other countries simply do not have due to the nature of their national renewable resources, so for the UK in particular the development of indigenous renewable resources is primarily a political choice, which is obviously impacted by the costs associated with technology and engineering challenges, rather than having no choice at all.

Since the early 1990s, gas has displaced coal and oil as a fuel input for electrical generation; this has had a favourable impact on the overall level of national CO_2 emissions; Figure 20 shows this trend of reducing CO_2 from power stations through the 1990s even though the total amount of electrical energy supplied was increasing. However, the broad trend for power station emissions increased from 1999 – 2006/7, almost back up to 1992 levels. The 2008 global financial crisis and UK recession caused a dip in emissions and energy supplied in 2008/2009, with an increase back in 2010. A further drop in overall and power station CO_2 levels can be seen in 2011.

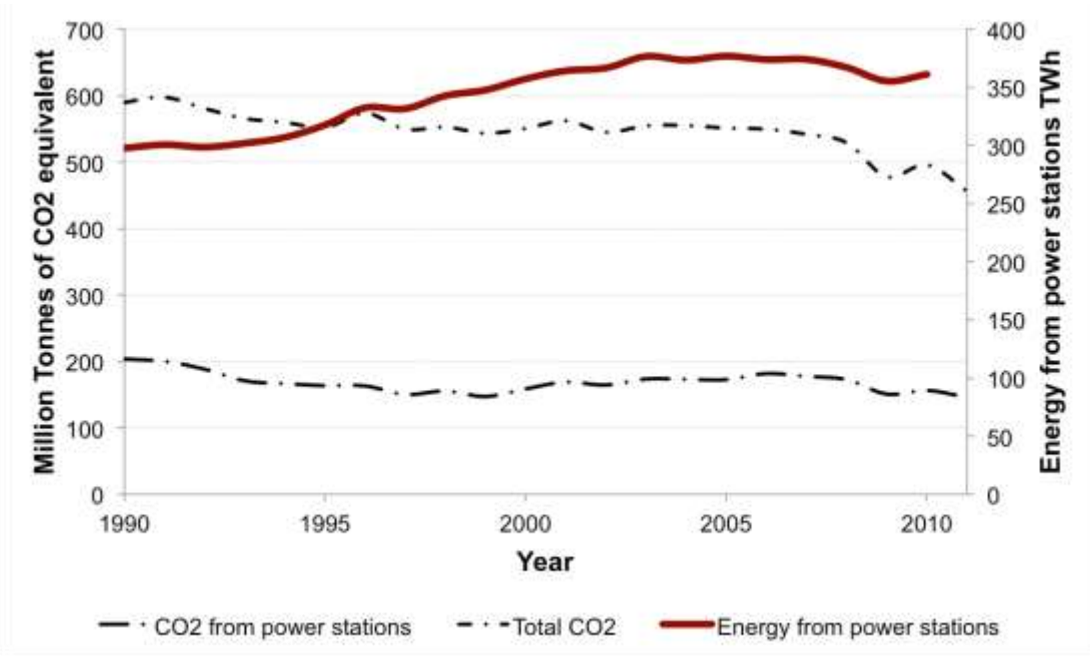


Figure 20 – UK CO_2 emissions (overall and power stations) 1990 – 2011. data from (DECC GHG, 2013a)

The UK can be viewed as a pioneer in opening up the energy sector to private ownership. Today, there is virtually no state ownership of energy assets and the markets are deemed to be competitive.

The gas sector was transformed in the 1980s and 1990s with the privatisation of the monopoly gas utility, British Gas, and the introduction of competition. Today, there are a number of licensed wholesale and retail suppliers. The National Grid operates the high-pressure transmission grid throughout Great Britain and four gas distribution companies own five low-pressure gas distribution networks.

The UK electricity sector began a transformation in 1990 through a process of unbundling and privatisation. Today, the generation sector is non state-owned, with the exception of the Magnox nuclear power plant at Wylfa in northwest Wales (the site is owned by the Nuclear Decommissioning Authority, but operated by Magnox Limited, which itself is owned by Energy Solutions). This 470 MW Magnox power plant is due to stop producing during 2014, and will bring the end of an era of Magnox generation in the UK. The break-up of the former monopoly generating boards started in 1990 (Central Electricity Generating Board (CEGB) in England and Wales, South of Scotland Electricity Board and the North of Scotland Hydro-Electric Board) with the aim of allowing the entry of new independent generators in order to create a competitive market structure. National Grid owns and operates the England and Wales high-voltage transmission system; Scottish Power Transmission owns the Scottish transmission system in the south and Scottish Hydro Electric Transmission Limited in the north, with the Northern Ireland network owned by Northern Ireland Electricity. Seven different companies currently hold distribution licenses for 14 distribution areas in Great Britain (Figure 21). These are termed Distribution Network Operators (DNO).

Figure 21 - Distribution Network Companies source: National Grid Website

Retail supply licenses, which are separate and unbundled from transmission, distribution and generation licenses, are dominated by six large companies that supply most retail consumers (NPower, E.ON, SSE, British Gas, EDF, Scottish Power). NPower is owned by the German utility RWE, E.ON Energy is owned by its parent German utility company, Scottish Power is owned by the Spanish utility Iberdrola, and EDF is a French utility. SSE (Scottish and Southern Energy) is a UK based utility, and British Gas is owned by Centrica, which is also a UK based plc. In part, due to the political fallout from increasing energy prices, confusion in multiple tariffs for retail consumers and a general perception of poor retail customer service and profiteering, there has been more political interest in increasing the number of suppliers available to retail customers.

There are no energy-price controls in the UK and prices are set freely by the market through bilateral contracts between generators and suppliers, and transactions through the spot markets (which are anonymous). For the provision of network services, the Office of Gas and Electricity Markets (Ofgem) regulates electricity and gas network access charges through five-year price control periods that set the maximum amount of revenue that the monopoly network owners can derive through charges they levy on users of their networks. These prices are agreed to cover the costs of providing a service (with performance targets) and earn them a return, whilst providing incentives to be more efficient and to innovate. However, due to concern that this system was not providing an adequate level of innovation, the Low-carbon Networks Fund (LNCF) was started in the price control period from 2010 – 2015 (OFGEM, 2012a). This framework allows the DNO companies to competitively bid for funding in order to carry out projects on parts of their network. Even though the framework is only half way through the timeframe – Ofgem consider the scheme to be a success, due to the learning experience that the DNOs and also Ofgem have already gained. A similar framework is to be paralleled with the LNCF from 2013, called the 'Network Innovation Competition' (NIC), (OFGEM, 2012b), with similar aims of learning by doing.

The UK imports gas from Europe and Norway via pipelines, and from further afield via tankers of LNG (Figure 17, and Appendix 7). Gas prices in Europe are commonly linked to oil prices, so oil price fluctuations can have significant impacts on European gas prices that can also feed through to UK wholesale gas prices, and hence to prices paid by UK customers. The long-term variability of fossil fuel prices cannot merely be hedged against in the market, and as long as Ofgem allows generators to eventually pass on the cost of increased fossil fuel prices to customers – then there is less risk to the generators of continuing to invest in fossil fuel plant. If Ofgem also allows the cost of carbon emissions to be passed onto customers – then fossil fuels may well continue to have a dominant market share. However, two separate drivers for 'encouraging' generators to invest less in fossil fuel generation (and more in renewables) are the emissions performance standard of the Electricity Market Reform Bill (which has been a contentious aspect of the bill), and a potential for renewable generators to eventually provide electricity cheaper than that of fossil fuel generation.

5.2 UK electrical market framework

Currently in the UK, the British Electricity Trading and Transmission Arrangements (BETTA) determine the arrangements and methods of sale, purchase and transmission of wholesale electricity (OFGEM, 2005a; OFGEM, 2005b). There are presently four main distinct markets for trading physical electrical energy and services (as opposed to futures or derivatives of physical energy); the forward market, the power exchange market, the balancing mechanism market, and the ancillary services market that is less directly connected to the sale of electricity. The volume of electricity sold through the first three of these markets are described by the Association of Electricity Producers as over 90% through the forward market, 3% through the power exchanges, and 2-3% through the Balancing Market (EUK, 2010).

5.2.1 The Forward Market

The forward market is where wholesale electricity is traded using bilateral contracts between key parties; in the main the bulk generators of electricity and the ‘suppliers’ of retail electricity to final consumers. Forward market contracts between generators and suppliers can take any form, and can be complex in nature including clauses for delivery of different amounts of energy at different periods of the day. Each normal day is divided into 48 half hour periods with a short day (46 periods) and a long day (50 periods) caused by British summer time clock changes. Dispatchable generators can take advantage of forward contracts with time horizons for delivery varying from typically 24 hours ahead to a year ahead. Likewise, stochastic renewable generators can also enter into long-term contracts with a ‘supplier’ but are not likely to include clauses for delivery at a specific time of day. An example would be a contract for a supplier to take the entire output of a wind farm for a specified period, *e.g.* 15 years (Scottish Power, 2006). In this case the ‘supplier’ is better able to manage the risk of imbalance within their entire portfolio, but there will be a cost penalty to the wind generator for the ‘supplier’ having to shoulder the risk of potential imbalances caused by the stochastic nature of nondispatchable renewable generation. These long-term contracts between a generator and a supplier are termed Power Purchase Agreements (PPA), and are an integral part of financing renewable energy developments. A developer will be unlikely to raise the finance required without a PPA, as providers of finance view a PPA as a defined source of income, in comparison to a more variable source of income from the power exchange market (spot market). Even if a developer were able to source project finance without a PPA, it would undoubtedly attract a higher rate of interest due to the perceived higher rate of risk.

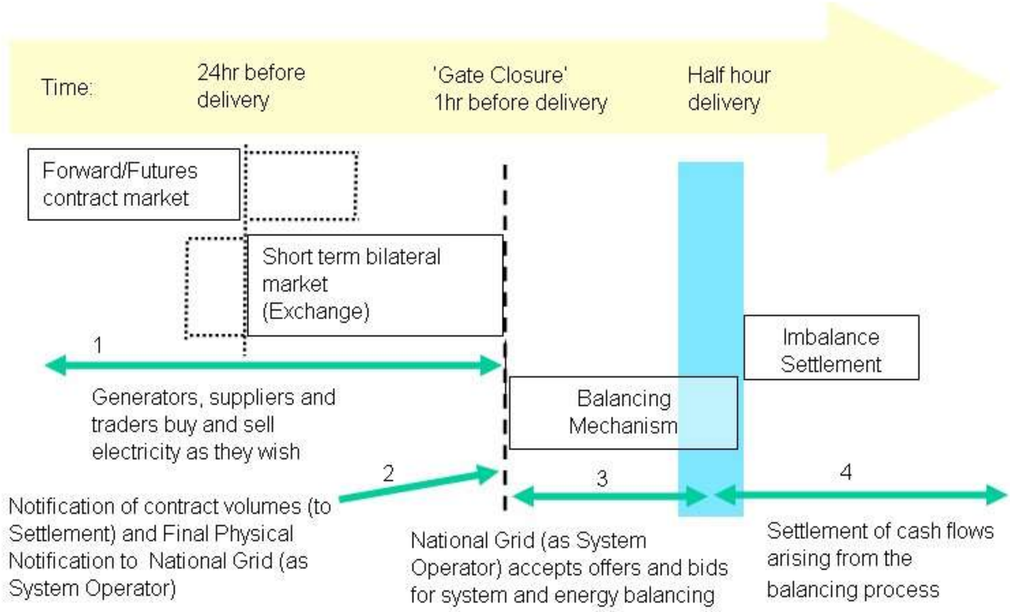


Figure 22 – Overview of BETTA market structure. source: (National Grid, 2012e)

Physical information from all forward market trades relating to a particular 30 minute period needs to be made available to the system operator (National Grid) before gate closure (60 minutes before the real-time start of the period in question) in order to allow the system operator to balance the system in real-time for the duration of the 30 minute period (Figure 22). FPN is the term used for this information (an acronym of Final Physical Notification), and is termed 'physical' due to the nature of the information *i.e.* the actual amount of physical energy of the trade rather than the price information associated with the trade, which is a confidential matter between the two parties to the forward trade. As mentioned above – this forward bilateral trade market accounts for over 90% of the volume of electricity traded in the UK.

5.2.2 The Power Exchange Market (Spot Market)

The next largest market is the power exchange market, which allows participants to trade in more standardised electricity products anonymously. Typical products include an amount of energy to be delivered during one 30-minute period, and also over 2 and 4 hour blocks, and take a simpler standardised form to aid liquidity and trade within the market. The electronic trade matching services provided by power exchanges can be viewed as the market of last resort, where imbalanced contractual positions on the forward market may be brought back to balance before gate closure, by buying or selling products anonymously through the exchanges. Stochastic renewable generation traded in this market are self-limited to products that have time horizons for delivery that can be forecast with a reasonable degree of accuracy, namely days to hours ahead. The products are also subject to FPN regulations, and so can also only be traded before gate closure (one hour before real-time). In addition to the physical information, a weighted average price of the products is also calculated by the power exchange, and provides the market index data price for electricity for that particular 30-minute period. The market index data price has a bearing on the prices in the other markets and is often referred to as the spot market price. Although this market only accounts for 3% of the volume of electricity traded in the UK, the price of energy traded in this market allows for the price discovery of traded electrical energy, and can therefore be used as a benchmark for other pricing contracts.

5.2.3 The Balancing Mechanism

The third market is the balancing mechanism market which is conducted by the system operator (National Grid Plc.) in order to balance the network in real-time. Generators and Suppliers of electrical energy provide bids, in order to decrease generation or increase demand, and to provide offers, in order to increase generation or decrease demand. These bids and offers are complex and include information such as the amount and price of energy to be added to or taken from the network, and also various technical parameters regarding the speed at which the generation or demand can be varied. The system operator compares FPNs to its forecasted system demand and accepts bids and offers to physically balance the system during a particular

30minute period. The 60-minute window between gate closure and the real-time start of the 30-minute period allows the system operator to evaluate bids/offers not only on price but also by considering network constraints and the technical limits of the bid or offer *e.g.* how quickly can a generator ramp up or down output during the forecasted imbalance. At the end of the period the balancing and settlement code company (Elexon) uses metered data to calculate the physical imbalances of parties that had submitted a FPN for a particular 30-minute period. The physical imbalances take into account deviations due to bids/offers accepted by the system operator through the balancing mechanism market. Ex-post system buy prices and system sell prices are calculated and form a basis with which to eventually pass on the costs of correcting the imbalance to those parties that caused the imbalance. The eventual settlement prices are intended to encourage parties to limit the size of their imbalances, which benefits the system as a whole. National Grid can be viewed as being responsible for physically balancing the system in real-time using the balancing mechanism market, whereas Elexon can be viewed as being responsible for the ex-post settlement of the costs of the real-time balancing to the parties that caused the imbalance (Elexon ETA, 2012).

5.2.4 The Ancillary Services Market

The ancillary services market forms a fourth distinct market from the forward market, the power exchange market and the balancing mechanism market. The system operator purchases several different types of ancillary services in order to cope with unexpected circumstances, and in order to keep the network frequency and voltage within statutory limits in real-time. These services include frequency response, reserve services (over different timeframes), reactive power, maximum generation, generation curtailment, and black start capacity (National Grid-Services, 2012).

5.3 Bulk storage operation within the UK electricity market

All energy-generating plant has a statistical chance of being available when required to contribute to periods of peak demand, and in reality all plant is intermittent to some degree, including ‘base-load’ nuclear. All generating plant requires maintenance, and planned shutdowns mean that all plant is not statistically available for 100% of the time. However, the difference to the system of a planned shutdown, rather than an emergency shutdown is marked. A planned shutdown by its very nature can be accommodated by other dispatchable generating plant increasing their output to meet demand, whereas an emergency shutdown requires the implementation and use of the ancillary services that the system operator has contracted. The nature of the variability of wind and solar generation provides a different set of risks to the system than the planned 'variability' from dispatchable generating plant. This source of variation in the output from wind and solar is one of the main challenges of accommodating an increased penetration of non-dispatchable renewables. Allan et al., (2010) investigated the effect whereby the aggregated output of geographically diversified wind energy sources is less variable than a single site source, and explain that this is naturally extended if the generating mix includes a wider portfolio of different renewable resources, including wave and tidal *e.g.* a more diverse portfolio of energy generating technologies can provide benefits in terms of security of supply or single fuel or technology dependency. This is also a conclusion from the Pöryry report to the Committee on Climate Change on the technical constraints on renewable generation to 2050 (POYRY, 2011). In short, the system benefits from a differing mix of renewable generation technologies over a wider geographical area.

Conceptually the benefit of bulk energy storage originates from the operational characteristics of an electrical grid as a continuous supply chain of electric power, which functions as a just in time system in which electrical energy is generated and transmitted to demand as required. It is remarkable to think that a generating plant possibly hundreds of miles distant has simultaneously created the electrical energy used to power the computer used to write this sentence. Electrical energy systems are designed in order to cope with the peak levels of demand, and in the UK this usually happens in the coldest part of any given year at around 5-7pm during a normal working day (non-holiday Monday – Friday). Indeed, a charging structure for the use of the transmission system in these peak periods (called triads) determines the payment that licensed suppliers pay the transmission system operator for the entire year; this Transmission Network Use of System (TNUoS) charge for suppliers is a significant part of revenue for the transmission system operator.

Without the ability to locally store energy post-conversion, there must be sufficient generation capacity to provide for peak demand requirements, as well as transmission and distribution capacity to allow this peak flow of energy from the generators to the demand. This is true of all electrical energy systems – not just the UK. Therefore, the generation capacity, transmission and distribution assets must be sized to handle peak power transfer requirements despite the likelihood that much of that asset capacity sits idle during a day as well as for large portions of the year. This can be seen in the seasonal forecast weekly average shown in Figure 23 and the daily forecast and initial out turn of system demand shown in Figure 24.

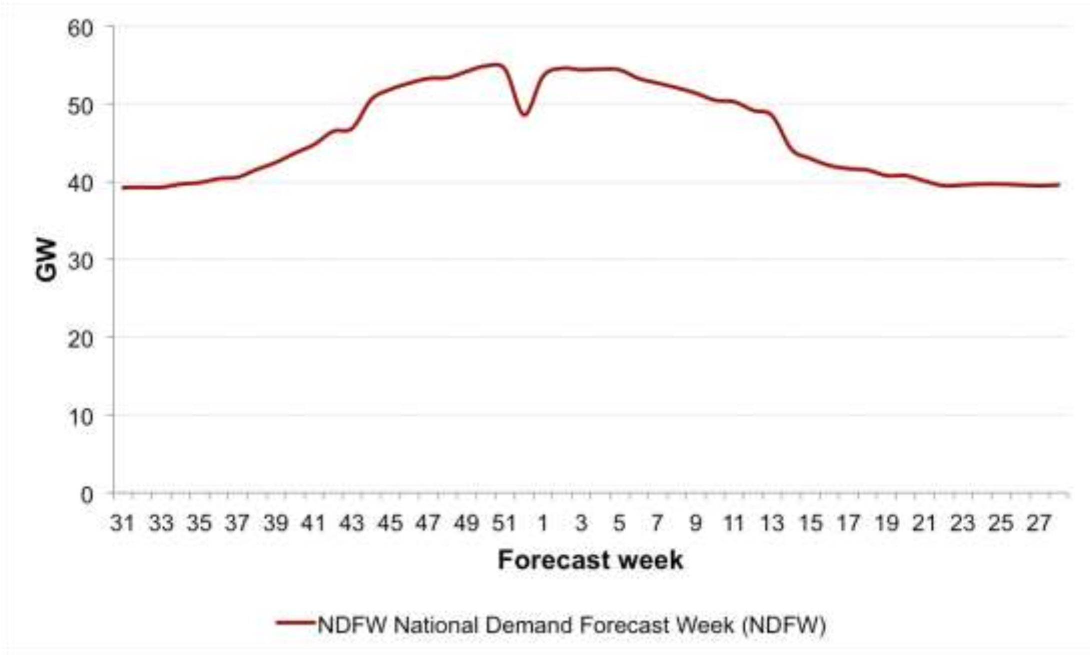


Figure 23 - National Grid's weekly system demand forecast for next 52 weeks, data from (National Grid, 2012a)

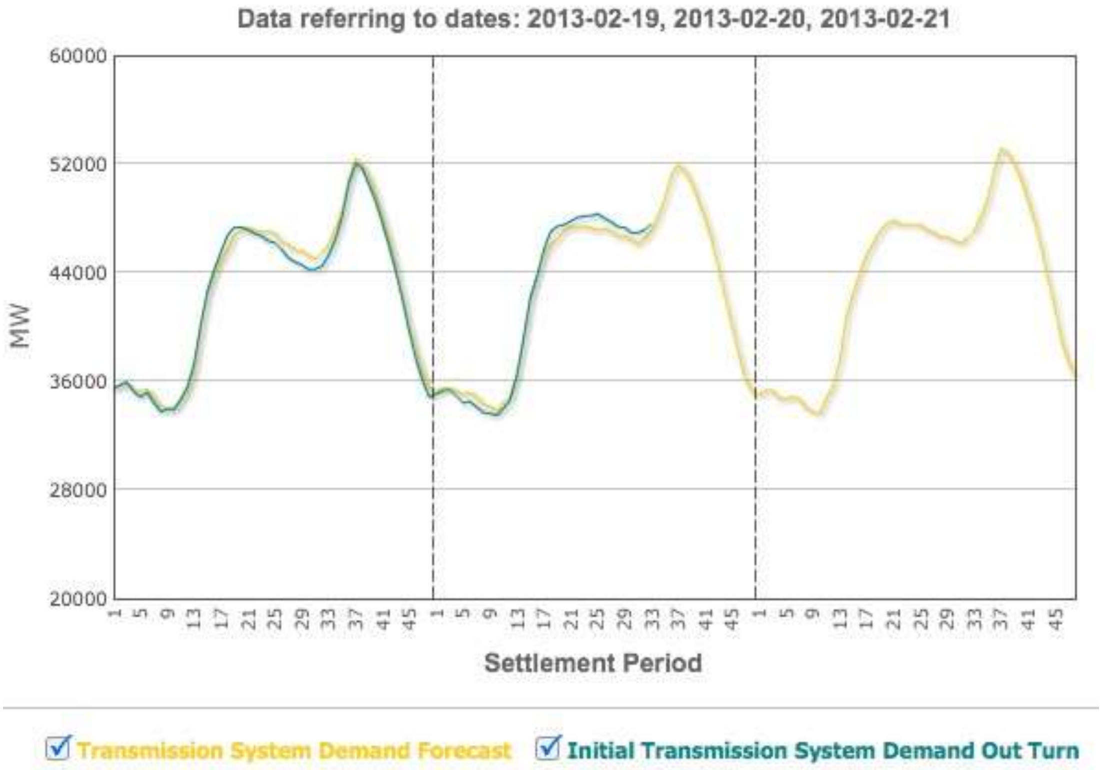


Figure 24 – Electrical system demand forecast and initial Out Turn. (BMReports, 2013)

At a system level, electrical power generation is continuously ramped up and down to ensure that the intricate balance between supply and demand is maintained. This ramping up and down of generation plant puts additional strains on generation plant, but certain types of generation technology are more suited to higher ramp rates than others. All plant that contains a steam cycle using boiler equipment is design limited to the rate at which the boiler can heat up and cool down, in order to reduce material stresses on the equipment, and thus reduce fatigue and the likelihood of crack formation. Open cycle gas turbines (jet engines for the power sector) and hydro turbines are however able to ramp their output up and down without the same degree of thermal limitations. Generation plants are designed around a particular full-load output and part-loading reduces a power plant's efficiency from its full-load designed efficiency, resulting in higher fuel consumption and higher emissions per kilowatt-hour produced (IEA, 2010). Plants may also shut down (rather than part load) during times when other cheaper generation is available. Plant starts and part loading also causes more wear on the equipment and reduces the lifetime of power plants.

In many supply systems, the ability to decouple inputs from outputs provides a more resilient and secure system, however, this decoupling of supply and demand using storage will have an associated cost. The overall system has to determine if the increased costs of this decoupling are of greater benefit to the increased resilience and security now afforded to the system. Pre-conversion bulk energy storage in the form of fuels has provided the stores of energy for electrical systems from their inception, and the question of how much of this pre-conversion storage it may be beneficial to replace with post-conversion rechargeable storage in future electrical systems is an interesting one. Conceptually, a greater level of rechargeable storage would provide a benefit to the constant balancing between electricity supply and demand (Dunn et al., 2011), and allow conventional fossil fuelled generators with CCS the potential to run at their highest designed efficiencies. However, the technology choice and location of post-conversion storage would determine the type of benefit to the system. A report titled *'Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low-carbon Energy Future'* (Strbac et al., 2012) for the Carbon Trust provides a detailed overview of these system benefits for the first time. The report provides a comparison between the costs of a future electrical system with and without storage, and makes it clear that there are significant system savings from incorporating storage in the system. Much of the savings are from the reduced amount of fuel required to meet demand throughout a year, and also from the reduced peak capacity required to accommodate a much larger component of non-dispatchable renewable energy generation (mainly wind). In short, if the output from renewable generation can be stored rather than curtailed, it is available to be used at a later time. Thus there is a reduction in the need for fuels to provide this energy at a later time, and therefore a system saving in terms of fuel costs. However, the challenge for policy makers is to allow investors in storage the ability to capture these split benefits, *e.g.* storage may benefit the system as a whole, but in the UK's market structure with different stakeholders and licensees, it is not currently the case that investors in storage would be able to capture a financial return for benefitting the system as a whole. It is undoubtedly the case that monopoly vertically integrated monopoly provider of the UK's energy systems would be able to capture any system savings, however, there is little appetite to contemplate a complete reversal of the market approach and ownership undertaken over the last 20 years in order to provide for a lower cost approach to future networks. If storage is to be incentivised, it will have to be undertaken within the overall market framework, but it should be remembered that the existing bulk storage schemes were brought about under a fundamentally different regime.

Post conversion bulk electrical energy storage in the UK is primarily in the form of four pumped storage schemes (Chapter 6.2.4). The generation business units of SSE and Scottish Power own two of the schemes, and revenues are thought to be driven by a multitude of different factors. The storage schemes are able to use their capacity to offer services to the balancing mechanism, can buy and sell energy through the power exchange market (spot market) and can also be used internally to provide benefits to the other plants in the generation portfolio, whether renewable or fossil fuel. First Hydro, which does not have other generation plant, owns the other two pumped storage schemes and is therefore not able to offer benefits to other internally owned generation assets. However, there seems no particular reason why they could not contract with a separate owner of generation assets.

The aggregated output from the four pumped storage schemes in the UK is illustrated for the 48 hour period of the 6th and 7th of January 2009 in Figure 25. The data for aggregated power is available at a granularity of 5 minutes, rather than the typical granularity of 30 minutes of the spot market price period defined itself defined by the balancing mechanism periods. This data for two days suggests that the storage schemes are used to store energy between approximately 11pm and 6am, and then release this stored energy between approximately 6am and 11pm the next day. This underlying use 'waveform' in the aggregated output is overlaid with greater outputs at times of increased spot market prices, *e.g.* between 4pm and 7pm. However, at this level of granularity it can be clearly seen that there are sub-half hourly changes in the output, which are thought to be due to provision of services to the balancing mechanism, or internally to provide benefits to other generation plant.

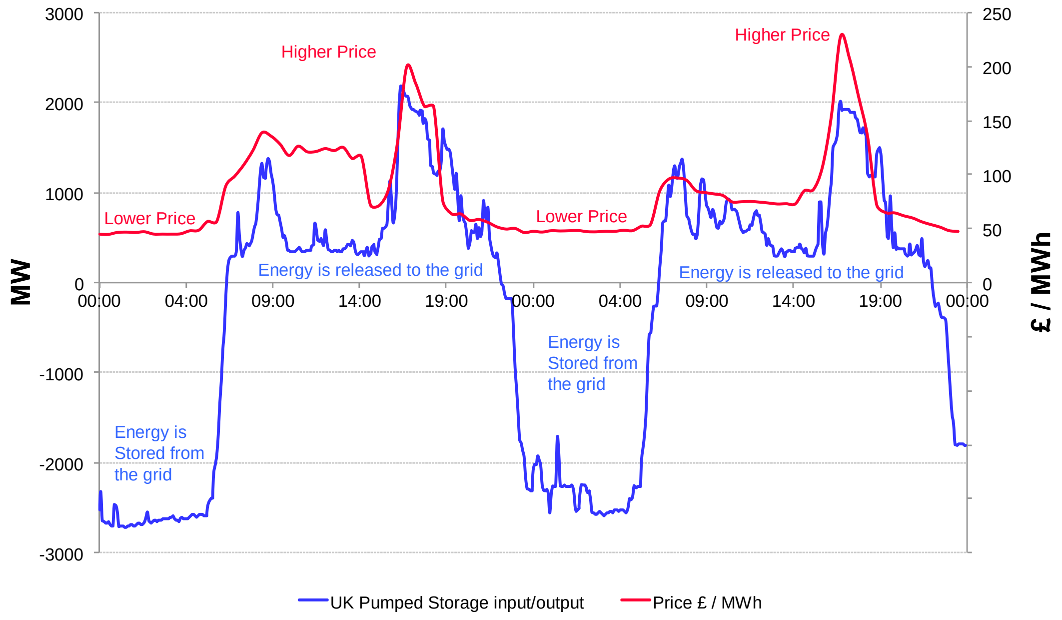


Figure 25 – Aggregate pumped storage output with prices – 6th and 7th January 2009, data from elexonportal.co.uk

This snapshot therefore suggests that even with an aggregated output from the four pumped storage schemes (which may produce a slight smoothing effect) that the schemes are scheduled in a complex manner. This scheduling must be predicated on optimising the revenue available to the storage device, but in the case of SSE or Scottish Power, it may be predicated on optimising the revenue to the generating business unit as a whole.

5.4 Storage charging, wind power and spot market price

During research, the question arose regarding the correlation between wind generation and pumped storage schemes, and whether pumped storage schemes were likely to store wind energy. This was an interesting viewpoint posed by Dr Donald Swift-Hook in a paper titled *'Grid-connected intermittent renewables are the last to be stored'* (Swift-Hook, 2010).

The relationship between storage charging, wind output and market index price data is shown in Figure 26, Figure 27, and Figure 28 using historic data from the 4th of November – 31st December 2009 sourced from BMReports and Elexon websites (BMReports, 2013; Elexon, 2012). The timeframe was chosen as the most recent quarter of data available at the time.

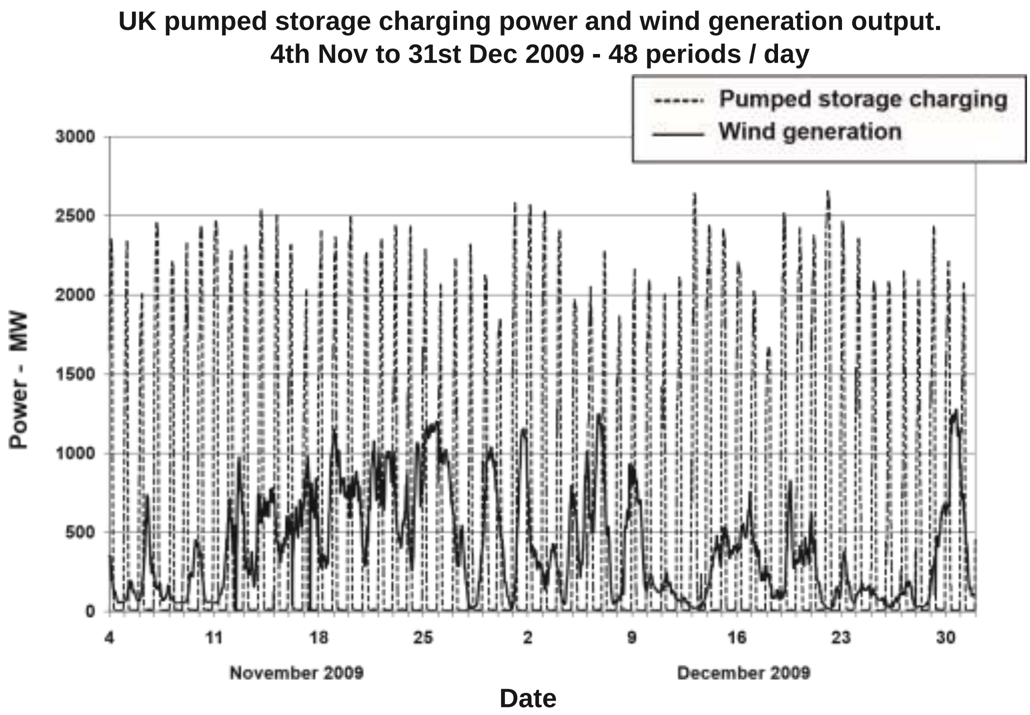


Figure 26 – UK pumped storage power versus wind generation Nov – Dec 2009, data from BMReports and Elexon.

Figure 26 shows the UK network pumped storage charging load and wind generation in units of power (MW) for the 48 periods per day from 00:00 on the 4th of November 2009 to 24:00 on the 31st of December 2009, (the figure does not show the discharging power from the pumped storage schemes, and the y-axis sign is opposite to that of Figure 25). It can be seen from this figure that over the timeframe plotted, charging of the storage schemes happens each and every day regardless of the output of wind generation.

Scatter plot of pumped storage charging versus wind power
4th Nov to 31st Dec 2009: 48 periods per day.

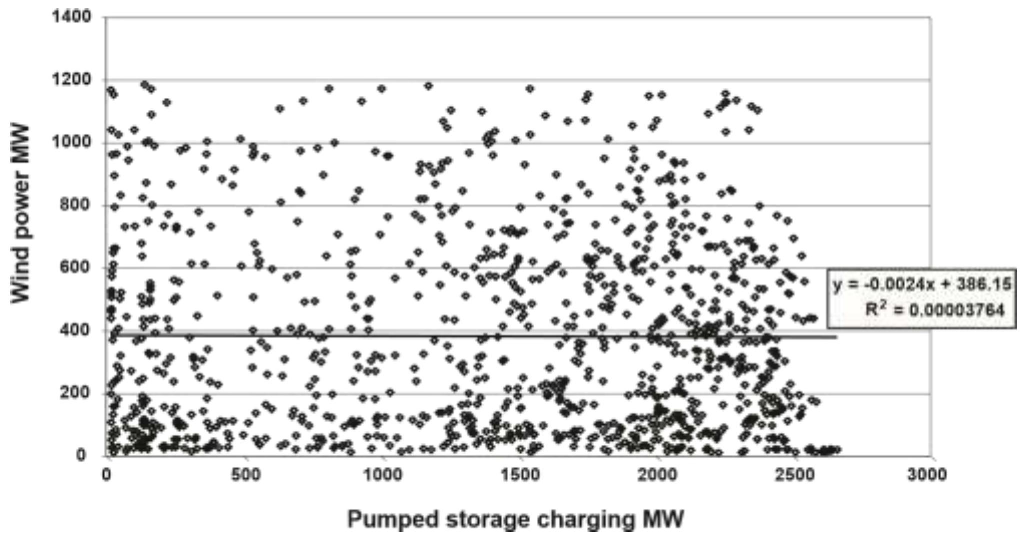


Figure 27 – Wind Power versus Pumped Storage charging, data from BMReports and Elexon.

Figure 27 uses the same data as Figure 26 but the output from wind generation is plotted against the charging power of pumped storage for each half-hourly period. It is clearly seen that there is no particular relationship between wind generation and the charging of pumped storage schemes in the UK over November and December of 2009. Given this lack of a relationship and also due to the anonymity afforded by market structures, it is not possible to determine how much wind energy was actually stored in a given period. It was therefore argued in a response paper (Wilson et al., 2011) that it was incorrect to suggest as Dr Swift-Hook did, that *'grid-connected intermittent renewables like wind energy will never be stored unless nothing else is available',* or indeed they may even be *'the last to be stored'* as these statements imply a degree of certainty, which the market data does not seem to support.

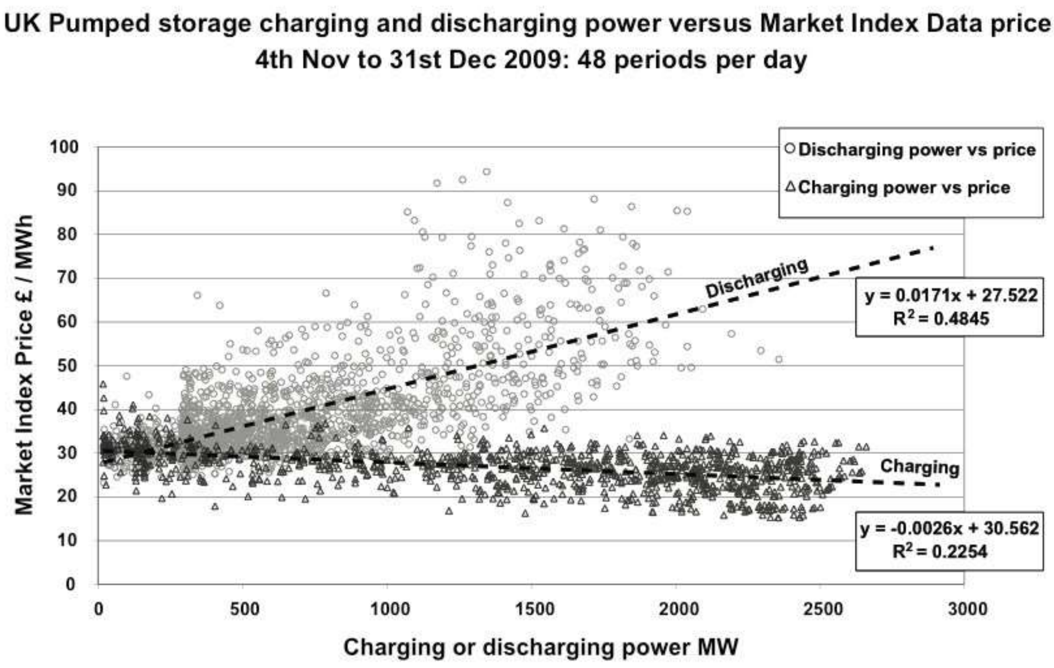


Figure 28 – Storage charging discharging versus spot price, data from BMReports and Elexon.

Charging trend line y= -0.0026x + 30.562, R^2 = 0.2254, observations = 1086, xcoefficient t-stat = -17.76, intercept t-stat = 126.96

Discharging trend line y= 0.0171x + 27.522, R^2 = 0.4845, observations = 1751, xcoefficient t-stat = 40.54, intercept t-stat = 81.51

Furthermore, it was decided to compare the market index price (spot price) against the pumped storage power input and output values. Figure 28 shows a scatter plot of pumped storage charging and discharging loads (in units of power) against the market index price (in units of £/MWh) for each period over the same timeframe as Figure 26. The data points with values less than 17.5 MW of either storage charging or discharging were removed from the figure to improve clarity. It is thought that the low values represent the operational load of the storage facilities as opposed to the charging load, or periods with little or no discharging. On the x-axis it can be inferred that storage charging loads are broadly clustered at a higher value than that of storage discharging loads. Furthermore, on the y-axis it can be inferred that the charging price is broadly clustered at a lower market index price than that of discharging, as it is profitable to sell the energy at a higher price than it was bought.

It is believed that within the UK's market structure, renewable energy generation has been and will continue to be stored when it profits storage operators to do so. It is a market decision, and, if increased renewable generation leads to greater diurnal price variability, it is expected that existing storage operators would take advantage of this. In general terms, it is likely that the levels of wind generation in 2009 were having an insignificant impact on the underlying price of traded energy through the spot market (although this would be an interesting research topic in its own right). It is therefore unlikely that wind generation would have a relationship to pumped storage charging. However, as more and more renewable generation becomes connected to the UK network, it is likely that it will start to impact upon prices within the spot market; it can therefore be speculated that a relationship will develop over time between wind generation output and storage scheme charging.

5.5 Is storage counterproductive for fuel saving?

A further interesting point raised by Dr Swift-Hook's paper was contained in the statement that *'storage is counter-productive for fuel saving'*, which seemed to be based on only one side of the storage equation; the charging. The other side of the storage equation is how much fuel is saved when the storage facility is discharged. If it is assumed that all diurnal time-shifting storage takes place through a power exchange then the additional fuels required to meet the extra demand created by charging storage are likely to be from more efficient generating plant, as the storage operator is not likely to store energy from less efficient plant, due to its higher cost. This stored energy is then likely to be sold back at a time when the power exchange market prices are more expensive, *e.g.* when the marginal price is set by less efficient plant. This ability of storage to time-shift the electricity generated by more efficient plant to offset the electricity generated by less efficient plant could indeed lead to overall fuel savings – it depends on the efficiencies of the various generating plants and storage devices. It was therefore not thought valid to argue using only one side of this argument *i.e.* that storing renewable energy would lead to an increase in fuels to match the immediate demand, without also considering the other half of the fuel saving equation, which is the fuel saved by using the stored energy at a later time. Indeed, the report briefly discussed from Strbac et al., (2012) uses the fuel savings at a system level brought about by the storage of renewable energy as the major savings in system operating expenditure.

Dr Swift-Hook also overlooked the potential fuel-increases associated with starting-up or shutting down various generating plant. Adding to the amount of startups and shut downs not only increases fuel use but also requires more plant maintenance. Generation plant operators with access to storage may wish to keep a plant running in the short term, even if it is unprofitable, in order that the plant is available at a future time when it is indeed expected to be profitable. Charging storage does increase the immediate overall demand due to the extra load on the system, but in doing so can allow plants to remain generating (possibly at a lower reduced output), rather than having to be shut down. In addition to offsetting less efficient plant at a future time, there may also be a fuel saving resulting from the reduction in the overall plant start-ups and shut down events facilitated by the energy storage system, although this fuel saving from start-ups may be less significant than the fuel saving from the later substitution of fossil fuel generation with renewable energy. Indeed this aspect of bulk electricity storage in the context of wind energy generation is far from new; early research highlighted this role (Infield, 1984).

The defining characteristic of electrical energy storage in an electricity system is precisely that it allows some deviation between the instantaneous demand for electricity and instantaneous supply. Storage allows for the possibility of intertemporal substitution of electricity supply, storing electricity when market prices are low and supplying electricity when prices are high. The incentive to private market participants to provide bulk storage capacity for time-shifting is precisely the ability to take advantage of differences in the price of electricity in different periods. The ongoing use of UK storage for diurnal time shifting, in the context of significant diurnal price variations, demonstrates the strength of this, as shown in Figure 28.

Dr Swift-Hook's viewpoint was couched in terms of fuel saving, not in terms of the economics of storage. *If* the objective of the system were to be to substitute the largest amount of fuel then storage may appear at first glance to be sub-optimal. However, renewables generation can only actually substitute for fuel when fuelbased generation technologies are being operated. If in the future the supply of renewable energy is greater than demand for a particular market period, then further fuel substitution could only conceivably take place at a future market period when demand is greater than renewable energy supply *i.e.* at a time when fuel is actually being used. In this context, storage is a clear means by which (future) fuel use can in effect ultimately be substituted by (present) renewable generation. This important benefit of storage is again clearly shown in the report from Strbac et al., (2012). However, fuel substitution is not an explicit stated goal of the UK's energy policy, although it may be considered implicit.

6 Bulk Energy Storage in the UK

Stores of energy in the form of fuels can be considered to be similar to rechargeable energy storage in a limited sense, as they are both conceptually available to provide energy. However, the work available from a fuel store of energy will be depleted by its conversion to another form of energy such as electricity or heat as the entropy of the system increases. Fuels are therefore considered to be single use only as once they have been converted; they will have to be physically replenished. In this sense they may be considered to be no different from energy storage, whose store of energy equally needs replenished once it has been used, although the nature of electrical energy storage is such that it is a prerequisite that the device or system can be recharged by electricity, stored, and then converted back to electricity. This is not possible with conventionally won fossil or nuclear fuels, but the developing technologies involved in synthetic fuel production such as hydrogen, biofuels and possible derivatives blur this area between single use stores of energy and energy storage.

The nature of existing electrical energy infrastructure requires that generators provide electrical energy in a just in time basis to match demand so that the frequency and voltage of the electrical supply is kept within strictly controlled limits. In essence the system can be considered to be demand led (as generation will change to meet demand) although demand side management strategies aim to help this matching of supply and demand from the demand side, and are expected to play a greater role in future energy systems.

The transition to low-carbon energy systems in the UK is expected to rely on the ongoing development and deployment of a number of low-carbon technologies including renewable generation, nuclear, and coal/gas combustion with carbon capture and storage (CCS). Of these, the thermal plant of nuclear and coal/gas with CCS, fit into the existing network paradigm of electricity being generated by a relatively small number of large-scale centralised power stations linked to a central transmission grid. The increased level of renewable energy capacity that is expected to be connected to the UK electrical network (CCC, 2011) poses several new challenges including the risk that periods of electricity generation will not coincide with periods of electricity demand *i.e.* the risk of primary energy not being available to renewable generators in order to meet the instantaneous demand. The relationship between wind power output and electricity demand was examined by Sinden, (2007) and reported that the wind resource is rarely load following in a UK context on a daily basis. Wind and wave do have a greater seasonal resource in the winter when electrical demand is higher and are therefore broadly seasonally correlated to existing UK electrical demand. In parts of the world with a peak electrical demand driven by air-conditioning units throughout the hotter parts of the day, the availability of solar insolation (which is correlated to the need for air-conditioning) is better matched to the underlying peak demand on a daily as well as a seasonal basis. Weather and tidal dependent technologies are classed as non-dispatchable; their outputs cannot be increased to match demand if the primary energy inputs are not available, which is in contrast to renewables based on biomass or geothermal energy that could be dispatched within the limitations of their technologies. It is estimated that contributions of above 20% of total electricity supplied to the GB network from non-dispatchable renewable energy sources will require much greater balancing and system reserve requirements than contributions below 20% (Gross et al., 2007). A reflection of this can be seen in the GB transmission system operator's indication that an increase of Short Term Operational Reserve Requirement (STORR) will be required from 4.3 GW in 2011/12 to ~ 7 GW in 2020 (National Grid, 2012b).

Onshore wind turbines have matured as a technology with continuous development brought about through deployment, whereas offshore wind is a commercial but considered less developed technology. As presented in chapter 4.1, the UK has a large practical wind resource, which is expected to be developed at a faster rate, and to a much larger extent than wave, tidal or solar derived generation in the timeframe to 2030, due to the size of the practical resource, the risk of the technology, financing, and the expected levelised costs of generated energy. The integration of wind power is already creating specific challenges for power system operators in Denmark, Spain and Germany as the characteristics of wind generation and other renewables mean that new methods of network management are required; the existing centralised paradigm of controllable generation will no longer be sufficient (Carrasco et al., 2006; Mathiesen

& Lund, 2009). Wind generation is stochastic, but potentially predictable over shorter timeframes, and has a lower annual capacity factor in comparison to most thermal plant. Demand is generally not stochastic at an aggregated system level and is well understood in terms of annual, daily and hourly cycles and variations. Demand is therefore predictable to a degree, but due to its correlation with weather patterns, predictions become more accurate the shorter the forecast window. The accuracy of forecasting supply and demand will therefore be strongly based upon the accuracy of meteorological models, which are themselves based upon the available computing power and improvement in modelling techniques, and as improvements are made to the accuracy of these models, this should feed through to improvements in forecasting electrical energy supply and demands, and thus provide greater clarity to system operators.

One possible solution to reduce the impact to system reliability of connecting greater amounts of stochastic non-dispatchable renewable energy is to provide greater energy storage within electrical networks. For the sake of clarity in this chapter, any storage device that can be charged using electricity is defined as rechargeable storage, and any store of primary energy that cannot be replenished using electricity is defined as a fuel, as although they provide a store of energy that can be partially converted to electricity, the reverse is not true. Difficulty in semantics can sometimes arise as depleted stores of fuels can themselves be 'recharged' with more fuels.

The electrical content of fuels is not only dependent on the chemical energy content of the fuel itself, but also on the conversion efficiencies of converting this chemical energy into electricity. Historically fuels are not utilised to store excess electricity, they are utilised to provide a convenient and economical store of energy that is then converted into electricity. As a simple analogy, rechargeable batteries (secondary batteries) would be classed as rechargeable storage and non-rechargeable batteries (primary batteries) would be classed as fuels in this work. The units for the energy stored in rechargeable storage or the equivalent electrical energy contained within fuels are multiples of kWh *i.e.* the amount of electrical energy stored; whereas the units for the power output of rechargeable storage or energy conversion (generating) technologies are multiples of kW. There is a tendency for storage to be discussed in terms of the power output alone, rather than a combination of power and energy capacity. This tendency is thought to arise from the use of fuels to provide the energy stores of networks, and moreover, that they would always be available to transform into electrical energy at the time required using dispatchable generation; historically there was little need to put a value on the units of fuel energy stored, as it was always expected to be available when required.

6.1 Background to fuels and networks

Fossil fuels provide a convenient store of chemical energy that can be converted into electricity on demand, and electrical generators that use fossil fuels are classed as dispatchable; their output can be controlled within the limitations of the generating technology. Fossil fuels are accorded a considerable importance at a political level throughout the world. An example of the strategic importance of the energy stored in fossil fuels can be found in the EU directive 2006/67/EC (2006/67/EC, 2006), which legislates that *'Member States are required to build up and constantly maintain minimum stocks of petroleum products equal to at least 90 days of the average daily internal consumption during the previous calendar year'*. Whereas oil provides a large share of the primary energy inputs for European transport networks rather than electrical generation, this legislation should be viewed as a political response rather than a market response to provide a degree of security of supply within the European petroleum products market. This implicit level of storage is an indication not only of the importance of oil as a primary energy input, but also of the risks associated with its supply chains. This European Legislation dovetails with the International Energy Agency (IEA) membership's strategic oil inventories. The IEA can be viewed as an agency that promotes security of supply on different timeframes for its 28 members (and therefore for other non-members too), and was set-up in response to the 1973/74 oil crisis to mitigate the shocks from oil supply disruption. It is now involved in most areas of energy systems, not just those predicated on fossil fuels. On the 23rd of July 2011, the IEA announced via a press release that member countries had agreed to release 60 million barrels of oil from strategic stores in the coming month, in response to the ongoing disruption to the oil supplies from Libya. The IEA's executive director

Nobuo Tanaka said, *'Today, for the third time in the history of the International Energy Agency, our member countries have decided to act together to ensure that adequate supplies of oil are available to the global market. This decisive action demonstrates the IEA's strong commitment to well-supplied markets and to ensuring a soft landing for world energy markets.' Total oil stocks in IEA member countries amount to over 4.1 billion barrels, and nearly 1.6 billion barrels of this are public stocks held exclusively for emergency purposes. IEA net oil-importing countries have a legal obligation to hold emergency oil reserves equivalent to at least 90 days of net oil imports. These countries are holding stock levels well above this minimum amount, currently at 146 days of net imports* (IEA, 2011).

This type of implicit obligation for the level of storage of petroleum products has not been repeated with EU directives regarding gas (2004/67/EC) or electricity (2005/89/EC), where the amount of storage is determined by member states. However, new regulations have been adopted by the EU commission in July 2009 (EU/0363, 2009), partly in response to the Russian-Ukrainian gas crisis of January 2009, in order to provide a further degree of security of supply to the EU gas markets. There have been several price and debt disputes between Russian gas supplier Gazprom and Ukrainian oil and gas companies including Naftogaz Ukrainy that have formed the backdrop to these discussions, especially that of January 2009, resulting in gas transport through the Ukraine being shut off. Eighteen EU countries were affected, with some suffering complete shutdowns in gas supply. The assessment by Pirani et al. (2009) provides a comprehensive overview to the longstanding dispute between Russia as a gas supplier and the Ukraine as a gas transit country as well as a gas importer. The problems in 2009 showed the weakness in the Energy Charter Treaty that was supposed to provide a rapid response to exactly this type of dispute. The fact that Russia had never ratified the Energy Charter Treaty, coupled with political influence, and a longstanding wish to remove the discounts that Ukraine paid for gas from Gazprom (in comparison to European prices) all combined to a standoff between the supplier of gas and the transit company. A European Parliament response was a proposal (P7_TA(2010)0322) containing the text *'The main objective of the proposal is to increase the security of gas supply by creating the incentives to invest in necessary* *interconnections to meet the N-1 indicator, as well as the reverse flows.'* that was adopted on 21/9/10 (EU/0363, 2009).

Since 2009, diversification of Natural Gas supply routes to Europe has happened from several directions including pipelines other than through the Ukraine *e.g.* the Nord Stream pipelines through the Baltic Sea direct from Russia to Germany opening in November 2011 and October 2012; the increase in LNG carrier supplied natural gas into European pipelines. These all contribute to an increase in the security of supply for natural gas to Europe (and therefore also to the security of supply for electricity from gas powered generation plants). The changes to the supply routes of the European natural gas market are thought to be contributing to a reduction in the price spreads between the summer and winter gas prices (Risk.net, 2012), which have been the main revenue stream for the development of seasonal storage for natural gas. Ceteris paribus, a reduction in the seasonal price spread leads to a reduced economic incentive to increase the amount of gas storage available to the network. The data and map of the gas infrastructure of Europe can be found at the Gas Infrastructure Europe website (GSE, 2012).

Fossil fuels and electricity are both energy vectors, albeit with geologically different timeframes between the storage and release of energy; fossil fuels are the stored solar energy from millions of years ago. Fuels have an attribute of being economic stores of energy, whilst the electrical charge needed to create the flow of electricity has the unfortunate attribute of being extremely difficult and expensive to store directly, usually by separating two oppositely charged conductors with an insulator (capacitors and electrochemical capacitors). The large cost and low energy density in volumetric or gravimetric terms for capacitors and electrochemical capacitors in comparison to fuels precludes their use for bulk electrical energy storage. Therefore, if electricity is to be stored, it is changed into another form of energy that is easier to store in larger quantities, for longer times and at lower costs, and then converted back to electricity when required. There is always a round-trip efficiency penalty with rechargeable storage for electricity, which is determined by the type of technology.

Electrical networks have been in operation since the late 19th century (Ausubel & Marchetti, 1996), providing a source of energy that is clean at the point of use and immensely adaptable. Network operators have always had to balance the difference between network supply and demand within defined limits, in order that equipment connected to the network and the network itself is not damaged.

The UK transmission network operator currently uses many different market based services in order to match network supply with demand over different time periods; mandatory frequency response, firm frequency response, frequency control demand management, fast (spinning) reserve, fast start, demand management, short term operating reserve requirement, residual reserve and contingency reserve (National Grid-Services, 2012). All electrical systems have a variation on these types of services, whether market based or internal to a vertically integrated monopoly supplier, indeed before the deregulation of the UK's electrical sector, these practical and pragmatic methods of balancing the electrical network over different time horizons were used. These methods have carried on – except now within the marketbased framework.

Although rechargeable storage capacity has increased alongside the growth of electricity networks, it has done so at a much slower pace than that of generating capacity, as other methods of balancing supply and demand have been favoured. Increasing the effective network size by connecting local networks to form regional networks and then to form national and international networks has allowed for the pooling of response and reserve plant to provide the balancing and ancillary services required. The amount of response and reserve plant required for connected cross border networks is smaller than that required for similar but unconnected networks (Neuhoff et al., 2011). Increasing the effective network size not only provides a benefit and greater resilience to the supply side when a portfolio of different primary energy inputs and generating technologies are used, but also provides a similar aggregated benefit at the demand side as a greater number of users with less than perfectly correlated load profiles are connected to the network (Allan et al., 2010).

The network thus benefits from having a portfolio of generation technologies that compete not only in price but also in terms of characteristics, to provide a flexible power output to the network. Several technologies are limited in operability either by being non-dispatchable, the technical constraint rate that they can ramp their output up or down, or their minimal stable generation value. As previously mentioned wind generation can be forecast up to a point, but not directly dispatched, and can be regulated down or 'curtailed'. Large thermal plants such as coal, nuclear and combined cycle gas turbines take many hours to increase their output from a cold start, as thermal stresses on turbines, pipework and boiler equipment have to be kept within limits. However, dispatchable thermal generators do provide response and reserve services to the network as they can generate at a reduced output (part loading), which enables them to increase or decrease their output over timeframes appropriate to providing balancing services. Hydro-pumped storage schemes, open cycle gas turbines and diesel generators can increase and decrease their output in minutes rather than hours, and so also provide balancing services to the network. On the demand side, Frequency Response by Demand Management services allows the network operator to contractually interrupt the supply to certain large electricity users. Dynamic Demand Control (DDC) also aims to provide economic frequency stabilisation and peak shaving through the individual control of many smaller and highly distributed loads *e.g.* domestic fridges and freezers, and although a very promising addition to network stability, DDC has not been utilised on a significant scale so far (Short et al., 2007).

There are thus many tools that network operators can utilise in order to keep their network voltage within defined limits. Rechargeable storage may at times be complementary to these existing forms of balancing, and at times may be viewed as competing. In the market based approach to energy systems in the UK, it is envisioned that the lowest cost approach to balancing will be favoured, unless there are defined market mechanisms to encourage various approaches over others.

Overall, the lower cost of providing additional dispatchable generating capacity coupled with an increase in the effective size of electrical networks and demand management have historically allowed network operators to balance supply with demand with only relatively small amounts of the higher cost forms of rechargeable storage.

In order to better understand and compare the scale of primary energy stores available to the UK network, the historical stores of primary energy available to the UK electrical network are studied. These primary energy stores, which can be replenished, are compared to the four hydro-pumped storage schemes available to the UK network.

6.2 Existing storage of the UK electricity network

This section looks at the existing electrical storage of the UK electrical network by examining the electrical content of nuclear fuel stocks, distributed coal stocks and gas in storage, followed by the rechargeable storage provided by hydro-pumped storage schemes. The fossil fuel stores give an indication of the orders of magnitude of chemical energy available to be converted into electricity. Oil has not been investigated due to the difficulty in sourcing data on oil stocks for electricity production. However it is noted that oil fuelled generators provided ~1.2% of the total electricity supplied to the UK grid over the year 2010, which is a slightly greater amount than that provided by hydro-natural flow ~1%. (DUKES 5.6, 2013).

6.2.1 Nuclear fuel stocks

The amount of nuclear fuel stocks is not publicly available; as stated in the Energy Markets Outlook to parliament, *'The stockpiling of fuel in the UK is the responsibility of the utilities concerned and information on the stock levels in the UK is commercially confidential.'* (EMO, 2009). However, a paper on world nuclear stocks by (Maeda, 2005) stated the following about commercial inventories of nuclear fuel – *'The analysis we did this time found that the commercial inventory has been almost maintained from the previous report analysis (2003), which is approximately 110,000 tonnes of Uranium, 150% of world annual consumption.'* It is therefore felt that nuclear fuel stocks for UK electricity production can conservatively be estimated at over a year.

6.2.2 Coal Stocks

Figure 29 shows the monthly variation as stock levels are adjusted throughout the years from January 1995 to November 2012. (DUKES 2.6, 2013), it is interesting to note the seasonality of building up stocks in anticipation of the forecast demand during the winter ahead, and the unusually large increase in stocks in 2009 followed by a small increase in stock levels in 2010, reverting back to trend in 2011. Something out of the normal seemed to drive the increase in coal stocks during 2009. This could be due to a sharp drop in international coal prices, or may show that coal fired generators sought to build up stocks to use if a repeat of the hiatus in the European gas networks mentioned previously caused a reduction in the ability of gas fired generators to compete. Whatever the reason, it shows that the UK was capable of storing coal stocks of almost 23,000,000 tonnes in the recent past.

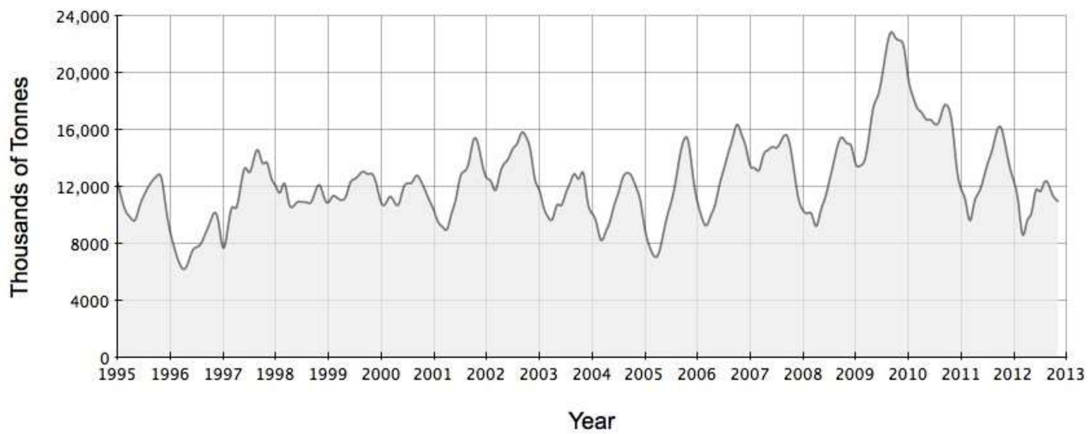


Figure 29 - Monthly UK distributed coal stocks 1995 – 2012; thousands of tonnes (DUKES 2.6, 2013)

The average monthly value of distributed coal stocks for electricity generators over this time period was found to be 12,513,000 tonnes. The stocks ranged between 6,226,000 tonnes in April 1996 to 22,863,000 tonnes in September 2009. Combining these data with the monthly data for electricity generators' coal consumption gives an average stock level of just over 100 days (DUKES 2.6, 2013). This 100 day figure should however be regarded with a high degree of caution – as it is unclear which coal fired power stations actually have the stocks, and their peak power outputs. Very broadly though, it seems that stocks of coal are well above 30 days of power station output. Indeed, since mid 2005, reported monthly UK coal stocks have not dropped below 8,500,000 tonnes, compared to the maximum monthly usage of coal of 6,600,000 tonnes in January 2006 (see Figure 30).

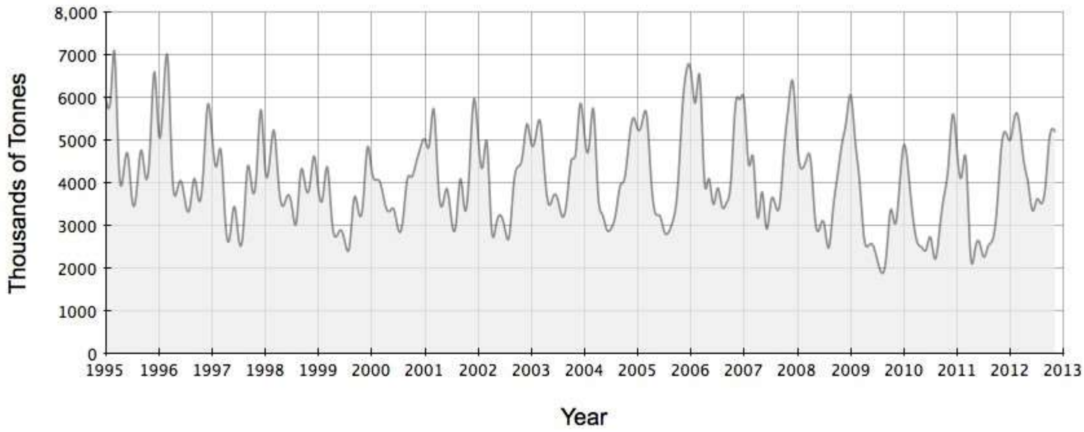


Figure 30 – Monthly coal consumption by GB electrical generators 1995 – 2012; thousands of tonnes (DUKES 2.6, 2013)

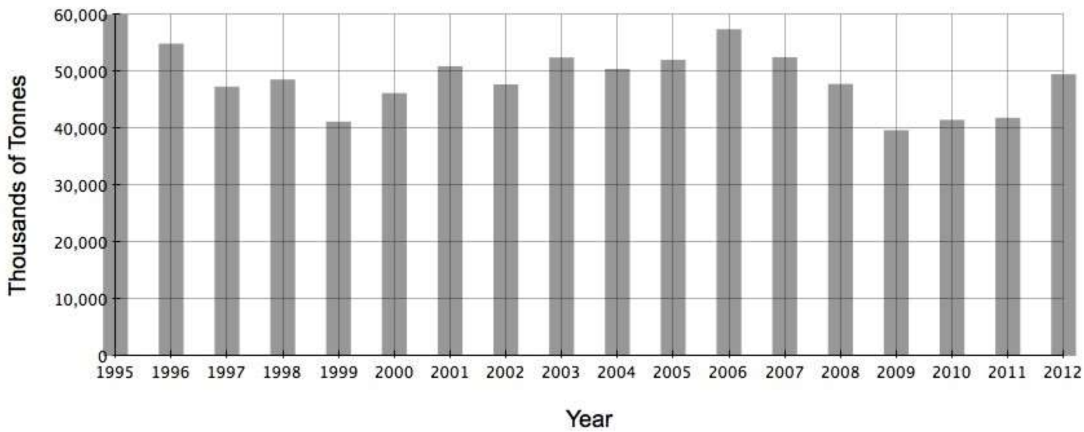


Figure 31 - Annual coal consumption by GB electrical generators 1995 – 2012; thousands of tonnes (DUKES 2.6, 2013)

Figure 31 shows the annual coal consumption of GB electrical generators, and clearly shows the increase in coal use from 2009. The figure for 2012 does not include the monthly figure for December (as it is not yet available), but if this is greater than the November figure (as it has been in all other years with this data set) then the total figure for 2012 will be nearly 55 million tonnes, compared to ~42 million tonnes for the previous year. At a ratio of 2.2 tonnes of CO_2 per tonne of coal used for electrical generation (pp8-table 1a, DEFRA, 2012), this ~13 million tonne increase has a CO_2 footprint of at least 28 million tonnes of CO_2. This is a large retrospective step in terms of reducing emissions from the power sector and the UK's overall CO_2 emissions – and to put this increase of 28 million tonnes in context, the total CO_2 emissions allocated to the power sector in 2011 was 182.16 million tonnes, and the total UK CO_2 emissions for 2011 were 458.6 million tonnes (DECC GHG, 2013b).

Taking the average, minimum and maximum values for coal stocks from the monthly data used for Figure 29, with an estimated gross calorific value (higher heating value) of 24.9 GJ per tonne (DUKES A.1, 2011) equates to a calorific value of approximately 83,600 GWh for the average, 43,000 GWh for the minimum and 158,300 GWh for the maximum level of coal stocks. Making the assumption that the average efficiency of UK coal plants from 2004 to 2008 is ~35.8%, (DUKES 5.10, 2010) gives the electrical energy contained within mean UK coal stocks of almost **31,000 GWh** before transmission and distribution losses. The data for the average, maximum and minimum is shown in Table 9.

1995-2011	Tonnes of Coal Stocks	Gross Calorific Value	Electrical energy content at 35.8% gross thermal efficiency
Average	12,513,000	86,550 GWh	**31,000 GWh**
Maximum	22,863,000	158,300 GWh	56,700 GWh
Minimum	6,226,000	43,000 GWh	15,400 GWh

Table 9 – Electrical content of UK coal stocks, 1995 - 2012 (DUKES 2.6, 2013)

Figure 32 details the amount of coal produced and imported into the UK from 2000 to 2010. The reduction in stocks throughout 2010, from 20 million tonnes to 12 million tonnes (shown in Figure 29 above) had an obvious impact on the level of imports for that year. UK produced coal seemed to stay fairly static between 2008 – 2010 possibly indicating that UK producers have long term supply contracts in place and indicating that the swing variability in the demand for coal is supplied by imports rather than UK producers. This is also shown in a different format in Figure 33 (which is a copy of Figure 18).

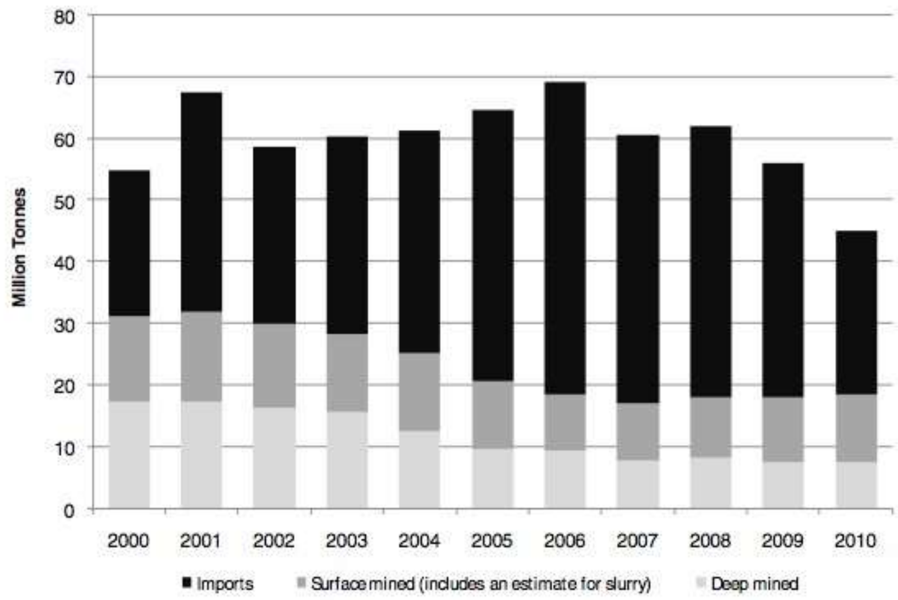


Figure 32 - UK coal production and imports 2000 – 2010 source: (DECC Coal, 2011a)

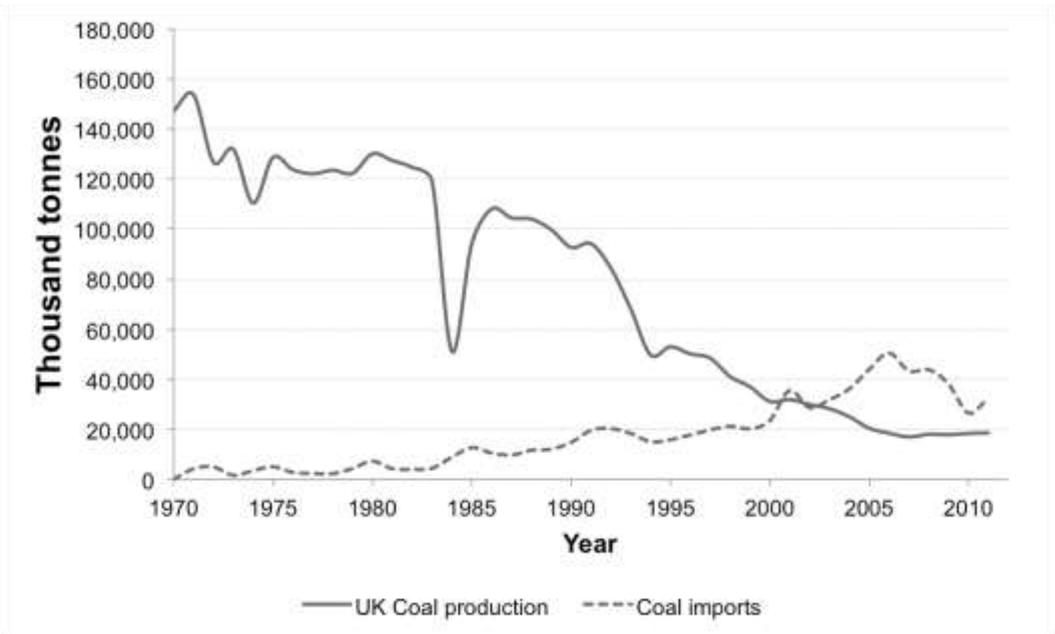


Figure 33 - UK Coal production and imports 1970 – 2010 data from (DECC Coal, 2011b)

Since 1970, UK coal imports have grown steadily, increasing more rapidly over a short period of time in the early 2000s. Imports in 2001 UK (36,000,000 tonnes) exceeded UK production (32,000,000 tonnes) for the first time. This rapid growth in imports continued reaching a record 51,000,000 tonnes in 2006. Since then, levels have declined to nearly 27,000,000 tonnes in 2010 equating to 52 per cent of UK coal supply.

The origin of imported coal can be seen in Table 10. The main suppliers for steam coal for power generators in 2010 are Russia (46%), Colombia (32%) and the USA (12%). The amount of coking coal (used in steel production rather than power generation), is also detailed for comparison and totals roughly a third of the tonnage of steam coal, but due to the different mineral properties required for coking coal, it is supplied by the USA and Australia.

Origin of coal imported to the UK in 2010					
	Steam coal 1000s Tonnes	**% of Imported Steam Coal**	**Electrical Energy equivalent (GWh)**	**Coking coal 1000s Tonnes**	**Total 1000s Tonnes**
Russia	9356	46%	23167	351	9707
Colombia	6360	32%	15748	66	6426
USA	2390	12%	5918	2132	4522
Australia	-	-		3235	3235
European Union[1]	881	4%	2182	1	882
R. of South Africa	781	4%	1934	-	781
Canada	-	-		434	434
Indonesia	275	1%	681	-	275
Other Countries	88	-	218	16	104
Total all countries	**20131**	**100%**	**49848**	**6235**	**26366**
1. Includes non-EU coal routed through the Netherlands					

Table 10 - Origin of UK coal imports 2010, data from (DECC Coal, 2011a)

'Coal has far and away the largest reserves and resources of any of the energy commodities, and accounted for almost 30 % of global primary energy consumption in 2010 (hard coal 27.9 %, lignite 1.7 %)' (DERA, 2012).

If it were not for coal's obvious disadvantages in terms of CO_2 emissions, it is a primary fuel that has several advantages over natural gas, oil and nuclear sources. It has a more widespread distribution around the world than natural gas and oil (reducing the likelihood of a price controlling cartel being formed), and requires less specialised infrastructure to store. However its environmental credentials are seen as the bête noire of the transition towards a low-carbon economy. The environmental degradation of the exploitation of coal resources where it is actually mined is another aspect of the fuel's fall from favour, and although the world's coal reserves are thought to be very much larger than the resources for oil and gas, it is still a finite resource. The World Coal Association estimates for the years of proven reserves at current levels of production are shown in Table 11, and although these values are subject to large changes due to technological advances, changes in the rate of production, and increases of reserves – the ratios between the different fossil fuels is thought to be indicative.

	Oil	**Gas**	**Coal**
Years of Proven Reserves at current rates of production.	46	59	118

Table 11 – Years of production of fossil fuels, source: (WCA, 2012)

There is a considerable seasonal variation of UK power station coal stocks (Figure 29) and as the level is not mandated, it is presumed that this variation is caused by factors the coal-fired generators take into consideration. Coal stocks have a cost of purchase and of storage, and a generator that can reduce their cost of holding stocks by keeping an optimal level should be have an advantage to their competitors. However, forecasting the expected demands and prices for electricity months in advance, and therefore the potential to run coal fired power stations at a profit, is not a trivial task. The major drivers that determine the size of coal stocks for energy producers is unknown, but would be an interesting study in its own right. The supply chain risks for coal delivery are not always international in nature, such as train track disruptions for those generators that depend upon train transport for coal delivery. In terms of the indigenous risks versus international risks of coal supply, (Grubb et al., 2006) state that the major interruptions in modern times were the 1984 – 1985 miners strike in the UK, and domestic fuel blockades, rather than international risks. These supply risks may be able to be mitigated, depending on the contractual arrangement of the buyer and seller, but is dependent on the counterparty risk of the seller being solvent at the time a supply disruption occurs, and therefore is able to compensate the buyer.

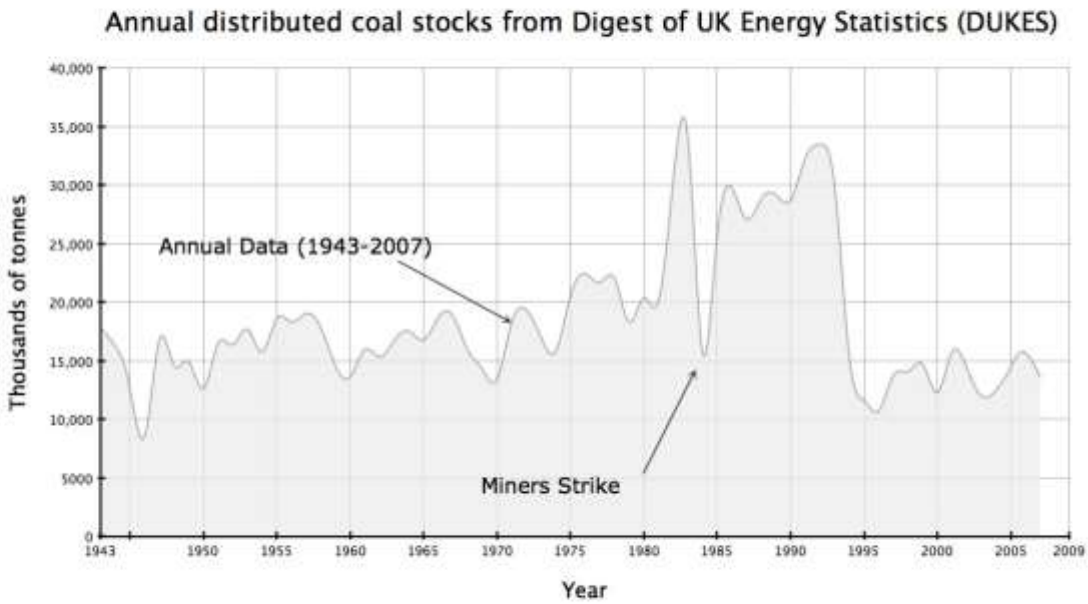


Figure 34 - Average UK Coal stocks per annum 1943 – 2007, thousands of tonnes (DECC Coal, 2011b)

In Figure 34 above, the amount of coal stocks averaged over a year (DECC Coal, 2011b) shows the build up of stocks from roughly 20,000,000 tonnes in 1981 to a record level of roughly 34,000,000 tonnes in 1983, followed by a sharp drop in 1984 to roughly 16,000,000 tonnes (also shown in production values in Figure 33). This build up in stocks was a major factor in the National Coal Board's strategy in reducing the impact of the miners strike on the UK energy system and was key to the way in which the strike unfolded, ultimately with closure of a large number of coal mines. The data includes coal stocks for coking coal as well as steam coal – and the values will thus be greater than the equivalent data in Figure 29.

The large reduction in coal stocks from 1993 to a lower average trend is thought to indicate the move from coal to gas as a primary energy source in the UK's then deregulated energy market – the so called 'Dash for Gas' (Newberry, 1998) where gas as a fuel for electricity generation rose from providing less than 1% 1991 of the fuel input for electricity generation to 17% in 1995 and 34% in 1999. These trends can also be seen in Figure 35 below.

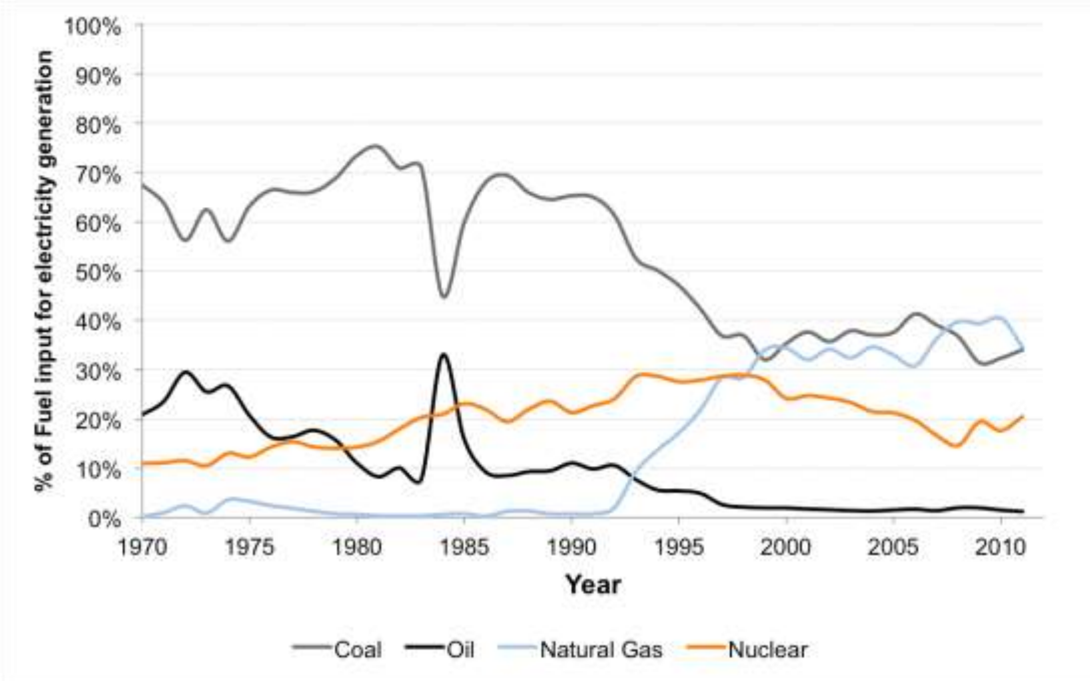


Figure 35 – UK Fuel inputs 1970 – 2011, data from (DUKES 5.1.1, 2011)

Overall, the data for coal stocks suggests that coal continues to provide a significant amount of pre-conversion electrical energy storage in the UK network, although this will likely change significantly due to the planned shut down of several of the existing coal generation fleet.

6.2.3 Natural Gas

Another fuel that provides energy storage to the UK electrical network is natural gas, although the data are not as clear as the data for coal. In the mid 1980's the UK moved away from a depletion policy for exploiting the UK's continental shelf gas resource, which prioritised the rate of extraction in order to lengthen the time period of depletion, to a policy encouraging the market to maximise the development of the gas resource (Stern, 2004). This change of policy, carried onward by successive Governments, had not prioritised gas storage as a key element of the gas supply chain. This problem was however identified, as witnessed in the Ministerial written statement to the House of Commons in May 2006 (SoSTI, 2006). Investment in import supply capacity *e.g.* the Interconnector, Langeled, South Wales, and Balgzand Bacton Line pipelines, and LNG terminals have spread the risk of supply shocks by diversifying supply routes, but, dependent on the contractual arrangements of the supply, may not have contributed to swing capacity, which is currently provided by the depleting UK gas resource (Hunt & Technols, 1999). Even if gas storage is available on a particular gas network, ownership and access by third parties are key factors in the effective utilisation of a gas storage facility in order to promote a benefit to the market as a whole (Bertoletti et al., 2008).

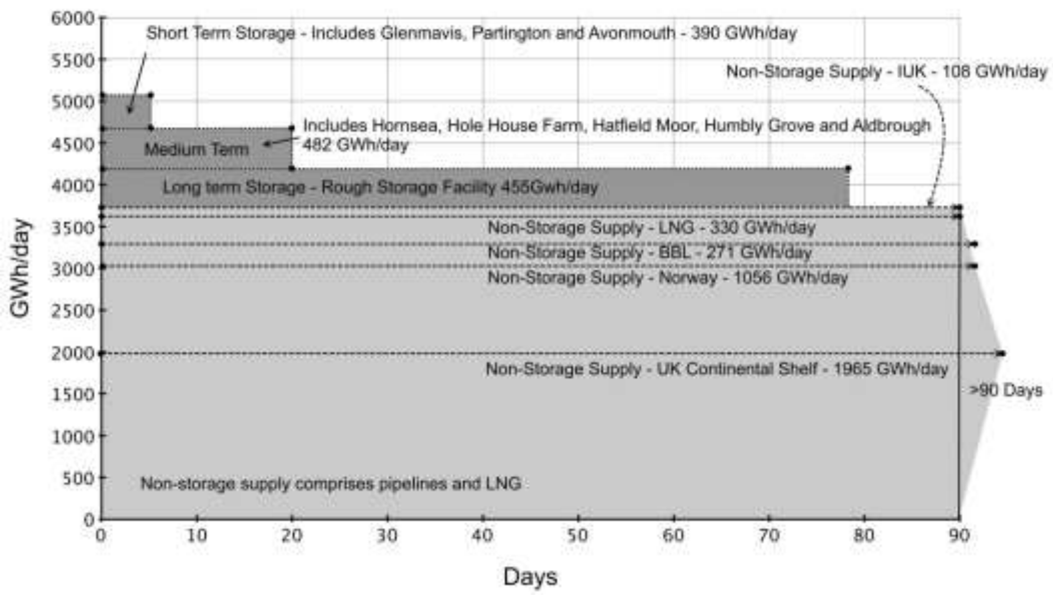


Figure 36 - Preliminary UK Gas storage and non-storage supply assumptions for winter 2009/2010, data from (National Grid, 2009)

Figure 36 shows the preliminary winter 2009/2010 gas storage capacity in the UK of 47,126 GWh (the areas in dark grey at the top of the figure marked as short, medium and long term storage) and is dominated by the Rough storage facility (the UK's only seasonal storage or long term facility). This has a capacity of 35,530 GWh (3.3 billion cubic metres of natural gas stored at pressures of over 200 bar), but only a delivery rate of around 455 GWh (42.4 million cubic metres) of gas per day. By assuming a constant discharge rate this total capacity of 47,126 GWh of gas storage has a maximum delivery rate of 1327 GWh/day for the first 5 days, 937 GWh/day for the next 15 days, and 455 GWh/day for the following 58 days. (The discharge of a gas storage facility is not expected to be linear in nature, but a simplified linear approach has been chosen for the purposes of this work). For comparison the data for non-storage supply (pipelines and LNG terminals) have been included, which are assumed to provide ongoing capacity in the short term. The capacities will change over the medium term as the contribution from the depleting UK Continental Shelf is reduced. Maximum daily demand for natural gas through the National Transmission System in winter 2007/08 was 4,588 GWh on 17th December 2007. These data are taken from National Grid's preliminary safety & firm monitor requirements 2009/10 (National Grid, 2009).

Data from the winter 2011/2012 (National Grid, 2011b) is compared to the 2009/2010 preliminary data in Table 12 below.

Safety Monitor and Firm Gas Monitor Requirements –				
	Preliminary 2009/2010		20011/2012	
Gas Storage Type	Space - GWh	Deliverability - GWh / day	Space - GWh	Deliverability - GWh / day
Short (LNG)	1970	390	677	143
Medium (MRS)	9576	482	8767	457
Long (Rough)	35580	455	39500	476
Total	47126	1327	48944	1076
Non-Storage Supply		3730		4345

Table 12 - Comparison of Gas Safety Monitors 2009 & 2012

In comparing the data from the two timeframes it can be seen that there has been a significant increase in the non-storage supplies from 3730 GWh/day in 2009/2010 to 4345 GWh/day in 2011/2012. There has also been an increase in the long-term storage at the Rough facility from 35580 GWh to 39500 GWh, and a significant decrease in the short-term storage facilities of 1970 GWh to 677 GWh. The increase in non-storage supply is particularly interesting due to its size (an increase of ~16.5% in two years), and is thought to be mainly due to an increase in imported LNG capacity as supported by Figure 37 below.

140 30 Day average system entry volumes October 2005 to May 2011

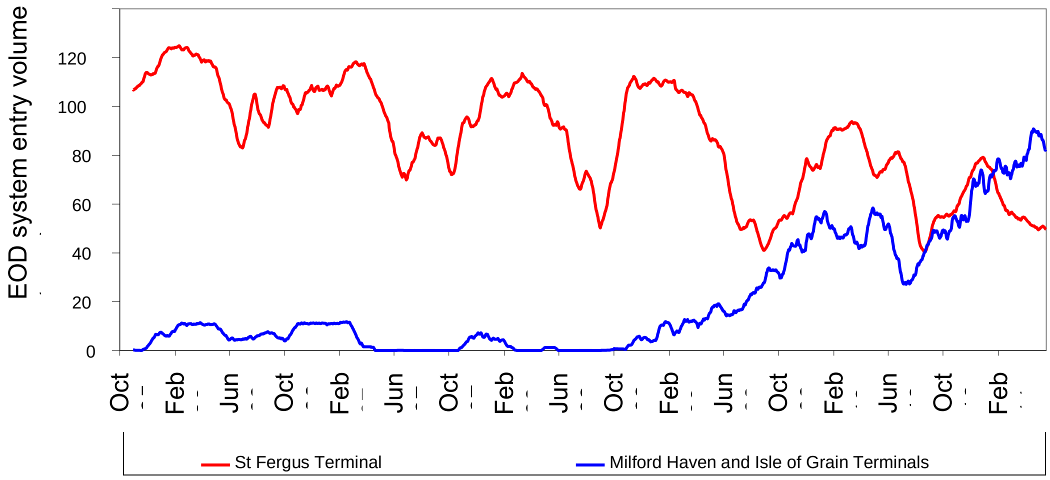


Figure 37 - St Fergus and Milford Haven supply volumes, source (National Grid, 2011a)

Figure 37 is copied from page 42 (National Grid, 2011a) and shows the end of day system entry volumes in million cubic metres of gas on a 30 day average basis. To compare the volume values with energy values, a ratio of Energy (GWh) = Volume (MCM) * Calorific value (MJ/m3) / 3.6 = Volume (MCM) * 10.833 using the standard Calorific Value of 39 MJ/m3 (National Grid, 2012c). The y-axis in Figure 37 therefore has 100mcm equivalent to an energy content of 1083 GWh supplied by the terminal on a daily basis (averaged over 30 previous days). There is an obvious increasing trend to the LNG imports through the Milford Haven and Isle of Grain terminals, that has roughly doubled from the time of the preliminary Safety Monitor that looked at winter 2009/2010; the winter of 2010/11 saw the LNG imported at Milford Haven and Grain terminals exceeding St Fergus flows for the first time.

The changing nature of gas supply between the years 2000 and 2010 is also suggested by Figure 38, which is sourced from (National Grid, 2011a) page 41. This represents a decrease in the flows through the St Fergus terminal in Scotland, and increasing flows elsewhere. Milford Haven LNG terminal is located in West Wales, and the Isle of Grain LNG terminal is located at the mouth of the river Thames. (See Appendix 7 for a more detailed map of the natural gas infrastructure).

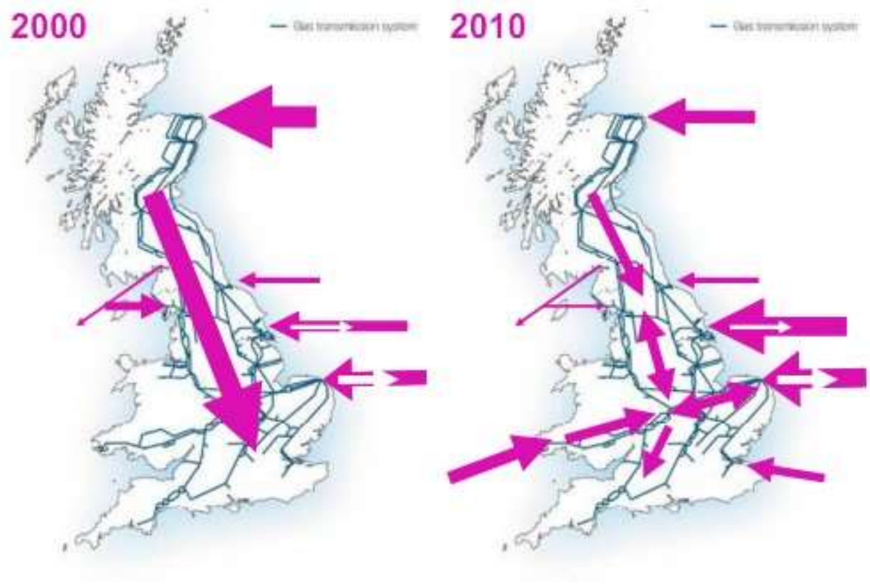


Figure 38 - Gas Flow patterns in the National Transmission System 2000 & 2010, source (National Grid, 2011a)

In presenting the raw data from National Grid, Figure 36 does not take into consideration network constraints, the non-linear discharge of the storage facilities, nor the daily linepacking storage in the pipelines. Linepacking provides additional gas throughout the gas network by increasing the pressure in anticipation of a peak demand. An indication of the scale of linepack in the National Transmission System is shown Figure 39 (sourced from page 40 (National Grid, 2011a). 10 million cubic metres on the y-axis corresponds to 108.3 GWh of Natural Gas, and it seems fairly common that within day swings of at least this magnitude occur.

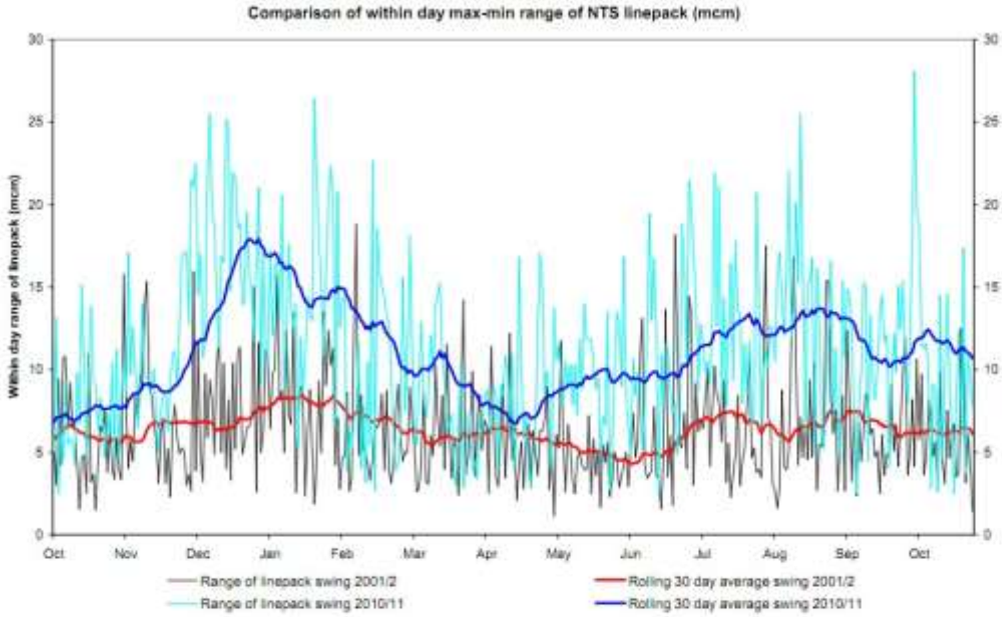


Figure 39 - Comparison of within day max-min range of National Transmission System Linepack. source (National Grid, 2011a)

Stocks of gas are problematic to compare readily with coal stocks for power stations for a number of reasons.

1. The Fuel Security Code gives the UK Secretary of State the ability to direct a power station to operate in a certain way, or with a view to achieving specified objectives (BERR, 2007). This ability to divert gas supplies previously available to electricity generation, combined with interruptible supply contracts, means that it is not possible to accurately gauge the amount of gas storage that would be available to electricity generation at times of extremely high gas demand.

2. Gas is used mostly for services other than generating electricity. Annually, about 30% of gas is consumed in the electricity-generating sector, and equally about 30% is consumed in the non-daily metered sector (DUKES 2.1.1, 2011). Figure 40 and Figure 41 show a sectorial comparison of yearly and daily data. It can be seen that the overall yearly values mask a large variation of seasonal gas demand from the non-power sector sectors; the

largest variation is due to non-daily metered gas demand, which is largely comprised of domestic heat and cooking demands.

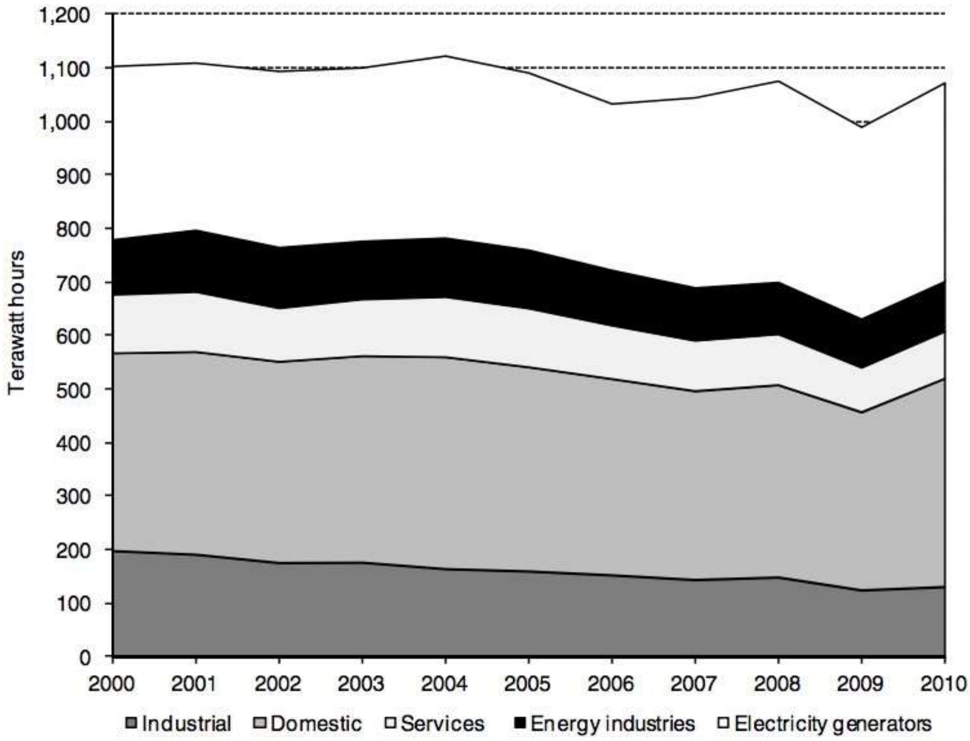


Figure 40 – Annual GB Gas usage by sector 2000 – 2010, source: (DUKES 2.1.1, 2011)

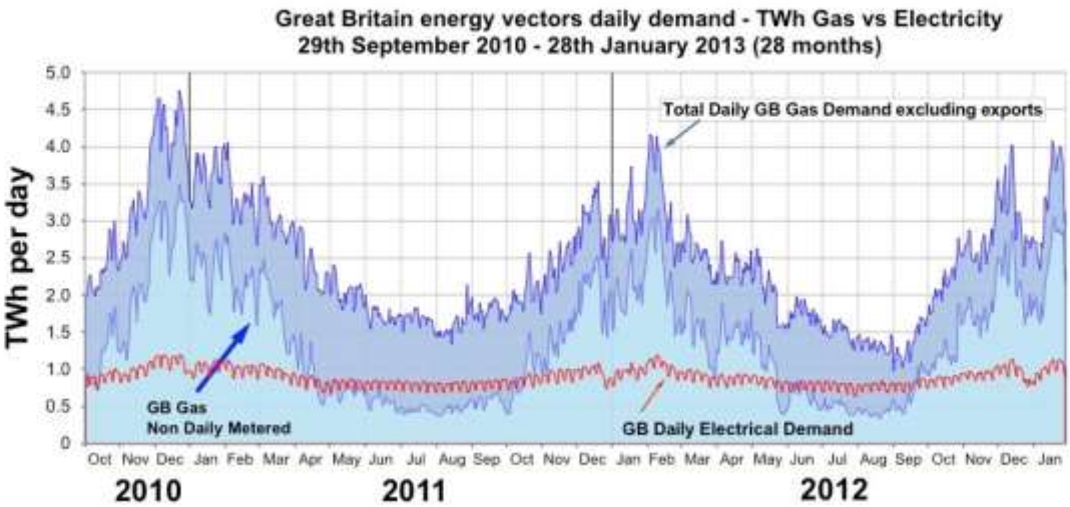


Figure 41 – GB Energy vectors for daily demand, Gas versus Electricity TWh/day, source (National

Grid, 2012d)

In order to try to compare stocks from gas with other storage for electricity this study therefore assumes that 30% of the gas in storage would be used to fuel gas generators in the UK, and that these generators have an overall efficiency of 50%.

The electrical equivalent of the gas in pre-conversion storage available to the power sector in 2010/2011 is therefore estimated to be about 48944 x 0.3 x 0.5 = ~**7300 GWh** (from Table 12 and above). Due to the difficulties in determining the percentage of gas storage available to the power sector, this figure provides an indication of the order of magnitude only, and is not intended as an accurate representation of the actual amount of electricity that may indeed be generated from gas in storage.

6.2.4 UK Hydro Pumped Storage Schemes

Hydro pumped storage schemes are the only large (>10 MWh) rechargeable storage schemes available to the UK electrical network. They have provided a range of balancing and ancillary services to the electrical network for many decades, but as the network requirements have changed over the years, they have been upgraded to allow for many more mode changes than designed at commissioning, and have thus become more flexible. Table 13 below details the hydro pumped storage schemes operational and planned in the UK. The 'Hours of Operation at full power' column is calculated as the energy capacity divided by the rated power capacity. The total UK Hydro-pumped storage capacity is therefore aggregated to **~27.6 GWh**.

Name of Scheme	Owner	Output MW	Storage Capacity GWh	Hours of Operation at full power	Location	Year of Commission
Ffestiniog	First Hydro	360	~1.3	3.6	Wales	1963
Cruachan	Iberdrola (SP)	440	~10	22.7	Scotland	1966

Foyers	Scottish & Southern Energy	300	~6.3	21	Scotland	1974
Dinorwig	First Hydro	1728	~10	5.8	Wales	1983
Sloy Upgrade	Scottish and Southern Energy	60	0.36	6	Scotland	Consent given in September 2010. Put on hold due to market conditions
Coire Glas	Scottish and Southern Energy	300-600	30	50	Scotland	2012 - In Scottish planning system
Balmacaan	Scottish and Southern Energy	300-600	30	50	Scotland	Awaiting outcome of Coire Glas planning

Table 13 – Current and planned Hydro Pumped Storage Schemes in the UK

Table 13 also details the proposals in the Scottish planning system in 2012 amounting to a possible additional ~60GWh (660-1260MW power) of pumped storage development in Scotland (Lannen, 2010). If the Scottish and Southern Energy proposals at Coire Glas and Balmacaan were given planning consent and were built to the upper end of their specification, this would treble the available electrical energy storage capacity of UK pumped storage schemes, but will only increase the power available by around 45%. As the planning proposals have been submitted by SSE Renewables, which is part of the generation business of SSE, the schemes would therefore be part of the generation asset base rather than the regulated asset base of the other distinct transmission and distribution businesses of SSE. The operation of these two schemes could be up to 50 hours at full rated output, which is a much increased timescale to the existing schemes, and suggests that SSE Generation may use these to balance other generation assets in their portfolio, *e.g.* to balance output from their renewable generation over longer than a 24 hour timeframe, possibly when a lull in wind resource is coupled with a high time of demand, such as a winter high pressure weather system that covers a large area of their wind generators.

The storage element of these planned schemes is obviously an important consideration for SSE, and differs from their 100MW Glendoe scheme commissioned in 2009 (but subsequently closed due to an internal rock fall 9 months later), that is a high head hydro scheme without the ability to pump water in order to store energy. The scheme became operational again in August 2012.

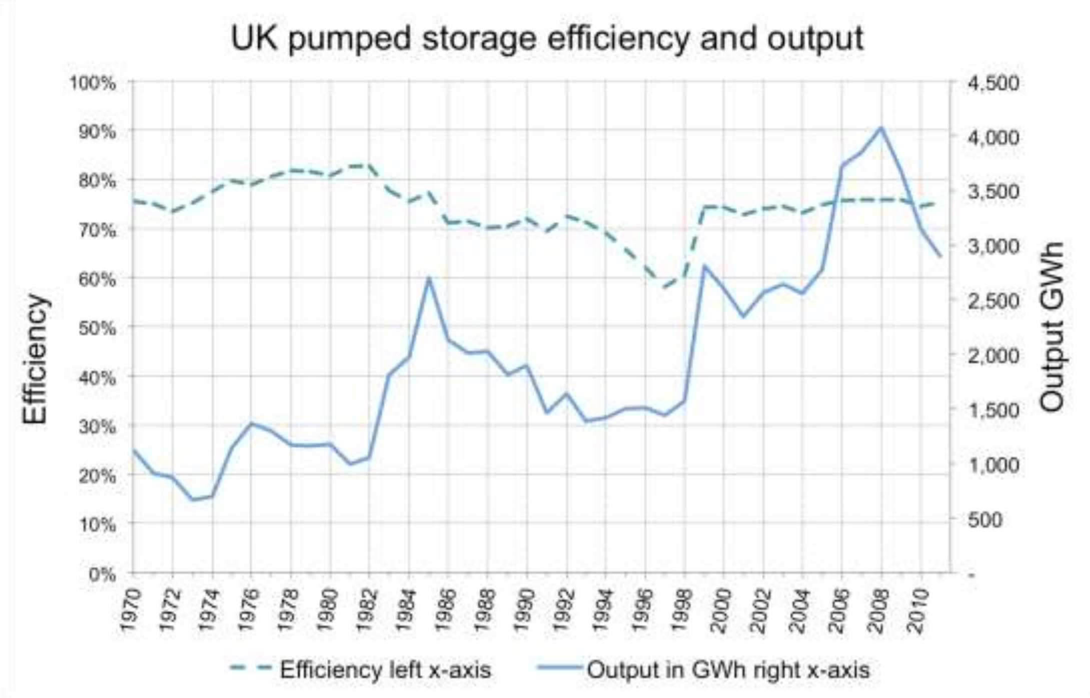


Figure 42 - UK pumped storage efficiency and output 1970 – 2010 (DUKES 5.6, 2013)

Figure 42 details all four pumped storage schemes aggregated output and efficiency from 1970 – 2010 (DUKES 5.6, 2013); in 2008 the existing pumped storage schemes supplied a record amount of 4,075 GWh of energy over the year, from an input of 5,371 GWh used for pumping. This equates to an average of 11.13 GWh delivered to the grid on a daily basis, which would suggest that the hydropumped storage schemes use at least some of their capacity to arbitrage over a daily cycle, in addition to providing ancillary services, by storing (buying) energy at a lower costs and returning (selling) this energy back to the market at a higher cost. In a market based system that does not currently pay for capacity such as the UK, the price differential from the time-shifting of energy would be expected to at least cover the round-trip efficiency losses as well as other operating costs. The annual roundtrip efficiency from Figure 42 seems to have stabilised around 75%. A capacity payment is to be reintroduced back to the UK market framework as part of the EMR bill, which may partly explain SSE's lack of construction with the Sloy upgrade (until the market frameworks are clearer).

The commissioning of Foyers (1974) and Dinorwig (1983) pumped storage schemes, and an incremental increase in Dinorwig's energy storage capacity in 2007 from ~9.4GWh to ~10GWh (1728MW power) are thought to have contributed to the increases that can be seen in Figure 42 and Figure 43.

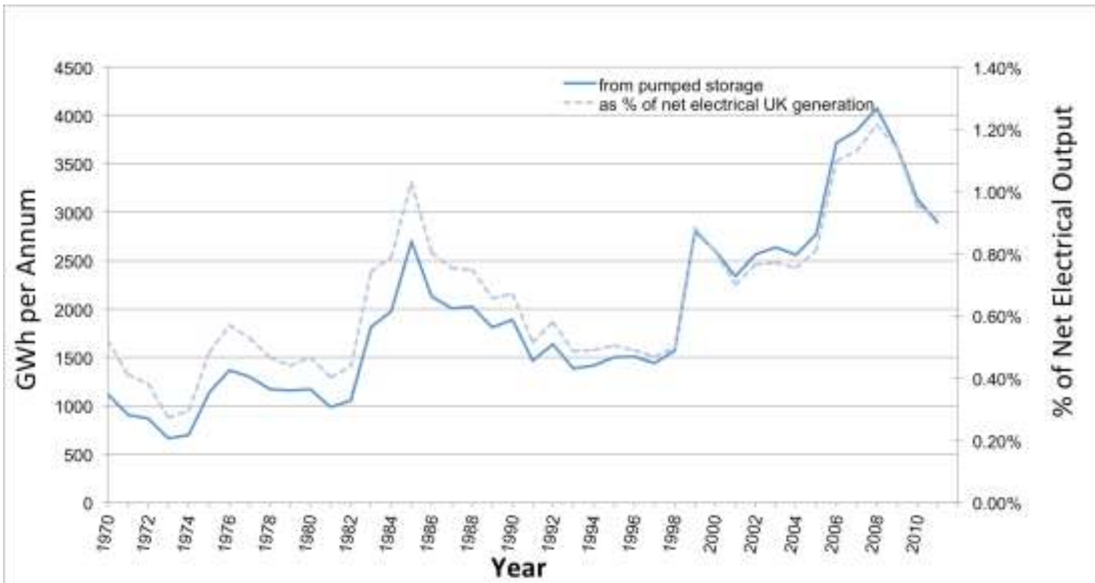


Figure 43 - Hydro Pumped Storage Output 1970 – 2011 (DUKES 5.6, 2013)

As all the UK schemes have top reservoirs that sit within rainfall catchment areas, it is likely that years with different rainfall patterns contribute to the round-trip efficiency difference as well as year-to-year operational changes, as any rainfall would effectively increase the apparent round-trip efficiency by increasing the measured annual energy output without a corresponding measured energy input from the network. The 2008 record output level was ~1.2% of the total electricity supplied to the UK by the major power producers (Figure 43). However, the use of the pumped storage schemes (and therefore the energy stored and produced) is governed by market forces in any given year, and should not be considered as a direct indication of the profitability of the schemes, although, an increase in the use of the schemes is expected to be positively correlated with increased turnover and presumably their profitability.

The UK's largest hydro-pumped storage scheme at Dinorwig Power Station in Snowdonia, North Wales has a capacity of **~10GWh**, which equates to the electrical equivalent of approximately **4000 tonnes** of pre-conversion distributed coal stocks using a 35.8% efficient coal plant.

6.3 UK Stores of Energy

The values for historical distributed coal stocks and gas storage point to electricity storage being overwhelmingly contained within the pre-conversion fuels stockpiled for the UK electrical network, estimated at **29,930 GWh** from coal and **7300 GWh** from natural gas. This **37,230 GWh** of stored electrical energy from fossil fuels is vastly greater than the amount of post-conversion rechargeable storage available from pumped storage at **~27.6 GWh**. The stored energy in nuclear fuels is unavailable, but thought to be greater than a year of output from nuclear plant (the input for nuclear for 2011 is reported as **181,732 GWh** in the data set from (DUKES 5.6, 2013).

This wide disparity between pre and post-conversion stores of energy was the case within the centrally planned vertically integrated Central Electricity Generating Board (CEGB) before market liberalisation in the UK, and remains the case in the regulated market today. The largest point sources of post-conversion rechargeable storage in the UK are the hydro-pumped storage schemes, whose rechargeable storage capacity is dwarfed by the electrical energy available from UK fuel stocks by three orders of magnitude, indeed, if the electrical energy contained within fossilfuels was to be replaced with rechargeable storage schemes it would require nearly 3700 Dinorwig sized hydro-pumped schemes.

The economic and environmental requirements of even a small increase in the number of post-conversion pumped storage schemes points to the challenge of replacing anything like the existing level of capacity provided by fuels with postconversion rechargeable storage. It would seem that a different approach to the optimal use of pre and post-conversion storage within future networks will be required if the UK moves away from the use of fuels to provide stores of energy, as it is simply not possible to store wind and solar energy prior to electrical energy conversion.

7 Development of the model to determine the upper boundary of revenue available from time-shifting bulk electrical energy

7.1 Background

In order to investigate the ability of bulk energy storage systems to capture certain revenue streams in the UK market, it was decided to focus on an objective method to determine the maximum available revenue from one particular revenue stream – namely the time-shifting of energy from a lower price period to that of a higher price period. In this study, buying electrical energy at a lower price to sell back to the market at a higher price is termed arbitrage, although not strictly correct in a formal definition due to trading in the same market, although at a different time. The ability of storage operators in the UK to optimise their profitability is a complex task that crucially itself requires an accurate and rigorous method of forecasting prices over the next day and beyond.

The area of price forecasting is a large scientific area in its own right, and it was therefore decided at an early stage of development to use historical price data (Weron, 2006; Weron, 2010; Weron et al., 2004), rather than investigate or develop a price forecasting tool and is set out in Section 7.2.

The academic context of the area of energy storage optimisation is set out in Section 7.6.

7.2 Use of historical data

It was decided to use historical price data as the input to the optimisation model for a number of different reasons. An important consideration was the ability to be able to test the model with a data stream that could be used by other researchers, without the difficulties that arise from scenario based forecasting. The degree of confidence in results based on future scenario based inputs is highly dependent on the assumptions used not only on the supply and demand profiles, but also on the link between future prices and the forecast supply and demand. It was thought that building a model that used historical price data would remove the need for these types of assumptions that create uncertainty in the final results. By using this methodology it should however be stated that the model was built to accept any price data set that could be created from a separate forecasting model, and would still be able to output results. One of the aims of the model was also to be a tool to provide a particular optimised buying and selling time-series output, based on a price data set input, regardless of whether this price data set input was actual historical price data or future scenario based price data. The model would therefore aim not only to give an output which was the upper boundary value for arbitrage revenue, but also the schedule of buying and selling in order to meet this value.

Use of historical price data is thought to be the equivalent of perfect forecasting and by this reasoning, using historical price data would indeed provide the upper boundary of the arbitrage revenue available to a given storage device for that particular timeframe *i.e.* a storage operator would never be able to derive more revenue than the upper boundary revenue calculated by the model via arbitrage alone. If this information is combined with lifetime costs of the storage devices (operations and maintenance, installation cost, connection costs, *etc.*), this should allow for a more informed decision of whether or not a given storage device is likely to provide a desired level of profitability.

The price data set was chosen to be the market index price data from one of the UK electrical spot markets. The term 'spot market price' will be used throughout this work, rather than the term 'market index price' that is used by the electrical trading sector.

Section 5.2 discussed the market structure for energy supply in the UK, with the description of the spot market for the anonymous trading of energy between registered parties. The spot market is viewed as the market of last resort, and provides price discovery through the ability to determine the price between willing buyers and sellers for blocks of products that cover each 30-minute period. These prices are agreed anonymously without the parties to the trade being aware of the counterparty. It is worth repeating that less than 3% of the total volume of electrical energy in the UK is traded through the spot markets, and as such it could be seen as having little impact on the overall price structure of traded electrical energy. However, the bilateral contracts that cover the majority of the traded electrical energy will themselves likely have clauses that link somehow to the spot price over time. Thus the trends in prices for the 3% of energy traded through the spot markets is eventually likely to have an impact on all electrical energy prices.

7.3 Accessing UK historical price data

The spot price data can be downloaded from https://www.elexonportal.co.uk/ (previously https://www.bsccentralservices.com) - a login is required to access the data; there is no cost to register.

The data is found under the 'Market Index Data and Volume' page, which itself is under the 'Financial and Credit' heading (*n.b.* not under 'system prices' which is also under the 'Financial and Credit' heading. See Figure 44 below.)

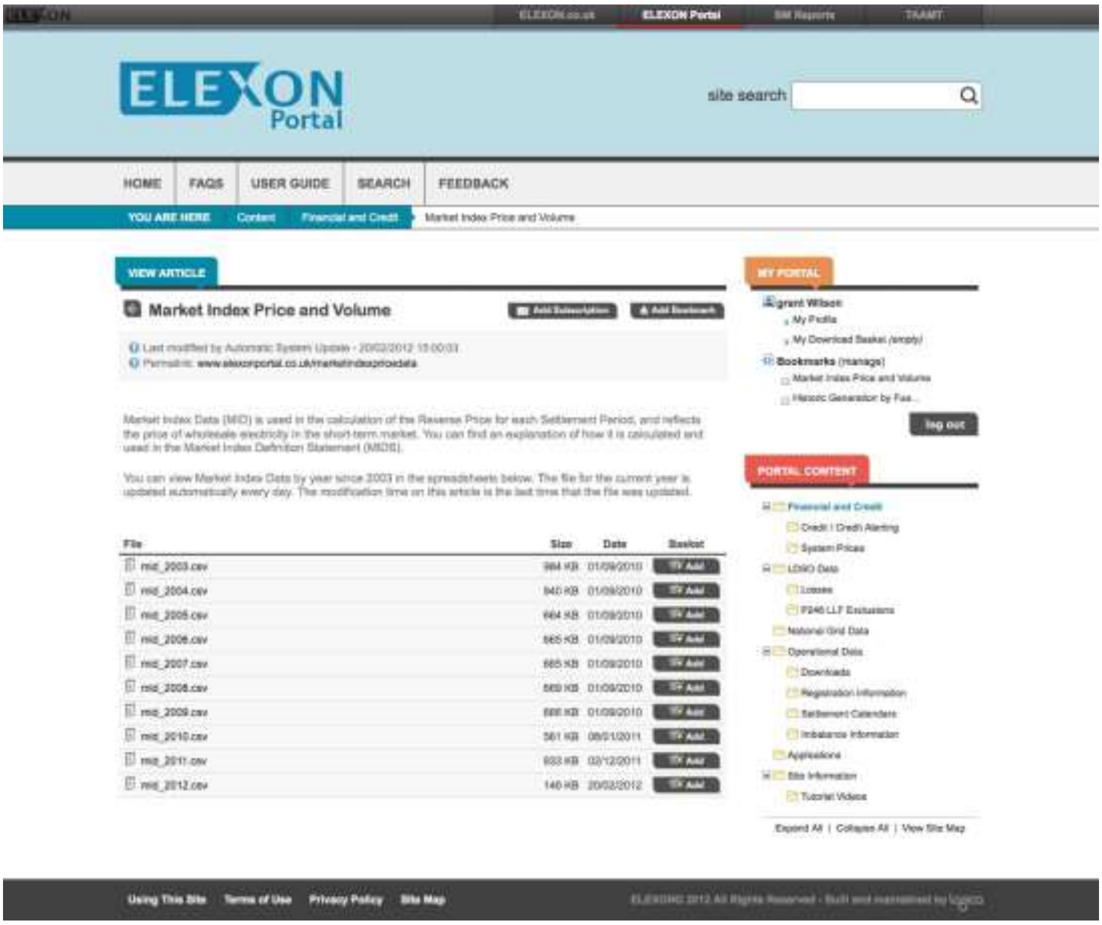


Figure 44 - Elexon Portal Webpage

The spot price data is available from 2003 – 2011 but due to the changes from the New Electricity Trading Arrangements to the British Electricity Trading and Transmission Arrangements on the 1st of April 2005 – data before 2005 is not used. The spot price is a discrete time-series of the weighted average of trades struck through the UK's power exchanges relating to a particular 30-minute period. Each standard 24-hour day is broken into 48 different half-hourly periods. The downloaded values are in £/MWh and can be easily changed to pence per kWh (p/kWh) by dividing the value by a factor of 10 *i.e.* £100/MWh is the equivalent of 10p/kWh.

The raw price files are prepared for use by the algorithm by using a set of instructions detailed in Appendix 3, to format the carriage returns and line feeds for acceptance by the Unix system and the Fortran program.

7.4 UK electrical energy spot price data analysis

The time-series for the spot price for 2009 was used to undertake some analysis into the underlying structure; this year is a non-leap year, and has 17520 discrete spot price values for the 17520 half-hourly periods. The raw spot price input files for Figure 45 - Figure 48 were manipulated using Matlab to use a diurnal window (48 half hour time periods) that starts at 00:00 and finishes at 24:00, with one short day being 46 time periods and one long day being 50 time periods to take account of daylight savings time shifts in the UK. The choice of a daily = 24 hour = 48 period window to look at the price file was chosen arbitrarily for the purposes of preparing the histograms, but the actual model algorithm works from the entire price file, rather than a daily window basis.

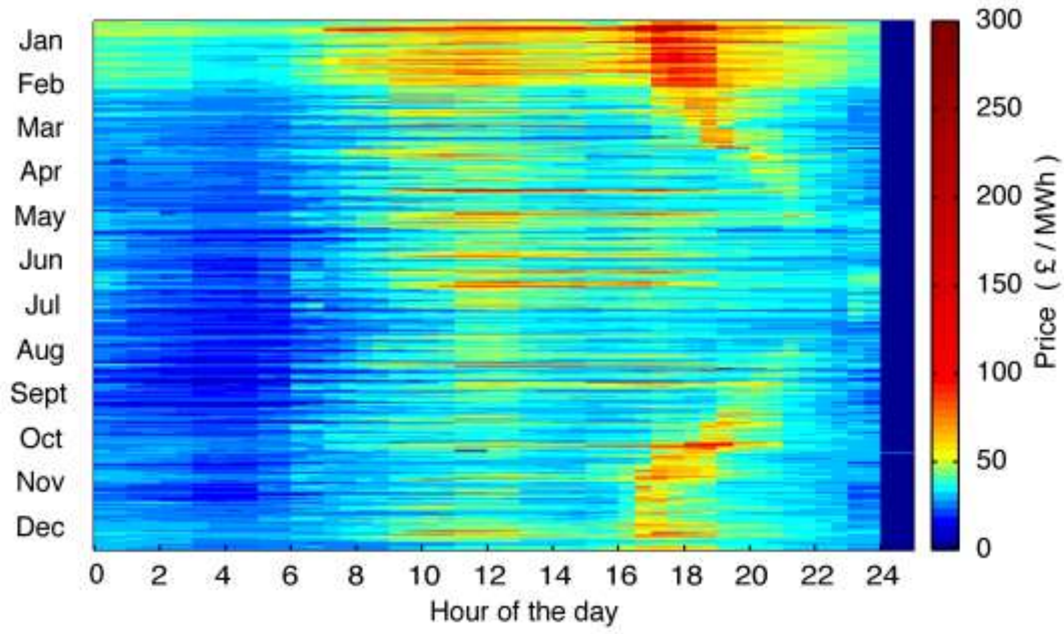


Figure 45 - 2009 UK spot price data: 'Heat map' illustrating the pattern of spot prices throughout the year, data from Elexon Portal.

Figure 45 illustrates 2009 prices as a 'heat map' and is corrected for daylight savings, with day 88 (in March) being 23 hours long and day 298 (in October) being 25 hours long. The different colours illustrate how the price changes throughout the day as well as throughout the year; it is interesting to note that the time of the highest daily price does seem to vary significantly from season to season, with the winter peak prices in the early evening 17:00 to 20:00 timeframe and the summer peak prices scattered throughout the daytime. The lowest prices do not show this seasonal variation to the same degree, and are likely to happen between the hours of 03:00 and 06:00 throughout the year (see Figure 47). It is this variation in the spot price of electrical energy that provides opportunities for energy storage device operators to exploit price differentials. From Figure 45 it also seems that there is a movement of higher prices in the evening that seems to track the time of darkness throughout the year. This has not been further investigated – but does seem interesting as to why the fall of darkness should provide such a distinct increase in prices (other than the obvious increase in load from lighting).

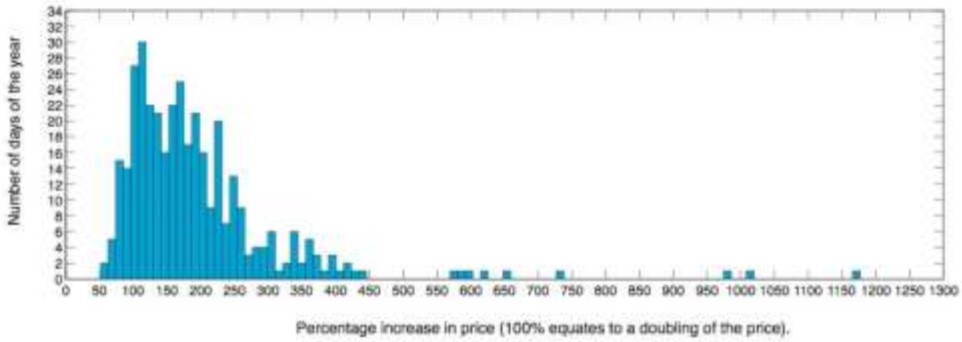


Figure 46 – 2009 UK spot price data: percentage change in price between the lowest daily spot price and the highest daily spot price (from 00:00 to 24:00), data from Elexon Portal

Figure 46 is a histogram showing the number of days when a certain percentage change in price happens. The percentage increase is calculated by determining the greatest possible change in price in each day (starting at 00:00 and finishing at 24:00). This may not, however, be the same as the difference between the absolute highest and lowest prices in a given day if the highest price occurs before the lowest price. This problem was resolved by coding in Matlab to check that the lower spot price was indeed before the highest spot price for any given day, if it was not, the lowest price point would be discounted, and the next lowest spot price would be checked. The histogram therefore shows the greatest time-dependent price difference where the higher price happens after the lowest price. The x-axis is the percentage change in price, where the percentage price increase is calculated relative to the lower price, therefore 0% in this histogram would equate to a higher price equal to the lower price = no change in price.

The starting point for the 24hr period window was investigated to determine whether starting at 00:30, 01:00, *etc.* would cause a large change in the calculated percentage price change results. By moving the start period incrementally from 00:00 to 24:00 it was found that the average for the percentage price change for the year only decreased ~1% between time period starts from 00:00 and 05:00, and that the 00:00 start time gave the highest yearly average change in price. This was tested for a number of different years, and the results were found to be similar. In contrast, using a start time between 05:00 – 21:00 gave a significantly reduced average figure for the price increase. The price histograms presented therefore all use a 24-hour window that begins at 00:00 and ends at 24:00. The model, however, was based on longer timeframes and is therefore thought to be unaffected by a daily start point with a 24 hour window.

It should be noted that the percentage price increase (as a measure of the ability to cover the costs of the efficiency losses in the system) is a relative rather than an absolute measure. A higher absolute price differential will afford a storage operator a greater absolute revenue *e.g.* buying at £25/MWh and selling at £50/MWh has the same percentage price change as buying at £100/MWh and selling at £200/MWh, but the latter will afford the storage operator greater absolute revenue than the former.

The spot price data suggests that the minimum percentage increase in price within any day of 2009 was 52%. This means that each and every day there was the opportunity to sell energy for at least 52% more than the buying price, *i.e.* there was a daily opportunity for a storage system that is more than 66% efficient = !"" %
(!!!.!" to) at least cover the cost of the round-trip energy efficiency losses of the storage system. Figure 46 also shows a few ‘super peaks’ above 400% increase, where there is a large relative increase in price; the maximum is greater than 1100%. The bulk of the increases are however concentrated in the 70% - 270% daily increase range.

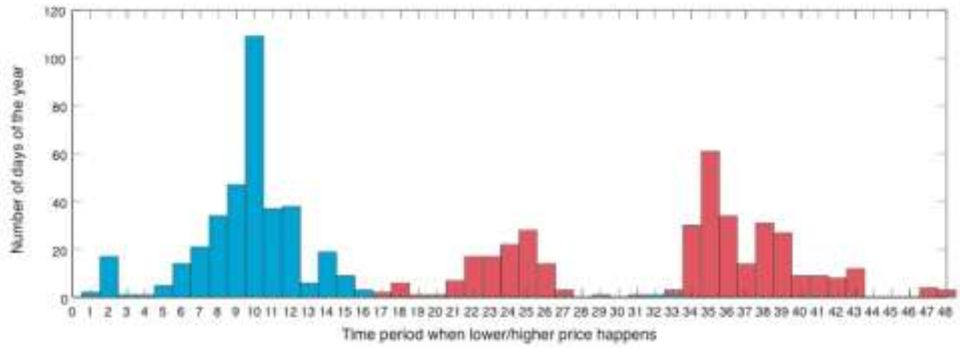


Figure 47 - 2009 UK market index price data: 30 minute time period within the day when the lower price happens (blue) and higher price happens (red), data from Elexon Portal.

Figure 47 is a histogram showing the 30-minute time-period within the day when the lowest and highest prices happened. It can be seen that the majority of the lowest price periods are between period 6 and period 15 (period 6 is between 02:30 - 03:00am and period 15 is between 07:00 - 07:30am). The highest price periods are split between two time values, one between periods 21 and 27 (10:00 – 13:30) and another between periods 34 and 43 (16:30 – 22:30). By visually comparing these results with the heat map (Figure 45) it is thought that the high prices centred on the evening generally happen in the winter, and the high prices centred on midday generally happen in the summer.

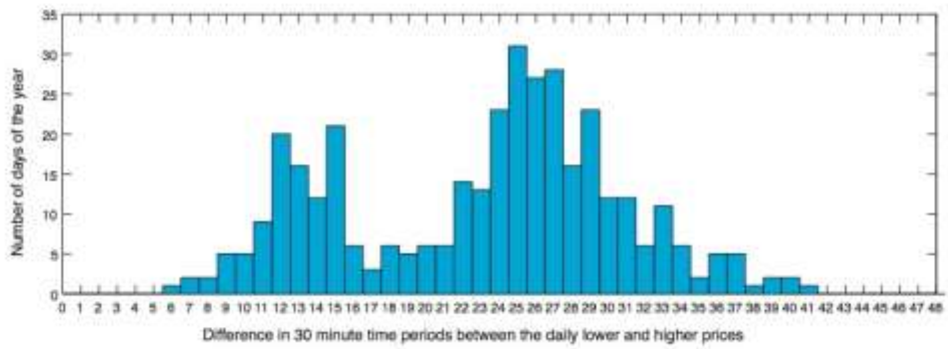


Figure 48 - 2009 UK spot price data – time difference in 30-minute time periods between the lower daily price and the higher daily price (from 00:00 to 24:00).

Figure 48 is a histogram of the time period difference between the time-dependent lowest and highest prices in 2009. This gives an indication of the length of time a storage operator would have to actually store the energy for (on a daily basis) between buying at the lowest price and selling at the highest price. This histogram shows two groups of storage time – one centred on 13 periods (6.5 hours) and another centred on 28 periods (14 hours). The two distinct groups are thought to reflect the summer and winter peak prices previously mentioned.

As interesting as these broad results are, they only reflect the lowest and highest price periods in a given day, *i.e.* they only reflect 2 out of the possible 48 prices available throughout a given day. They do not reflect the shoulder prices on either side of the lowest or highest prices, which are obviously important for bulk energy storage operators to maximise their revenue from arbitrage.

Investigation of the 2009 spot price data set suggests that in the UK market there existed the daily opportunity for a storage system of greater than 66% efficiency to cover the financial penalty from round-trip losses.

7.5 Model development and collaboration

The model was developed in collaboration with Edward Barbour from the University of Edinburgh who was undertaking a PhD at the Institute of Energy Systems considering the potential of storage to be linked to tidal generators. Over a 24-month period – the model was developed collaboratively, with several meetings and regular communication. The development was however a fairly on-off process due to the requirements of other priorities, with either party able to devote time to the development at particular points, and in particular areas. A few cul-de-sacs were explored but not progressed *e.g.* this author rewrote the code to take advantage of Fortran's ability to use subroutine calls, but this was eventually disregarded for ease of understanding. The code development was therefore developed in parallel at times – which led to differing variable names and differing methods to produce the same desired snippet of code. The advantages of this approach were deemed to outweigh the disadvantages, as there were several times when one approach seemed more elegant than another, and this would be chosen to take forward. At a later stage in the development a further PhD candidate Simon Gill at the Wind Energy DTC at the University of Strathclyde became involved in order to use the model as a tool to research the revenues available from the curtailment of wind in a particular distribution network. Eventually there were therefore several versions of the model that were coded to provide a different set of insights. The model validation and debugging process detailed in this work was undertaken solely by this author – as it was easier to control the development at this critical stage, rather than recode parts of the model through collaboration. The open nature of the development was challenging at times to coordinate, but enjoyable and productive due to idea sharing and collaboration.

This author views the idea of and development of the algorithm with 8 separate scenarios (the engine of the code) as a collaborative effort and joint ownership with Edward Barbour.

7.6 Review of existing optimisation methodologies for energy storage operation

Several studies have looked at optimising the schedule of operation of a storage device using different techniques to provide insights into differing areas of operation.

Maly & Kwan (1995) used multipass dynamic programming as a technique to investigate storage scheduling for battery based systems; the technique allowed for the non-linear equations governing the charging/discharging voltage and current .to be incorporated. The input prices were based on bi-period peak and off-peak price, or a tri-period price with a 'normal' price between peak and off-peak. The technique allowed internal losses and the non-linear terminal voltage to be accounted for; the internal losses were a function of the charge state of the battery.

Graves et al., (1999) used a linear optimisation algorithm to investigate the differences between several distinct power markets in the US over a number of years; they also sought to compare the revenue results of a storage device (20 MWh hours of 'inventory capacity', 1MW input and 75% round trip efficiency) between having access to hourly prices versus averaged prices of blocks of energy; the algorithm sought to maximise revenue within given constraints. Several interesting conclusions were derived from the results, including the increase in revenue derived by having access to hourly rather than averaged 'block' prices, and the variation in revenue between years *i.e.* the difference between years of the underlying variability of the spot prices. Also, the nature of the modelling technique suggested that there were charging price threshold below which the store should charge at full power, and above which the store should generate at full power. The optimisation ran over a two-week period (with the store starting and finishing at full capacity), and then combined with the following two week period; these were then aggregated to a year.

Korpaas et al. (2003) also used a dynamic programming algorithm to optimise storage in connection with wind generation over a day-ahead time period. The model included a separate power limit and efficiency for the input and output to the store. This method, like Maly & Kwan (1995), requires the discretisation of the storage level. The number of iterations is dependent on the product of the number of discrete timeframes in the optimisation timeframe window and the **square** of the number of discrete levels of the storage device. The method thus requires increasing iterations at longer windows of operation *e.g.* months to a year, and at increased granularity of the storage device state of charge levels.

Lu et al., (2004), looked at a weekly timeframes and used a multistage looping algorithm that sorted the discrete price into a week ahead composite curve. It then calculates the maximum amount of time the store can devote to charging and discharging and still return the store to full capacity by the end of the week. It then considers the price differential required to cover the round trip losses and breaks the composite curve into three price bands where it is always profitable to charge, always profitable to discharge, and the prices in-between where it is neither profitable to charge or discharge. The algorithm then calculates the optimal time associated with the charging given the constraints of maximum combined charging and discharging time and returning the store to full capacity. The composite curve was then broken into smaller composite curves if the store state of charge fell below zero, and the algorithm repeated for the smaller composite curve. These were then aggregated back into the weekly timeframe. The efficiency loss is only included as a variable on the charging side.

Mokrian & Stephen (2006) looked at the optimisation of storage over a 24-hour period, by comparing a linear, a dynamic and a multi-stage stochastic method of optimisation. The linear method presented was thought to give the upper boundary of the arbitrage revenue in order to compare other methods, but was also thought to be limited in terms of assessing the impact of non-perfect forecast prices. The linear method did allow for the inclusion of a self-discharge variable, although it was not clear how this was actually implemented. The dynamic method suffered from the problem of discretisation of possible state of charge levels not being accurate enough to accommodate the actual state of charge after efficiency losses were taken into account. The dynamic method was a trade off between the introduction of rounding errors and the increase of iterations due to a greater level of state of charge granularity. The stochastic approach allowed for the greater discretisation of the state of charge levels, but at a cost of a limited amount of decision stages *e.g*. every 8 or 6 hours rather than every hour or every half-hour. An interesting result was the significant variation alluded to by changing the time period when the 24-hour window of analysis started.

Figueiredo & Flynn (2006) looked at the costs as well as the revenue element of arbitrage, but used a fixed round-trip efficiency of 80% and a 'calculated' diurnal price pattern. These prices were from previous work and were averaged prices for individual time periods. Using 'averaged' prices is an over simplification when it comes to considering the revenue available to storage operators, as it will lead to an smoothing of the price variability and therefore an underestimation of the revenue available.

Walawalkar et al., (2007), is thought to have used a linear programming method to investigate the revenues available in the New York market using price data from 2001-2004. The binding constraints suggest that the stored energy is returned to its starting point every day. Costs are considered, and one of the main conclusions suggests that with this method the importance of increasing energy efficiency becomes clear.

Sioshansi et al., (2009) used a linear programming method that used optimization windows of consecutive two-weeks that were then aggregated to produce a yearly figure. A fifteenth day was added to the two-week window in order that the state of charge at the end of the 14^{th} day did not necessarily need to be the same as that at the start of the two week window (the fifteenth day data was then discarded and the next two-week window was then started). Round trip efficiency is accounted for on charging only, there is no self-discharge variable.

Youn & Cho (2009) also used a linear programming method to find the optimal solution to using storage alongside a distributed generator, which included a variable to account for the self discharge by accommodating this in an '*Effective Energy Price*', however, the technique was presented for 24 separate time periods of data, and it was unclear whether this technique could be used effectively with 17520 separate time periods of data.

Crampes & Moreaux (2010) looked at the Nash equilibrium of different market factors, but only considered this using an off-peak and peak price, rather than halfhourly price data. Urgaonkar et al. (2011) proposed using the technique of Lyapunov optimisation to optimise the use of an uninterruptable power supply to reduce the power costs of data centres.

Sioshansi et al., (2011) used a similar linear programming technique to their earlier work (Sioshansi et al., 2009), but now used a planning horizon of 8 days to optimise, rather than a planning horizon of 15 days. This 8-day ‘window’ allowed for a carry-over of stored energy (rather than the store starting and finishing the week with the same state of charge). The 8-day schedule was therefore cropped back to seven days, and the optimisation for the following 8-day planning horizon would start anew. The weekly optimisation schedules and revenues were then aggregated to produce annual data.

Connolly et al. (2011) used an algorithm to determine the maximum price in the year, and then searched for a timeframe around the maximum price to fill the storage device. It then finds the second highest price and repeats the process with limit checks for the device itself. Connolly’s method is capable of using long spot market price input data sets, but did not include a variable for self-discharge.

Solving this problem (the calculation of the upper boundary of revenue that a storage device could derive using price differentials within electrical spot market data) can therefore be approached with several different programming methods, with many researchers choosing to use a linear programming method. Due to the aim of this work to include a variable for self-discharge, the linear programming method was not used. Instead, a random walk method that used the asset of the high performance computing environment was preferred. The random walk approach also allowed the maximum revenue for long user-defined periods of interest (from days to years). The random walk approach trended towards a particular result, which was felt to represent the global optimum of the problem.

7.7 Model assumptions

During development of the model to calculate the upper boundary of the revenue available to the storage system the following assumptions were considered and accepted as part of the wider methodology:

1. **The storage device is a price taker and does not influence the overall spot market price.**

This is thought likely to be a good approximation for any individual gridconnected bulk storage device. However, if the overall level of rechargeable storage increased on the network, it is possible that cumulatively they could exert a smoothing effect on electrical spot prices, as bulk storage generally acts to create extra demand when prices are low, and provide supply when prices are higher. It is expected that greater levels of dispatchable bulk electrical storage could at some point begin to influence the price spread behind the arbitrage revenue stream; this is not thought likely to be an issue in the UK market in the short to medium term.

2. **The time taken to change the charging or discharging rate within the power limits of the storage device is not significant in terms of the spot price period of 30 minutes.**

The validity of this assumption depends on the device in question, but storage devices generally have high ramp rates that can change their output to their nameplate capacity within the 30-minute spot-price timeframe. Figure 49 shows actual data for the UK's four pumped storage schemes along with spot prices for the 6th and 7th of January 2011. (source: 5-minute grid data from Elexonportal.co.uk).

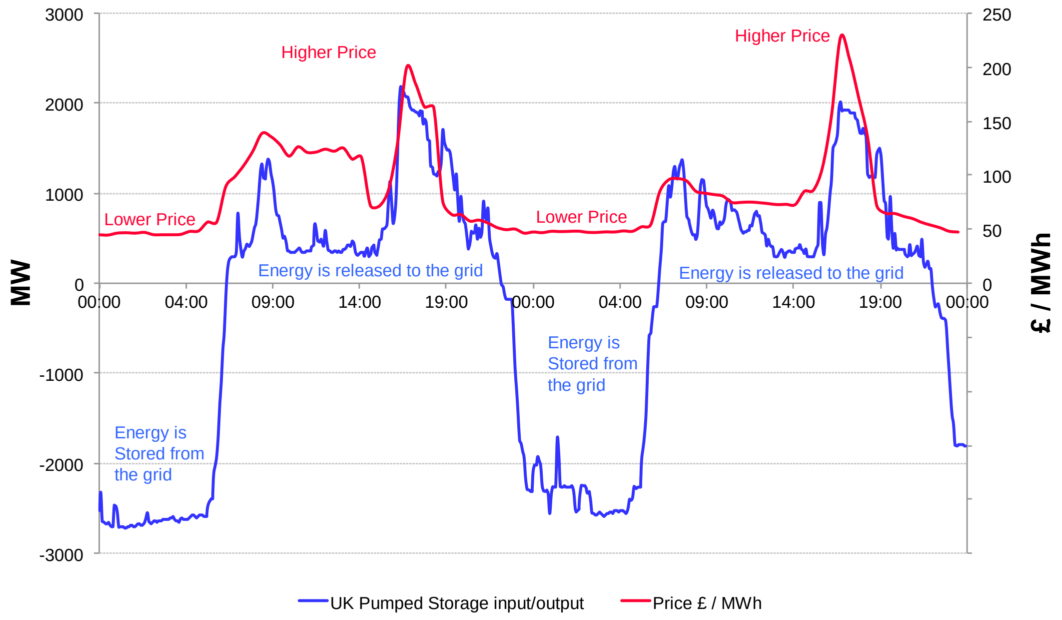


Figure 49 – UK Pumped storage operation and spot price. Data from elexonportal.co.uk

3. The storage device is not subject to network capacity constraints.

Any network constraint would reduce the ability of the storage device to operate – therefore reducing the potential revenue. The revenue of a constrained storage device would therefore be expected to be less than the upper boundary figure calculated for zero network constraints.

4. The storage device parameters are assumed to have constant values.

The assumption is that the charging/discharging efficiencies do not change with the charging rate, and the time constant describing the self-discharge remains constant in this model. The rate of charge or discharge does have a significant impact on the lifetime and the useable storage capacity and the round-trip efficiency of battery based storage devices. This additional level of complexity may be feasible with further enhancement of the model – but the assumption was thought to be valid for the initial model development. An interesting approach outlined in (Darling et al., 2011) regarding the evaluation of levelised costs based on distributions of assumed values may be a feasible approach for future work in order to get confidence intervals on the upper boundary estimation associated with uncertainty in device parameters.

5. Price forecasting

This work does not investigate the area of price forecasting, other than acknowledge that it is a large, complex and heavily researched field of work in its own right in both the public and private sphere. The book by Weron (2006) titled '*Modeling and Forecasting Electricity Loads and Prices: A Statistical Approach*' provides a comprehensive assessment of the complexity and number of techniques used in this area. The benefit of using publically available historical spot price data is described previously, and should allow other groups interested in this area to compare results.

7.8 Principles of the model

The model is based on the price differentials that are required to at least cover the financial penalty from round-trip energy losses implicit in any storage device. For example, if an energy storage device has a total round-trip efficiency of 50% then a sale price for electrical energy would need to be at least double the purchase price just to cover the energy lost from storing and releasing the electrical energy (the round-trip efficiency losses). This increase is calculated relative to the purchase price and therefore a doubling of the purchase price would equate to an increase of 100% relative to the purchase price.

The ability of any storage system to produce a positive revenue stream from the arbitrage of electrical energy will depend on the relative price variation of bought and sold electrical energy and the round-trip efficiency of the system (composed of both fixed and time-dependent efficiencies). This is true regardless of the separation in time between buying and selling. The algorithm, which is the engine within the model, is programmed to consider the price at two separate periods and also several efficiency losses that will reduce the amount of energy bought at the initial time period to be resold at the later time period.

The model is felt to be novel in that it is able to consider two different forms of efficiency losses: those that are time-dependent, and those that are not. The model calculates that there will be a fixed penalty for transferring energy into and out of the store, and once the energy has been transferred 'in store' there will also be a timedependent loss influenced by the amount of stored energy, as described by the exponential term in Equation (1). This time-dependent loss of energy attempts to model the self-discharge of a storage device.

In choosing to model this time dependent loss, it was decided to use an exponential decay rather than a linear decay. This was due mostly to the intrinsic property of an exponential decay that would naturally trend towards zero rather than the linear decay that could reduce the energy in the store below zero. A linear decay could be used, but would need an additional step to check whether the energy in the store became 'negative'. The exponential decay method was thought to be a more elegant solution, and was also thought to approximate the self-discharge losses experienced by thermal stores, by electrochemical stores and by mechanical stores (flywheels) better than a linear decay.

In simple terms, the energy output $\Delta E_!$ available from the store (at *time period* $t_!$), after an amount $\Delta E_!$ has been input to the store (at *time period* $t_!$) will be given by Equation (1) below.

$$\Delta E_! = \Delta E_! \eta_{!"\#\$\%\_!"\#\$} \left(\Delta t \right) = \Delta E_! \times \eta_{!"} \times \eta_{!"\#} \times exp^{\left(\frac{!_! ! !_!}{!}\right)} \quad (1)$$

In Equation (1), η_{in} is the fixed efficiency of the transfer of energy into the store (fixed charging efficiency), η_{out} is the fixed efficiency of the transfer of energy out of the store (fixed discharging efficiency), and the time-dependent self-discharge rate from the store is:

$$exp^{\left(\frac{!_! ! !_!}{!}\right)} \quad (2)$$

The combination of all 3 of these losses yields the round-trip efficiency of the storage process between $t_!$ and $t_!$, $\eta_{round\_trip}(\Delta t)$, where $\Delta t = t_! - t_!$.

Similarly, the energy input at $t_!$ changes the energy in the store at an intermediate period $t_!$ (where $t_! < t_! < t_!$) by an amount $\Delta E_!$, is given by Equation (3).

$$\Delta E_{!} = \Delta E_{!} \times \eta_{!"} \times exp\left(\frac{!_{!}\,!\,!_{!}}{!}\right) \quad (3)$$

If the price of electricity at $t_{!}$ is more than a factor of $\frac{!}{!\,!\,"\#\$\%\,\_!\,!\,"\#(\Delta !)}$ than the price at $t_{!}$, then buying energy at $t_{!}$ (to store) to then sell at $t_{!}$ will give a positive addition to the overall revenue available to the storage operator. This is the governing driver of the model; to establish whether a potential time-shifting of energy will indeed increase the overall revenue, after the fixed and time-dependent losses have been taken into account.

The simple flowchart shown in Figure 50 provides an overview of the operation of the model. The number 'n' in the diagram represents the iteration number, where total amount of iterations is user defined in the input variables to the model.

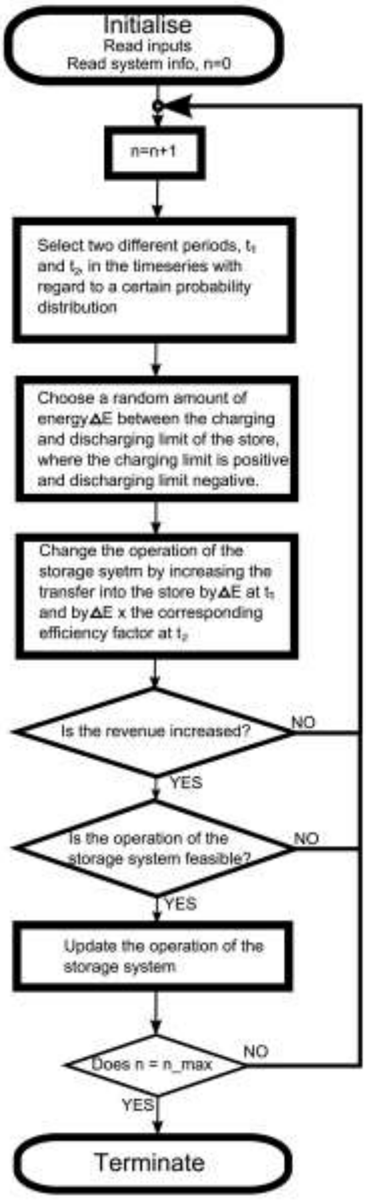


Figure 50 - Flowchart depicting the action of the model

7.9 Detailed description of the model

This section provides a detailed description of the random walk optimisation algorithm used to find the upper boundary of the revenue available from electrical energy arbitrage, and the schedule of operation to meet this upper boundary, of a storage device of specified characteristics. The algorithm runs an iterative procedure to randomly choose time periods to potentially move energy between; this is then evaluated to confirm whether the potential move would increase the overall revenue of the system. If it does, the move is accepted and another iteration of a potential move is started. If the potential move of energy however does not increase overall revenue, the move is discarded and another iteration of a potential move is started. The potential move is constrained by the characteristics of the storage system (efficiency, self-discharge, power limits, capacity) and also by the constraint that the energy contained within the store cannot be negative. Fortran90 was used as the programming language due to a large available resource of online information being available, which was very helpful in terms of syntax and problem solving.

In terms of the explanation in the previous section using variable names such as η_{in} , $t_!$ and $\Delta E_!$ that contain mathematical symbols, the variable names in Fortran had to use alphanumeric symbols only. Therefore η_{in} became `eta_in`, $t_!$ became `period_1` and $\Delta E_!$ became `dx(period_1)`. In this section, the typeface of courier font in light blue (`this_font`) denotes a variable name or snippet of code in Fortran. Coding was undertaken using the Aquamacs Emacs text editing environment.

7.9.1 Variables used in the Fortran code.

`period_1`	randomly selected period
`period_2`	randomly selected period
`eta_in`	fixed input transfer efficiency of the storage system
`eta_out`	fixed output transfer efficiency of the storage system
`tau`	storage time constant (provides time-dependent loss)
`dx`	a potential amount of energy to be moved
`n`	the counter for the iterations
`step_size`	the maximum limit of energy to be moved as `dx`
`numtrials`	the maximum number of iterations
`PLI`	Power Limit Into the store (kW)
`PLO`	Power Limit Out of the store (kW)
`ELI`	Energy Limit Into the store (kWh)
`ELO`	Energy Limit Out of the store (kWh)
`kwh_price(period_1)`	Spot market price at time `period_1` (p/kWh)
`Revenue(period_1)`	Revenue generated at time `period_1` from the sale of energy (pence)
`Cap_max`	the maximum capacity of the store (kWh)
`E_to_store(period_1)`	change in the state of charge at time `period_1`
`E_stored(period_1)`	the state of charge of the store at time `period_1`
`t(period_1)`	time (`period_1`)

Several other variables were used in the code – but these were for debugging and interim values and are not detailed above. The code is included in full in Appendix 6 – Model Code – Fortran.

It is felt that the random walk optimisation algorithm in effect searched the space of feasible solutions of the problem, and trended towards the global maximum. A feasible solution is defined as a schedule of operation of the storage system within the parameters set by the input variables, which could in principle be implemented - *i.e.* a solution would be technically realisable in the simplified model of a storage system and does not violate any of the parameters.

7.9.2 Model Inputs

The inputs to the model are:

- a time-series for the price of electricity over the optimisation period (denoted `kwh_price`)
- values for the efficiency of transferring energy into and out of the store, `eta_in` and `eta_out`
- a value for the maximum storage capacity of the device, `Cap_max`
- values for the storage charging and discharging power limits, `PLI` and `PLO`
- a value for the time constant of the store, tau (this can be directly converted into a self-discharge rate)
- a value for the maximum number of iterations, `numtrials`
- a value for the maximum amount of energy to be moved in one iteration, `step_size`

The outputs of the model include several arrays such as the energy moved into or out of the store after efficiency losses (`E_to_store)`, which provides the schedule of operation of the storage device; an array for providing the data for plotting, which includes the Output to the Grid (after efficiency losses) and Input from the Grid (before efficiency losses); and a single value for the total revenue yielded by the schedule of operation – the upper boundary of the revenue available from timeshifting energy. This upper boundary value is the scalar product of time-series `E_to_store`, and the `Output_to_grid`.

The format of the coding in Fortran follows a particular syntax, with the first part being devoted to the declaration of variables, the input of values for these variables and the initialisation of the arrays to be used. The middle part of the code is the engine of the model, which provides the random walk optimisation. The final part is the output of values to arrays once the random walk has reached the number of iterations set in the `numtrials` variable. Rather than detail the first and last parts of the code (as these are syntax and housekeeping issues and can be viewed in Appendix 6) the middle section only is described.

7.9.3 Operation of the algorithm

The following sequence describes the operation of the algorithm:

Firstly the algorithm chooses a random amount of energy to move into or out of the store (`dx`) limited by the `step_size` variable – equation (4). A positive `dx` corresponds to an increase in the energy stored (charging) and a negative `dx` corresponds to a decrease in the energy stored (discharging) at a particular period. `HARVEST` is a Fortran function to randomly generate a variable between 0 and 1. This step therefore allocates the `dx` variable a random value between plus and minus `step_size`.

```
dx = (step_size - ((HARVEST) * step_size * 2))
```
(4)

Two periods are then selected. Both are selected at random with reference to a variable called `window`. The `window` variable allows the algorithm only to consider the first `window` periods of the year *i.e.* if `window` is set to 192, then the algorithm will only consider the first 192 periods of the year = 4 days at 48 half hour time periods per day.

```
period_1 = NINT(1 + ((HARVEST) * (window-1)))
```
(5)

Equation (5) provides a random integer between 1 and `window` and assigns it to the variable `period_1`.

In the initial development of the code the second period was chosen with regard to a distribution around `period_1`. The distribution was influenced by a value chosen for a variable `nn_bias`, which was set by the user depending on the capacity of the device and the time-dependent loss rate of the store. It was thought that if there was a very high loss rate with time (a low figure for `tau`) then it would be unlikely that storing energy between two periods that were separated by long time periods would be helpful and therefore a value for `nn_bias` was set to provide `period_2` to be close to `period_1`.

The probability that a `period_2` was selected given `period_1` is described by equation (6). The parameter `nn_bias` therefore governed the width of the distribution.

```
prob_accept = EXP(-((period_1 - period_2)**2)/nn_bias)
```
(6)

The two time periods are then compared, and swapped if `period_2` was less than `period_1`.

However, in the latter stages of code development, this additional step of choosing a second random time period with reference to a probability around the first was not felt to outweigh the slight improvements in processing speed. It was therefore dropped in preference of a simpler method where the second period would be chosen using the same method as the first (as a random integer between 1 and `window`), and would be accepted if the `period_2` was less than `period_1` + `nn_bias`, equation (7).

```
IF(period_2<(period_1+nn_bias))THEN; accept=1;END IF
```
(7)

It is important to note that the change of energy `dx` is designed to be the change of energy **WITHIN** the store at `period_1` *i.e.* the **CHANGE OF THE STATE OF CHARGE** of the storage device. As an example, in order to charge the store with 10 units of energy at `period_1` with a fixed transfer efficiency in (`eta_in`) of 50%, the store requires to buy !______" !"#$% of energy = 20 units of energy from the

!"%

grid at `period_1`. Likewise, if the fixed export efficiency of the store (`eta_out`) was also 50%, then the store would only have $10\ units \times 50\% = 5\ units$ of energy at `period_2` to sell. The store would therefore have a fixed round-trip efficiency of !______!" ! !"#$%"#$% $= eta$!" $\times$ eta!"# $=50\%\times50\%=25\%$

At this point in the code the algorithm now has a positive or negative randomly selected amount of energy to move (`dx`) and two randomly selected periods to move the energy between (`period_1` and `period_2`).

As the periods relate to half hour blocks when using a UK data set, the absolute time between periods is half of the value of the difference between the value of the periods themselves *i.e.* if `period_1` = 1 and `period_2` = 11 then the actual time period between them would be 5 hours. Rather than using the algorithm to compute this for each determination of actual time (used to calculate the time-dependent loss in the store), it was decided to load an array into memory that can be called when required. This array is assigned the variable `t` so that `t(period_1)` when `period_1` = 10 has the array value of 5.

The time-dependent loss whilst the energy is within the store is given the variable `time_loss` and is described by equation (8)

```
time_loss = EXP((t(period_1)-t(period_2))/tau)
```
(8)

This time-dependent loss is modelled as an exponential decay. As `period_1` is always less than `period_2`, the expression `(t(period_1)-t(period_2))` is always negative. As `tau` is a user defined positive number, the result of equation (8) will always be between 0 and 1. If `tau` is a large number, there will be less decay per period, and for testing in Fortran without the ability to use an infinite value for `tau`, a value of `1E+30` was used.

`tau` is the timeframe over which the energy in the store is reduced to 1/e = 0.367879441 times its initial value, and can be thought of as an exponential time constant.

The round-trip efficiency of the store between two time periods `t(period_1)` and `t(period_2)` can be described by equation (9), where `Δt` = `(t(period_1)-t(period_2))`. This covers all the efficiency losses from the grid and back to the grid *e.g.* the amount of energy bought and subsequently sold.

$$\texttt{eta\_round\_trip}(\Delta t) = \texttt{eta\_in} \times \texttt{eta\_out} \times \texttt{time\_loss} \quad (9)$$

Overall, the inclusion of the novel `time_loss` variable added another layer of complexity in the model.

7.10 Algorithm scenarios

The model has so far been largely a matter of setting up arrays to represent the storage device, and choosing a random amount of energy to move between two randomly selected time periods in the time series. These activities can be thought of as simple procedures that prepare data to be compared in the middle section of the model.

The model then considers whether the proposed random amount of energy to move (`dx`) is positive (charging) or negative (discharging) at `period_1`, and also whether the net energy to/from the store at `E_to_store(period_1)` and `E_to_store(period_2)` is currently positive or negative or zero (*i.e.* net charge or net discharge or net zero charge/discharge). In other words, the algorithm considers whether the potential move aims to charge or discharge the store at `period_1`, and whether the existing flow of energy to/from the store is a net charge or net discharge or zero at the `period_1` and `period_2`. This results in 8 possible scenarios that determine the action of the algorithm.

This scenario choosing section of the model is the key to the implementation of the random walk to the optimal solution.

There were several rewrites and rethinks of this scenario choosing section of the model. For example, an early implementation of the code only accepted potential moves that increased the revenue by buying at `period_1` and selling at `period_2`, and the ability to buy earlier than `period_1` (at a later iteration) if this would increase revenue too. In this early implementation there were only two Scenarios for the code to choose from, but it did seem to trend towards an increased revenue amount with an increasing number of iterations. The yearlong historical price file was being used as an input, and as such there was no computable answer to compare the model's output against. However, the results were incorrect, which became apparent when the model was validated with price input files based upon square and saw tooth waves where an answer could be calculated beforehand.

In the initial stages of algorithm development the result trended to the wrong answer. Furthermore, there were several points during the development when it was unclear whether the style of algorithm and choice of mathematical method would actually prove fruitful in finding a non-deterministic solution to the problem. The key to overcoming these problems was the use of several other scenarios to allow for different `E_to_store` `period_1` and `period_2` conditions to be catered for. Ultimately, this block of 8 different scenarios is the engine behind the algorithm, which uses the brute force processing power of the high performance computing environment to trend towards a solution.

All of the Scenarios are subject to the modelled storage device limits, where the randomly selected block of energy to move is reduced to the limit set by the capacity of the storage device, or the power limits in to or out of the store. In order to compare these different limits that happen before or after certain efficiency losses, it was helpful to use the state of charge of the storage device at `period_1` to be the reference viewpoint for any efficiency losses. Any movement of energy (`dx`) is therefore the move of energy as seen from the perspective of the storage device at `period_1` *i.e.* it is the change of state of charge of the storage device at `period_1` (if the move is accepted). The amount of energy required from the grid to change the state of charge of the storage device by `dx` at `period_1` is subject to the fixed input transfer efficiency of the storage system eta_in. Equally energy out of the store will be subject to the fixed output transfer efficiency of the storage system eta_out, and the time_loss between period_1 and period_2 as the time_loss will reduce the amount of energy available to be discharged at period_2. Energy discharged to the grid at period_2 is therefore the multiplication of eta_out, time_loss and dx.

This is represented in Figure 51, which shows the fixed efficiencies losses only (no time-dependent losses and no period_1 or period_2).

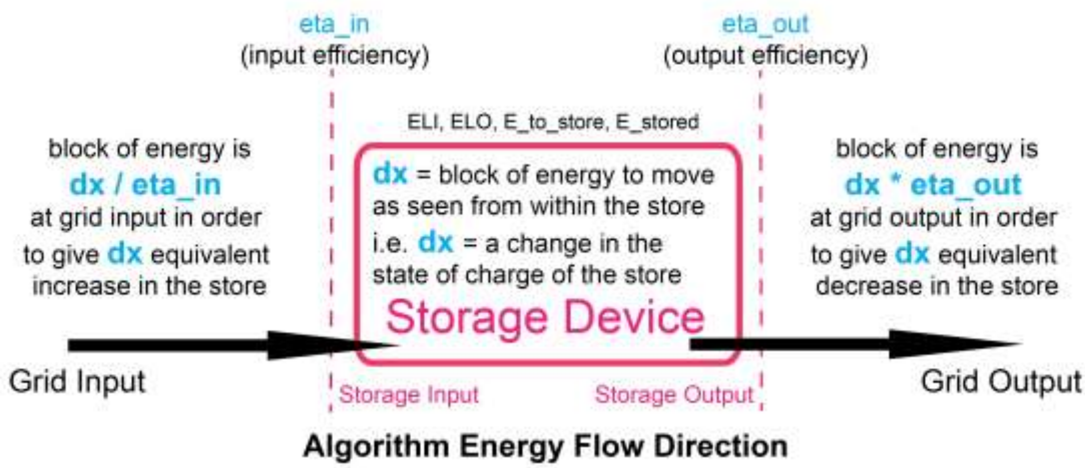


Figure 51 – Fixed efficiency diagram showing relation of dx to grid input/output.

The algorithm is programmed to detect firstly whether the randomly selected block of energy to potentially move (dx) is positive, corresponding to an increase in the E_to_store at period_1, or negative, corresponding to a decrease in the E_to_store at period_1. The first four Scenarios (1,2,3,4) are for a dx that is positive, and the last four Scenarios (5,6,7,8) are for a dx that is negative.

dx has a positive value when the net energy flows to the store at period_1 would be increased and a negative value when net energy flows to the store at period_1 would be decreased, this is similar to the sign protocol for E_to_store.

When E_to_store has a **positive** value it represents a flow of energy **into** the store at that period *i.e.* the store is being charged. Whereas when E_to_store has a **negative** value it represents a flow of energy **out** of the store at that period *i.e.* the store is being discharged.

For dx > 0 (a potential **increase** in the E_to_store at period_1 and **decrease** in the E_to_store at period_2))

Scenario 1 is chosen when the current values of:

E_to_store(period_1)≥0 AND E_to_store(period_2)>0

E_to_store(period_1) has a positive or zero value

E_to_store(period_2) has a positive value.

This means that currently there is energy flowing (or no energy flowing) **into** the store at period_1 and there is also energy flowing **into** the store at period_2. If the potential move is accepted, it means an **increase** in the net energy flow **in** at period_1 and also a **reduction** in the net energy flow **in** at period_2. If the potential move is accepted this effectively moves the storage of energy forward in time to capture a better price differential, which can also free up space for further iterations.

Scenario 2 is chosen when the current values of:

E_to_store(period_1)≥0 AND E_to_store(period_2)≤0

E_to_store(period_1) has a positive or zero value

E_to_store(period_2) has a negative or zero value.

This is the first Scenario that the algorithm will accept as all values of E_to_store are set to zero in an earlier part of the code to reset the system variables.

This means that currently there is energy flowing (or no energy flowing) **into** the store at period_1 and there is energy flowing (or no energy flowing) **out** of the store at period_2. If the potential move is accepted, it means an **increase** in the net energy flow **in** at `period_1` and also an **increase** in the net energy flow **out** at `period_2`. This Scenario 2 is the most understandable Scenario, as it basically moves energy into the store at `period_1` in order to release the energy at `period_2`. When the algorithm starts with no energy stored, Scenario 2 has to be be the first type of move accepted.

Scenario 3 is chosen when the current values of:

`E_to_store(period_1)<0 AND E_to_store(period_2)>0`

`E_to_store(period_1)` has a negative value

`E_to_store(period_2)` has a positive value.

This means that currently there is energy flowing **out** of the store at `period_1` and there is energy flowing **into** the store at `period_2`. If the potential move is accepted, it means a greater net energy flow **out of the store** at `period_1` and also a decrease in the net energy flow **in** at `period_2`.

Scenario 4 is chosen when the current values of:

`E_to_store(period_1)<0 AND E_to_store(period_2)≤0`

`E_to_store(period_1)` has a negative value

`E_to_store(period_2)` has a negative or zero value.

This means that currently there is energy flowing **out** of the store at `period_1` and there is energy flowing (or no energy flowing) **out** of the store at `period_2`. If the potential move is accepted, it means a **reduction** in the net energy flow **out** of the store at `period_1` and also an **increase** in the net energy flow **out** at `period_2.`

The above Scenarios 1,2,3 and 4 are all for a potential movement of energy that **increases** the net flow of energy **into** the store at `period_1` (or **decreases** the net flow of energy **out** of the store at `period_1`).

In contrast, Scenarios 5,6,7, and 8 are all for a potential movement of energy that **decreases** the net flow of energy **into** the store at `period_1` (or **increases** the net flow of energy **out** the store at `period_1`).

`For dx < 0` (a potential **decrease** in the `E_to_store` at `period_1` and **increase** in the `E_to_store` at `period_2`)

Scenario 5 is chosen when the current values of:

`E_to_store(period_1)>0 AND E_to_store(period_2)≥0`

`E_to_store(period_1)` has a positive value

`E_to_store(period_2)` has a positive or zero value.

This means that currently there is energy flowing **into** the store at `period_1` and there is energy flowing (or no energy flowing) **into** the store at `period_2`. If the potential move is accepted, it means a **reduction** in the net energy flow **into** the store at `period_1` and also an **increase** in the net energy flow **into** the store at `period_2.`

Scenario 6 is chosen when the current values of:

`E_to_store(period_1) > 0 AND E_to_store(period_2) < 0.`

`E_to_store(period_1)` has a positive value

`E_to_store(period_2)` has a negative value.

This means that currently there is energy flowing **into** the store at `period_1` and there is energy flowing **out** of the store at `period_2`. If the potential move is accepted, it means a **reduction** in the net energy flow **into** the store at `period_1` and also a **reduction** in the net energy flow **out** of the store at `period_2.`

Scenario 7 is chosen when the current values of:

`E_to_store(period_1)≤0 AND E_to_store(period_2)≥0`

`E_to_store(period_1)` has a negative or zero value

`E_to_store(period_2)` has a positive or zero value.

This means that currently there is energy flowing (or no energy flowing) **out** of the store at `period_1` and there is energy flowing (or no energy flowing) **into** the store at `period_2`. If the potential move is accepted, it means an **increase** in the net energy flow **out** of the store at `period_1` and also an **increase** in the net energy flow **into** the store at `period_2`.

Scenario 8 is chosen when the current values of:

`E_to_store(period_1)≤0 AND E_to_store(period_2)<0`

`E_to_store(period_1)` has a negative or zero value

`E_to_store(period_2)` has a negative value.

This means that currently there is energy flowing (or no energy flowing) **out** of the store at `period_1` and there is energy flowing **out** of the store at `period_2`. If the potential move is accepted, it means an **increase** in the net energy flow **out** of the store at `period_1` and also a **decrease** in the net energy flow **out** the store at `period_2`.

Any value of `dx=0` implies no action is taken as there is no potential move of energy.

Once the algorithm has chosen a Scenario dependent on the existing flows of energy at `period_1` and `period_2` and the sign of the potential move `dx,` it proceeds to check the maximum amount of energy that could be moved against several technical limits of the storage device and grid connection set by the user. The snippet of code for Scenario 2 is shown in Figure 52 where it can be seen that the remaining energy limit into (`dx1`) and remaining energy limit out of (`dx2`) the store is calculated, as is the remaining power available to or from the grid (`dx2`, `dx4`). All these are effectively values of power, *i.e.* energy transfer over a single 30 minute period.

```
!scenario 2
        IF(E_to_store(period_1)>=0 .AND. E_to_store(period_2)<=0) THEN
            scenario=2
            dx1 = (ELI-E_to_store(period_1))                                          !storage limit in
            dx2 = (E_to_store(period_2)-ELO)/time_loss                                !storage limit out
            dx3 = (grid_constraint(period_1)+Output_to_grid(period_1))*eta_in         !grid limit in
            dx4 = (grid_constraint(period_2)-Output_to_grid(period_2))/(eta_out*time_loss) !grid limit out
            dx = MIN (dx, dx1, dx2, dx3, dx4)
        END IF
```

Figure 52 – Scenario 2 code snippet

The limits are all checked from the reference point of `dx`, which is at `period_1` for reference for any time-dependent losses, and inside the store for reference for the standard input and output efficiency losses.

However, the variable `Output_to_grid` is from the reference point of the grid connection **rather** than a reference point inside the store similar to `dx`. This means that `dx` and `Output_to_grid` should always be of opposite signs and differ by the relevant efficiency losses. `Output_to_grid(period_x)` is what is actually bought from or sold back to the grid (depending on the sign) at `period_x`.

The snippet of code for every scenario is conceptually similar to the snippet for Scenario 2 in Figure 52 but differ in terms of the signs and inclusion of certain variables. Each snippet is designed to find the limiting factor between the random amount of energy to be moved (`dx`) and the condition of the grid and store power limits at `period_1` and `period_2`. At the end of the snippet of code `dx` is changed to the limiting factor in order that these technical limits are not subsequently breached. After the limiting factor has been calculated Scenarios 1,2,3,4 should all end up with a `dx` that still has a positive value, and Scenarios 5,6,7,8 should all end up with a `dx` that still has a zero or negative value.

The next step is to check that the state of charge of the store does not exceed the maximum storage capacity or fall below zero in the time period between `period_1 and period_2` = `t(period_1)≤t<t(period_2)`, and as Scenarios 1,2,3,4 all have the same sign of `dx` (similarly but with an opposite sign to Scenarios 5,6,7,8) the state of charge calculation happens at the end of each section rather than individually as part of each Scenario. The code snippet calculation for

Scenarios 1,2,3,4 is shown in Figure 53, and as before, the aim is to find the limiting value. In this case this would be the remaining space in the store at any `period_x` between `period_1` and `period_2` after time-dependent losses have been accounted for.

```
!This section checks the available space for moving energy between periods 1 and 2
            i_temp = MAXLOC(E_stored(period_1:(period_2-1)), DIM=1)
            i_temp2 = period_1+i_temp-1

            time_loss_3 = EXP((time(period_1)-time(i_temp2))/tau)
            m2 = Cap_max - MAXVAL(E_stored(period_1:(period_2 - 1)))
            dx5 = (m2/time_loss_3)

            IF(dx5<0) THEN
            dx5 = 0
            END IF

            dx = MIN(dx, dx5)
            IF (dx < 0) THEN; dx=0; ENDIF
```

Figure 53 – State of Charge limit code snippet.

As initially the store is empty (no net energy flows) = `E_to_store` = 0 for all time periods, the first move has to be made under Scenario 2. A move will be accepted provided that there is a price increase that covers the round-trip losses between `period_1` and `period_2`. After this first move there will now be energy flows at `period_1` and `period_2`, and energy stored in the device between the periods. This then allows other potential Scenarios to be chosen, other than just those of Scenario 2.

In this manner, the algorithm moves random blocks of energy into and out of the store (within limits specified by the user) and checks whether these potential moves would increase the revenue. It is a brute force non-deterministic approach that is able to handle the added complexity of a time-dependent loss variable.

Scenario 2 effectively represents a straight forward charging and discharging of energy, while the Scenarios can essentially be regarded as enhancements for suboptimal moves *e.g.* a move under Scenario 1 effectively moves a block of energy backwards in time by buying the energy at an earlier time, in order to capture a greater price differential than a Scenario 2 move previously made. However, this scenario can only arise after a Scenario 2 move has already provided a net energy flow into the store at the new iteration's `period_2`.

If a potential move increases the overall revenue, then the model accepts the move and updates the charging/discharging schedule (the `Output_to_grid` array), as well as the state of charge of the store between the periods.

The total revenue achieved over the time period in question is the sum of the array

$R(t), \sum_{!!!"\#!!"\#\$"} R(t)$ where $R(t) = kWh\_price(t) \times Output\_to\_grid(t)$ (10)

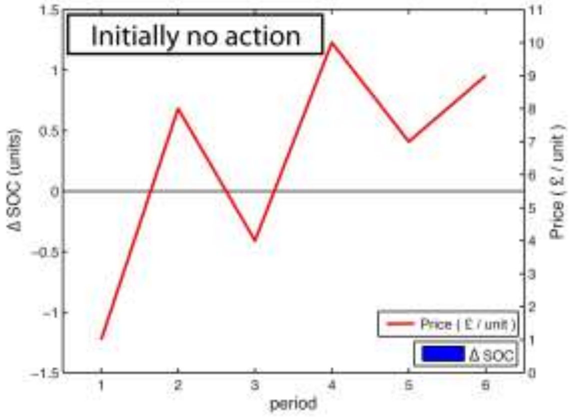
The model repeats these steps with each iteration until the user-defined number of iterations is reached (`numtrials`). Every time the model considers a potential move (whether it is accepted or not) it counts as an iteration and the counter, `n`, is incremented by 1. The optimisation procedure is ended once `n=numtrials`. For many of the runs undertaken to compare various changes to the inputs, a value of 1 billion iterations was chosen.

Once the algorithm reaches the number of iterations, the model then outputs the Fortran arrays in the computer's memory to various files to allow for plotting and comparison.

7.11 Simple example of model iterations

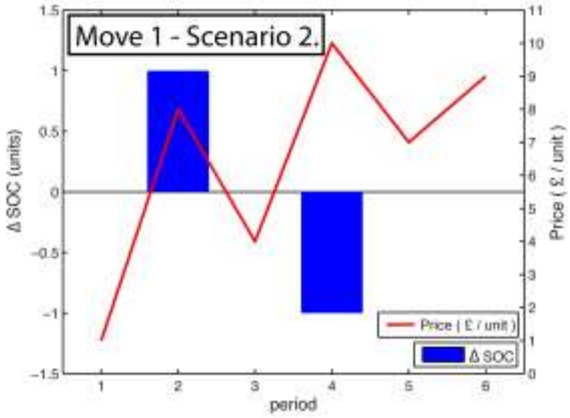
The diagrams in this section show an illustrative sequence of how the model finds the optimum solution for a 6 period time-series and a simple store.

The storage capacity is set at 3 units, the charging and discharging power limits into and out of the store are 1 unit per period and to keep things simple, there are no losses; `tau=infinity`, and, `eta_in = eta_out = 100%`. At the start there is no action of the storage system so the schedule of operation is initially flat (state of charge=0 at every period). The diagrams show a possible path the algorithm could take to the optimum result, with the blue rectangles representing the change in the state of charge (ΔSOC=`dx`) and the red line representing the price. It should be noted that even though the price is shown as a continuous line, it is really a stepped function where the price at the start of the integer time period describes the price until the beginning of the next integer time period.



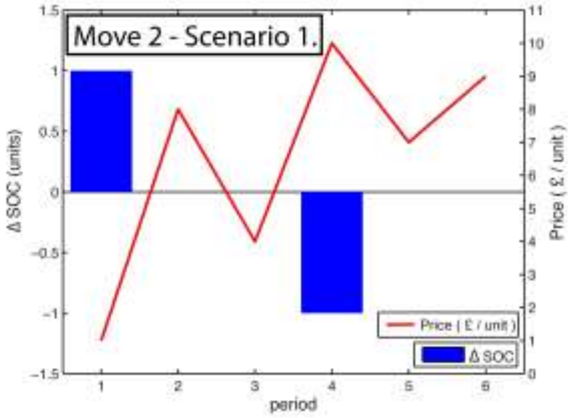
No action. Red line is the price line shown as a continuous line, even though it is discrete. Price at time period 1 (TP1) is £1

TP(1-6) = 1, 8, 4, 10, 7, 9 all in £s



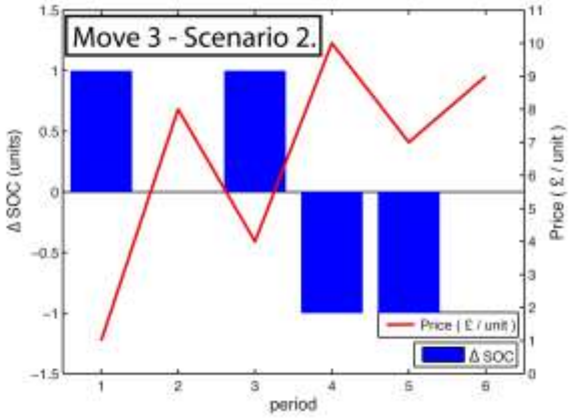
The first move charges at TP2 and discharges at TP4, which costs £8 at TP2 and raises £10 at TP4, therefore increasing the total revenue by £2.

Scenario 2 move.



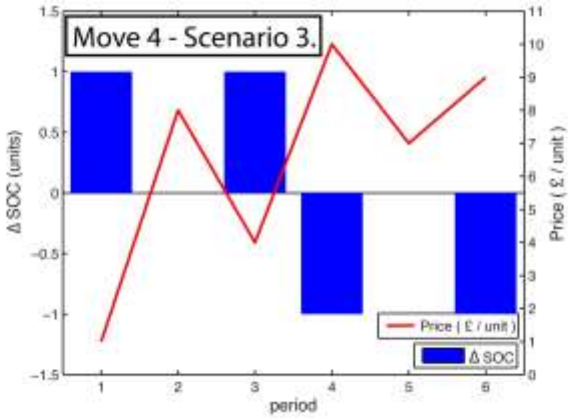
The second move charges at TP1 instead of at TP2, as charging at TP1 costs £1, rather than £8 at TP2. The energy is still sold at TP4, still raising £10. The total revenue is therefore increased by £7 over the previous move.

Scenario 1 move.



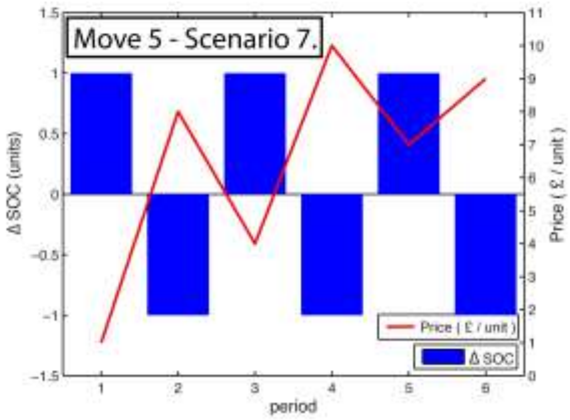
The third move charges at TP3 and discharges at TP5. It increases the total revenue by £3.

Scenario 2 move.



The fourth move increases the total revenue by £2, as discharging at TP6 generates more revenue than discharging at TP5.

Scenario 3 move.



The last move (move 5) realises that there is energy stored at TP2, which could be discharged and recharged at a lower price at TP5. This move is only allowed, as the energy discharged at TP2 is not required until after the store has been re-charged at TP5. Scenario 7 move.

Figure 54 – Algorithm moves and scenarios

The schedule after move 5 is the optimum schedule of operation of the storage device with PLI = PLO = 1unit/period over the price time-series given. There are no more moves of dx that could increase the revenue, and only this schedule of operation will generate total revenue of £15. However, even though this may be the upper boundary, this is only one of many paths to the optimum solution.

7.12 Price files to validate the model

The algorithm was tested using a series of different price files chosen with increasing complexity that are described in this section. The window was set to 336 half-hour periods (seven days) for validation and debugging. The file system used in launching the algorithm required a unique filename for each price series, and in order to allow for future flexibility in comparing different geographical markets, the price files were located in a folder named after the particular market.

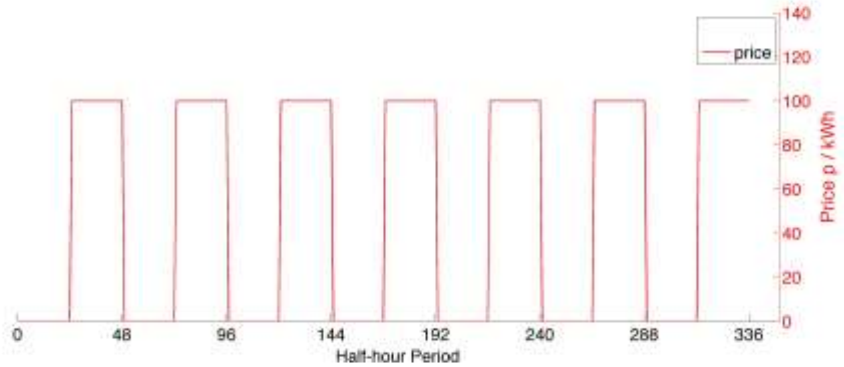


Figure 55 - Test price file `1900_cleaned_UK_crlf.txt` - Square wave 0 -> 100

The first test price file was a square wave with a 48 period cycle, a lower price of 0p/kWh and a higher price of 100p/kWh. It was named `1900_cleaned_UK_crlf.txt` and is shown in Figure 55.

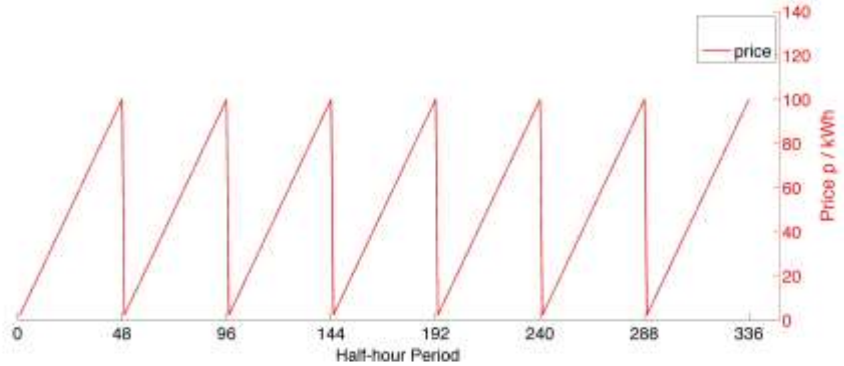


Figure 56 - Test price file `1901_cleaned_UK_crlf.txt` - Saw wave 0 -> 100

The second test price file was a saw wave with a 48 period cycle, a lower price of

0p/kWh and a higher price of 100p/kWh. It was named `1901_cleaned_UK_crlf.txt` and is shown in Figure 56.

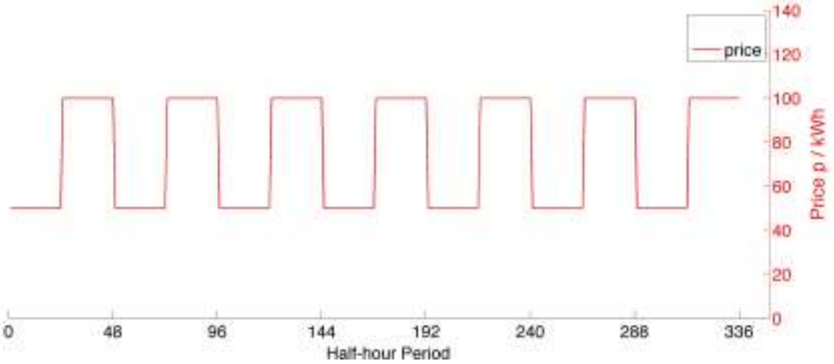


Figure 57 - Test price file `1902_cleaned_UK_crlf.txt` Square wave 50 -> 100

The third test price file was a square wave with a 48 period cycle, a lower price of 50p/kWh and a higher price of 100p/kWh. It was named `1902_cleaned_UK_crlf.txt` and is shown in Figure 57.

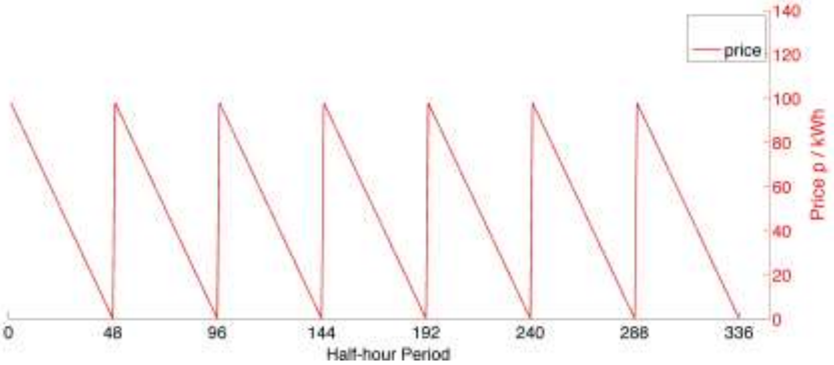


Figure 58 - Test price file `1903_cleaned_UK_crlf.txt` Saw wave 100 -> 0

The fourth test price file was a reverse saw wave with a 48 period cycle, a higher price of 100p/kWh and a lower price of 50p/kWh. It was named `1903_cleaned_UK_crlf.txt` and is shown in Figure 58. This was similar to the previous saw wave but now has a decreasing price slope rather than an increasing price slope.

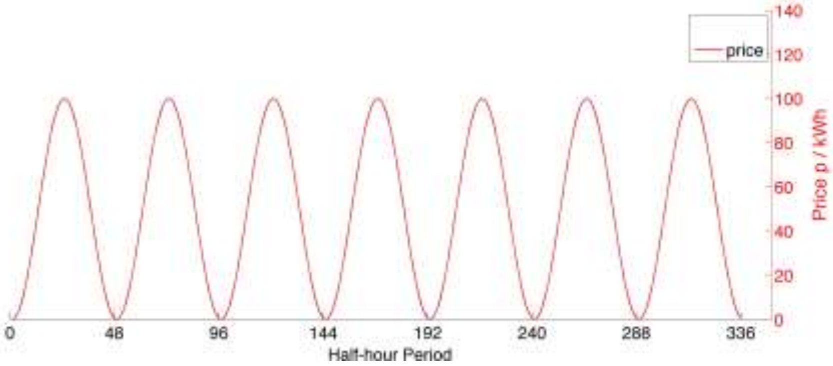


Figure 59 - Test price file `1904_cleaned_UK_crlf.txt` Sine wave 0 -> 100

The fifth test price file was a sine wave with a 48 period cycle, a lower price of 0p/kWh and a higher price of 100p/kWh. It was named `1904_cleaned_UK_crlf.txt` and is shown in Figure 59.

The following Figures show the values of the historical price data on the same scale and axis (other than Figure 63 and Figure 64) as the test price files for comparison *i.e.* the first seven days or 336 half-hourly periods of a particular year. Although these Figures show only a small part of the entire year the variation between different years can be clearly seen.

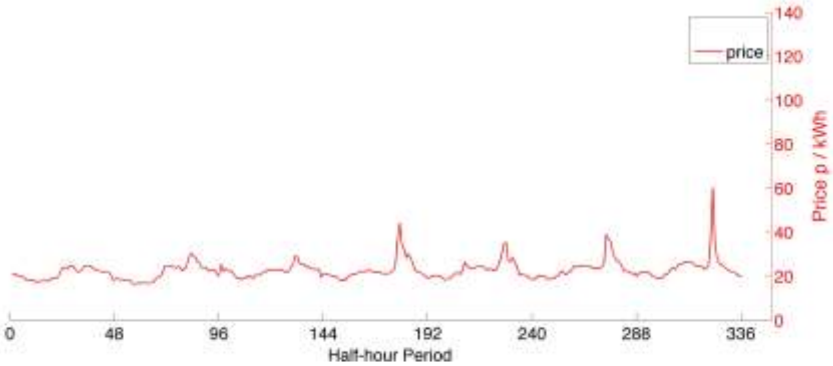


Figure 60 - UK historical price file `2005_cleaned_UK_crlf.txt` – showing the first seven days of 2005

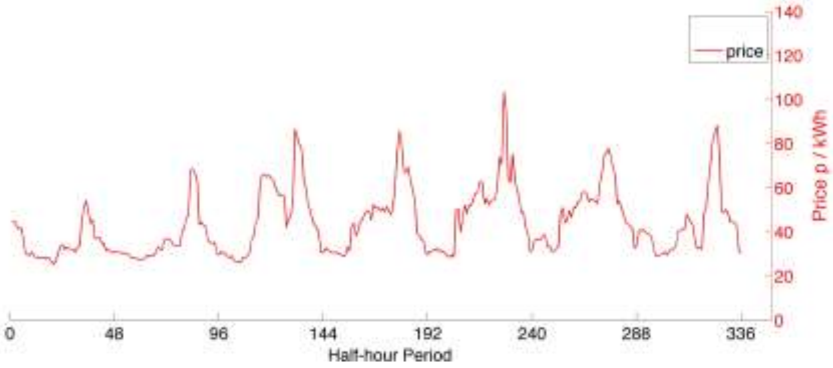


Figure 61 - UK historical price file `2006_cleaned_UK_crlf.txt` – showing the first seven days of 2006

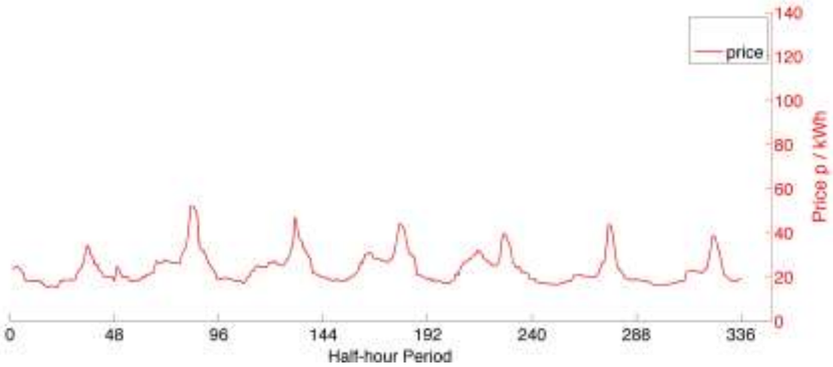


Figure 62 - UK historical price file `2007_cleaned_UK_crlf.txt` – showing the first seven days of 2007

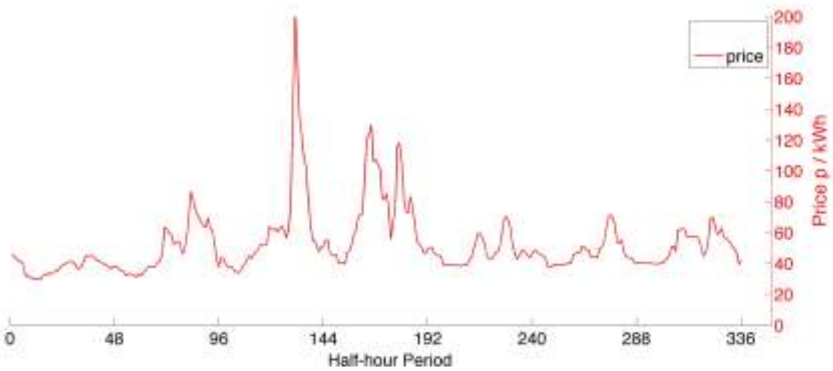


Figure 63 - UK historical price file `2008_cleaned_UK_crlf.txt` – showing the first seven days of 2008 (y axis is greater than other price file values)

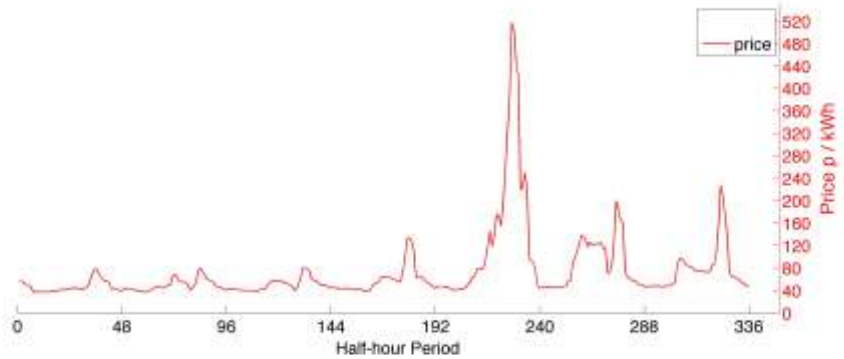


Figure 64 - UK historical price file `2009_cleaned_UK_crlf.txt` – showing the first seven days of 2009 (y axis is greater than other price file values)

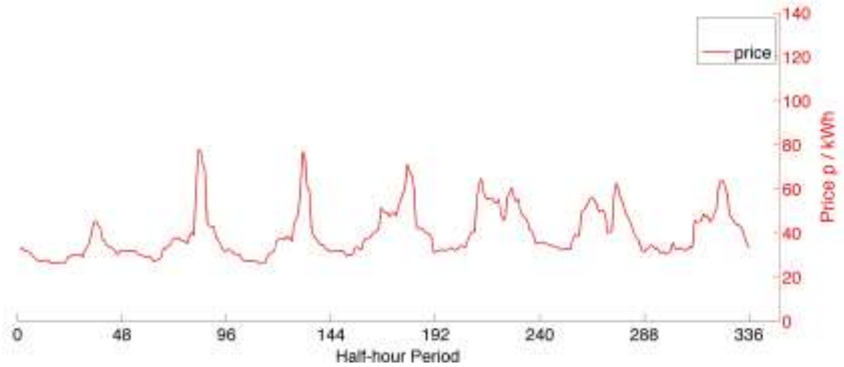


Figure 65 - UK historical price file `2010_cleaned_UK_crlf.txt` – showing the first seven days of 2010

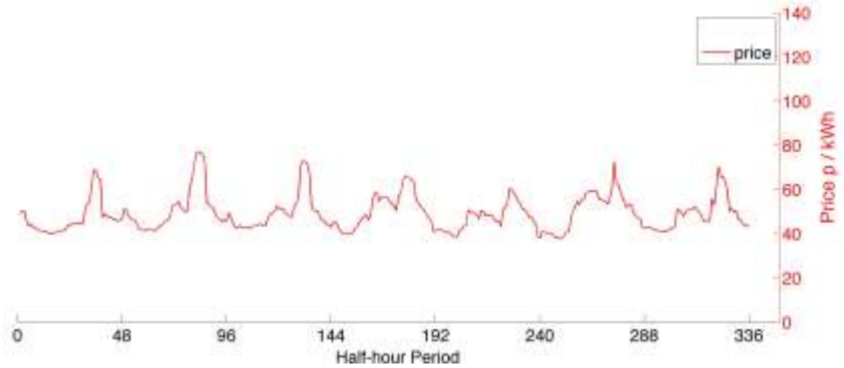


Figure 66 - UK historical price file `2011_cleaned_UK_crlf.txt` – showing the first seven days of 2011

7.13 Typical debugging process

The debugging process of the algorithm was intricate, laborious and involved the investigation of the increasingly complex test price files to determine whether the code was behaving. A typical debugging process is explained in this section.

In the debugging phase, many lines of code and extra file outputs were warranted to be able to dig into each iteration that was accepted *i.e.* not every iteration was analysed – only the iterations that actually led to the `Energy_to_store` being changed. This debugging framework written around the algorithm allowed for posthoc interrogation of the steps the algorithm was taking along the random path.

One major problem with the algorithm was found to be due to the assessment and setting of the `dx` limits, especially when the sign of the `dx` eventually chosen differed from the sign of the `dx` expected by the code. A set of `flag` variables were introduced that noted the iteration when the sign of the accepted `dx` differed with the sign of `dx` expected. The code was found to behave when the sign of `dx` corresponded with the expected sign of `dx`. If a problem with the `dx` sign arose, this seemed to propagate into `dx` sign problems in further iterations, so if one `dx` problem appeared it was likely that further `dx` problems would appear. It was therefore imperative to find solutions to **all** `dx` sign problems.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	eta_in	eta_out	Cap_max	PLI	PLO	tau	numtrials	step_size	nn_bias	market	year	upper_boundary_in_pounds	flag1	flag2	flag3	flag4	flag5	flag6	flag7	flag8	flags_total
2	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1900	399.9999	0	0	0	0	0	0	0	0	0
3	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1900	120.0001	0	0	0	0	0	0	0	0	0
4	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1900	399.9995	0	0	0	0	0	0	0	0	0
5	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1901	383.3275	0	0	0	0	0	0	0	0	0
6	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1901	106.1406	0	0	0	0	0	0	0	0	0
7	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1901	289.0383	0	5	0	0	0	0	0	0	5
8	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1902	200	0	0	0	0	0	0	0	0	0
9	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1902	0.00E+00	0	0	0	0	0	0	0	0	0
10	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1902	0.00E+00	0	0	0	0	0	0	0	0	0
11	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1903	287.4892	0	0	0	0	0	0	0	0	0
12	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1903	84.05562	0	0	0	0	0	0	0	0	0
13	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1903	287.8769	25	2	0	0	0	0	0	0	27
14	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1904	398.272	0	0	0	0	0	0	0	0	0
15	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1904	118.8484	0	0	0	0	0	0	0	1	1
16	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1904	381.1857	4	1	0	0	1	0	0	0	6

Figure 67 - master_output.txt file (copied from excel workbook)

Figure 67 shows the output of a debugging run of different inputs (`eta_in`, `eta_out`, and test price files). The columns named '`flag#`' show the number of times that a sign problem with `dx` was flagged (out of the total iterations of 10,000,000), and which scenario it related to *e.g.* with `flag1` representing `scenario1` problems, *etc*. From this set of runs it can be seen that run13 (corresponding to row13 in the spreadsheet in Figure 67) has been flagged 25 times in `scenario1` and 2 times in `scenario2`.

In order to debug, the `all_dx.txt` file was chosen from run15 of Figure 67 as it only had one instance of a `dx` problem (in `scenario8`).

The `all_dx.txt` file is a potentially large file and only used for debugging (it is deactivated on normal runs). It contains the values of many variables for all iterations that are accepted *i.e.* all the moves on the pathway to the final solution of the run. The `all_dx.txt` file has the following variables: `n` (the iteration number), `accept` (the state of acceptance of the iteration, which should always be 1 in this file), `period_1` (the first randomly selected period), `period_2` (the second randomly selected period), `scenario` (the scenario selected by the algorithm), `dx`, `dx1`, `dx2`, `dx3`, `dx4` (all the limits calculated by the algorithm for a given scenario), `Old_OTG1` (the existing value for the Output to grid at period_1), `Old_OTG2` (the existing value for the Output to grid at period_2), `New_OTG_1` (the new value for the Output to grid at period_1), `New_OTG_2` (the new value for the Output to grid at period_2), `Old_ETS1` (the old value for the Energy to store at period_1), `Old_ETS2` (the old value for the Energy to store at period_2), `ETS1` (the new value for the Energy to store at period_1), ETS2 (the new value for the Energy to store at period_2), Rev2-Rev1 (the change in revenue between the old situation and the new situation – should always be +ve), GC1, GC2 (the grid constraints at time periods 1 and 2), flag1, flag2, flag3, flag4, flag5, flag6, flag7, flag8 (all the flags), flag_total (the total of all the flags).

Figure 68 displays the initial part of an all_dx.txt file once the all_dx.txt file was imported into a spreadsheet. It was found that the 'filter' functionality of the program excel was very helpful in finding the iterations where the dx problems occurred.

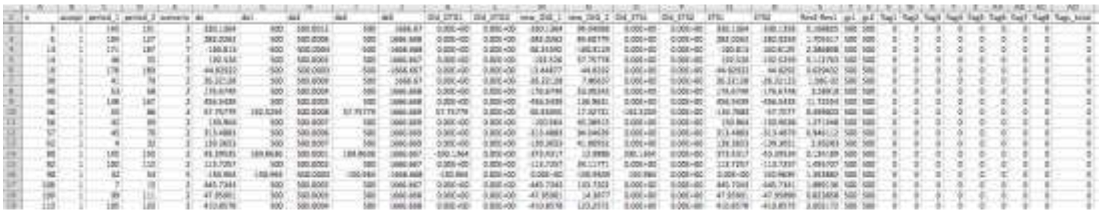


Figure 68 – initial part all_dx.txt file (copied from excel workbook)

The all_dx.txt file for run15 showed that the dx problem was flagged at iteration number 188063. On investigation of the variable values in this iteration it was found that the value for dx4 was greater than zero (when expected to be less than zero) and caused the problem with the sign of dx eventually chosen to be greater than zero (from the maximum of dx, dx1, dx2, dx3 and dx4).

dx4 is itself calculated from the snippet of code:

```
dx4 = -(Old_OTG2)/(eta_out*time_loss)
```

Where the sign of dx will be positive if the Old_OTG2 is less than zero. In this instance the value was -0.0087907054. Using the excel 'find' function, the erroneous amount was traced back to have occurred in iteration 186952, where it was in the New_OTG_2 column. Iteration 186952 was a scenario4 iteration, where the value assigned to New_OTG_2 comes from the snippet of code

```
New_OTG_2=Old_OTG2+(dx*time_loss*eta_out)
```

Using the filter function in the excel spreadsheet again to examine the data it was found that in every other instance of `scenario4` in this run, this snippet of code returns a +ve value for `New_OTG_2`. Thus the introduction of a `New_OTG_2` value that is –ve seems to have propagated through further iterations of the algorithm causing the `dx` problem. The values associated with this 186952 iteration are:

`Old_OTG2` = -0.064147949; `dx` = 0.1845241; `time_loss`= 1; `eta_out` = 0.3

In this particular instance the calculated –ve value is due to `dx`*0.3 not being of a high enough +ve value to provide a total +ve value when added to `Old_OTG2` (which is –ve), *i.e.* `dx<=Old_OTG2*(-3.333)` in this instance.

The `dx` figure has a value set by the `dx3` figure from the snippet of code

```
dx3 = Old_OTG1*eta_in
```

`Old_OTG1` = 0.1845241 and `eta_in` = 1 and both values are thought to be robust so it was decided to look into the other variable `Old_OTG2`.

The `Old_OTG2` = -0.064147949 value is created in iteration number 28123 which is a `scenario2` iteration. The starting point for this iteration contains zero values for all variables into and out of the store. The `dx` value is set by a randomly selected amount 0.064147949, which is used to set the `New_OTG_1` figure of 0.064147949 for time period 149. This `New_OTG_1` value is used as the `Old_OTG2` value for future iteration 186952. Examining the other iteration values it became clear that the code was writing the expected values to the variables `New_OTG_1` and `New_OTG_2` but the code was giving a zero value to the variables `New_ETS1` and `New_ETS2`. On detailed examination of the code it was discovered that a setting of `New_ETS` values was set to zero if the potential move of energy was less than 0.1 kWh. Therefore the values for the output to grid did not exactly match with the energy to store. The potential move of energy was then changed to be set to zero if this was less than 1xE-13 kWh. However, the problem still seemed to appear on occasion (Figure 69).

1	eta_in	eta_out	Cap_max	PLI	PLO	tau	numtrials	step_size	nn_bias	market	year	upper_boundary_in_pounds	flag1	flag2	flag3	flag4	flag5	flag6	flag7	flag8	flags_total
2	1	1	1000	1000	1000	1.00E+30	1E+07	500	48	TT	1900	399.9998	0	0	0	0	0	0	0	0	0
3	1	0.3	1000	1000	1000	1E+07	1E+07	500	48	TT	1900	119.9999	0	0	2	2	0	1	0	4	9
4	0.3	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1900	399.9995	0	0	0	0	0	0	0	0	0
5	1	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1901	383.3326	0	0	0	0	0	0	0	0	0
6	1	0.3	1000	1000	1000	1E+07	1E+07	500	48	TT	1901	106.2497	0	0	0	0	0	0	0	0	0
7	0.3	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1901	289.3761	0	1	0	0	0	0	0	0	1
8	1	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1902	199.9999	0	0	0	0	0	0	0	0	0
9	1	0.3	1000	1000	1000	1E+07	1E+07	500	48	TT	1902	0.00E+00	0	0	0	0	0	0	0	0	0
10	0.3	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1902	0.00E+00	0	0	0	0	0	0	0	0	0
11	1	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1903	287.4996	0	0	0	0	0	0	0	0	0
12	1	0.3	1000	1000	1000	1E+07	1E+07	500	48	TT	1903	84.06135	0	0	0	0	0	0	0	0	0
13	0.3	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1903	287.89	35	3	1	0	0	0	0	0	39
14	1	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1904	398.2892	0	0	0	0	0	0	0	0	0
15	1	0.3	1000	1000	1000	1E+07	1E+07	500	48	TT	1904	117.1994	0	0	0	0	0	0	0	0	0
16	0.3	1	1000	1000	1000	1E+07	1E+07	500	48	TT	1904	375.2293	3	3	2	1	0	1	0	1	11

Figure 69 - potential move of energy set to zero if less than 1xE-13 kWh

It was therefore decided to stop the problem if it appeared from reoccurring by introducing a checking step at each scenario `dx` comparison. If the value of `dx` caused a flag *i.e.* the sign was opposite to that expected, then the `dx` value and `accept` variable were both set to zero. This caused this potential move to be discarded, and forced the algorithm to consider another potential move. Due to the small numbers of `dx` problems seen in the debugging process, this was not thought likely to use many of the iterations required to find a suitable solution (by not accepting a potential move), and provided a more robust code, that rejected `dx` problems once they occurred, in order to stop the issue propagating through further iterations. This gave a solution to the `dx` problem arising as can be seen from the flag values in Figure 70.

1	eta_in	eta_out	Cap_max	PLI	PLO	tau	numtrials	step_size	nn_bias	market	year	upper_boundary_in_pounds	flag1	flag2	flag3	flag4	flag5	flag6	flag7	flag8	flags_total
2	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1900	399.9999	0	0	0	0	0	0	0	0	0
3	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1900	120.0001	0	0	0	0	0	0	0	0	0
4	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1900	399.9995	0	0	0	0	0	0	0	0	0
5	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1901	383.3275	0	0	0	0	0	0	0	0	0
6	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1901	106.1406	0	0	0	0	0	0	0	0	0
7	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1901	289.0211	0	0	0	0	0	0	0	0	0
8	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1902	200	0	0	0	0	0	0	0	0	0
9	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1902	0.00E+00	0	0	0	0	0	0	0	0	0
10	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1902	0.00E+00	0	0	0	0	0	0	0	0	0
11	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1903	287.4892	0	0	0	0	0	0	0	0	0
12	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1903	84.05562	0	0	0	0	0	0	0	0	0
13	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1903	280.1937	0	0	0	0	0	0	0	0	0
14	1	1	1000	1000	1000	10000000	10000000	500	48	TT	1904	398.272	0	0	0	0	0	0	0	0	0
15	1	0.3	1000	1000	1000	10000000	10000000	500	48	TT	1904	118.8503	0	0	0	0	0	0	0	0	0
16	0.3	1	1000	1000	1000	10000000	10000000	500	48	TT	1904	380.5055	0	0	0	0	0	0	0	0	0

Figure 70 - dx problem solved by introduction of checking step in each scenario

This description is but one example of the laborious and intricate nature of the development of the code, there were many other debugging stages in the development of the algorithm, which have been left out of the work due to the intricate and longwinded nature of the process. Many of these were part of the steep syntax learning curve of Fortran90 and bash scripting, and many were to do with the methodology of the algorithm itself. In the search to discover what was going on in the algorithm, a framework for information retrieval had to be designed in order to collect useful information to illuminate why the algorithm was not working as expected. This process of building, testing, discovery, building, testing, discovery was challenging.

7.14 Algorithm validation results

The nature of the development process required that the model was examined, changed and then retested with test price files in order to ascertain whether the algorithm was behaving as expected. This section shows the results from the algorithm once the algorithm was felt to be working as expected in order to allow a degree of confidence when applied to historical price files. All runs of the algorithm in this section had a `Cap_max` of 1000 kWh, and the number of iterations `numtrials` = 1,000,000,000. The power limits in and out `PLI` = `PLO` = 1000 kW, which means that the storage device can be completely emptied or filled in 2 time periods = 1 hour. The runs were also carried out using a year of historical price data of 365 days in normal years and 366 days in the leap year of 2008. In the Figures in this section the price values are plotted in red, the `Output_to_grid` values are plotted in blue, and the State of Charge (`E_stored`) of the device is plotted with a dashed black line. The `Output_to_grid` is –ve when energy is being stored (bought), and +ve when energy is being released (sold). The price values are plotted against the right ordinate axis in red, and the `Output_to_grid` and State of Charge (`E_stored`) values are plotted against the left ordinate axis. Only the first seven days (336 time periods) of data are plotted in the Figures.

Testing the algorithm with the square wave named `1900_cleaned_UK_crlf.txt` and with zero losses for the round-trip efficiency, it was found that energy was bought and sold more frequently than anticipated.

This can be seen in Figure 71, and was thought to be caused by the values of the fixed and time-dependent losses. As the model sees no efficiency penalties for moving energy at the same price, the algorithm buys and sells energy during the higher price. The corresponding state of charge of the storage system is shown in Figure 72 and shows that the store was full at the end of the lower price periods, and empty at the end of the higher price periods. Thus, regardless of the buying and selling of energy during the upper price periods, the algorithm worked mostly as expected and calculated an upper boundary figure of £36500 for the year or £100 per day. The increased buying and selling is a side effect of this particular set of input variables with no losses and a zero price for the lower price point.

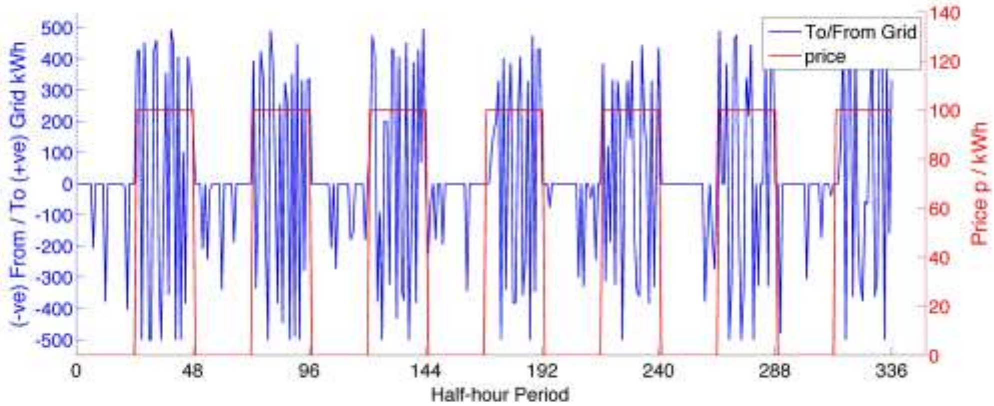


Figure 71 - Output to grid - zero losses - `1900_cleaned_UK_crlf.txt`

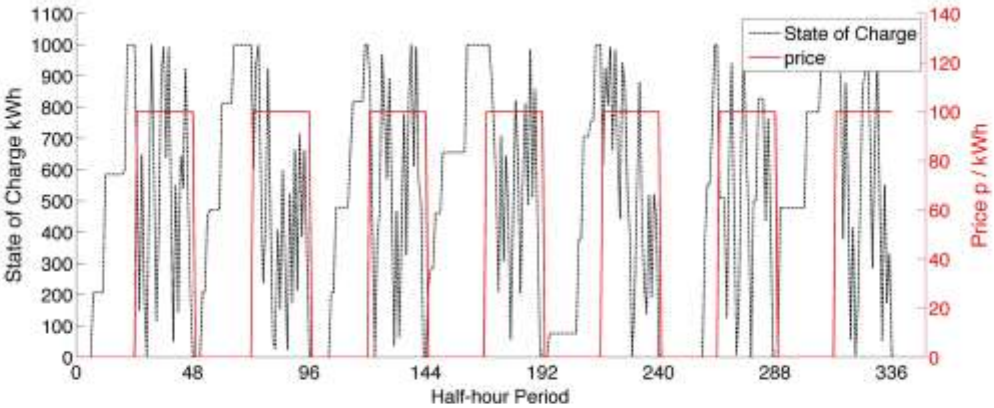


Figure 72 - State of Charge - zero losses - `1900_cleaned_UK_crlf.txt`

The algorithm was then run with similar inputs, only differing by the timedependent loss having a value of 24 rather than infinity. This produced the results shown in Figure 73 and Figure 74. Even though the buying and selling of energy at the upper price has been controlled by the inclusion of a time-dependent loss, the algorithm is buying energy several times during the zero cost price periods with no regard to minimising the energy bought. This shows an important limitation of the algorithm in its current form, where the focus is on the maximisation of revenue, not the minimisation of energy bought. In Figure 74 the downward slopes of the state of charge (black dashed line) show that the time-dependent loss is having an effect, but the algorithm does not prioritise when the energy is bought as long as the store is full by the end of the lower price periods, and empty at the end of the upper price periods. The upper boundary value is £35386, which is less than the £36500 from the previous run with no losses. This is due to a power limit into the store, which requires a minimum of two time periods to fill or empty the store. The second time period after the step change in price is subject to a time-dependent loss (of one time period), which reduces the amount of energy able to be sold – thus reducing the upper boundary value.

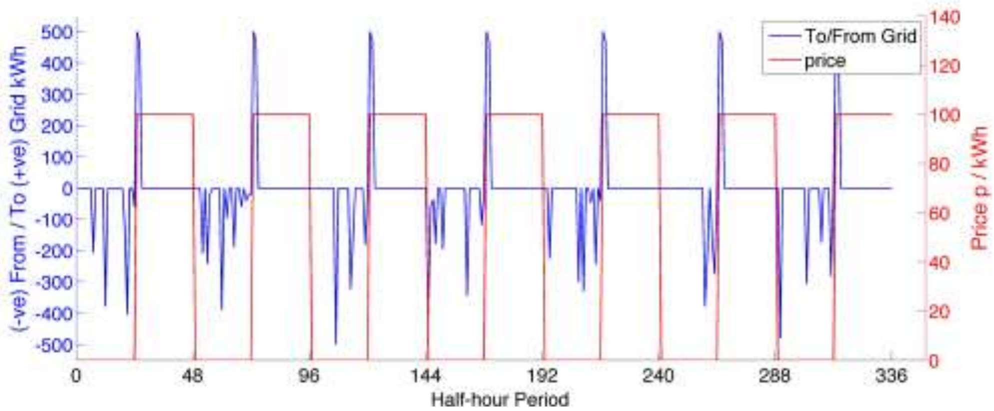


Figure 73 - Output to grid – time-dependent loss - `1900_cleaned_UK_crlf.txt`

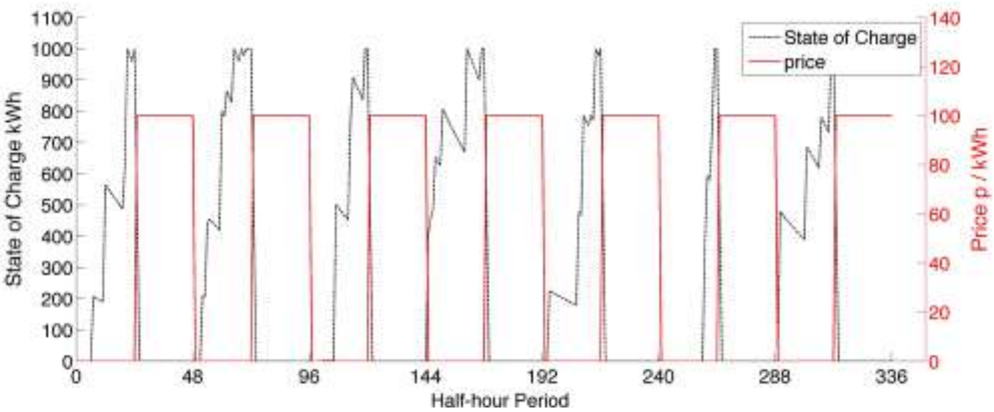


Figure 74 - State of Charge – time-dependent loss - `1900_cleaned_UK_crlf.txt`

The algorithm was then run with similar inputs (with a time-dependent loss having a value of 24) but used the square wave test price file `1902_cleaned_UK_crlf.txt` with a lower value of 50p/kWh rather than zero p/kWh. This produced the results shown in Figure 75 and Figure 76. These show that the algorithm no longer buys energy during random periods at the lower price – as the time-dependent loss now equates to a financial penalty when coupled with a nonzero value for the energy bought. The upper boundary value is £16943. The algorithm thus produces an output where the time the energy is stored is minimised *i.e.* the algorithm favours energy bought and sold on the periods closest to the step change in price. This is as expected.

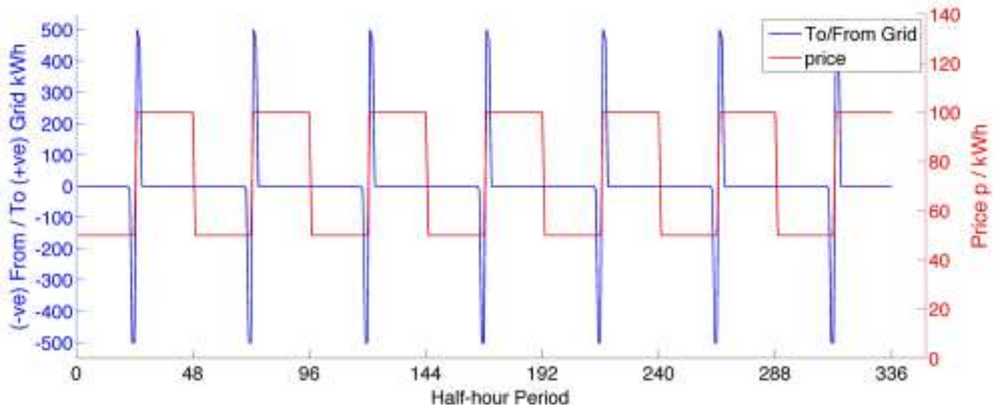


Figure 75 – Output to grid – time-dependent loss - `1902_cleaned_UK_crlf.txt`

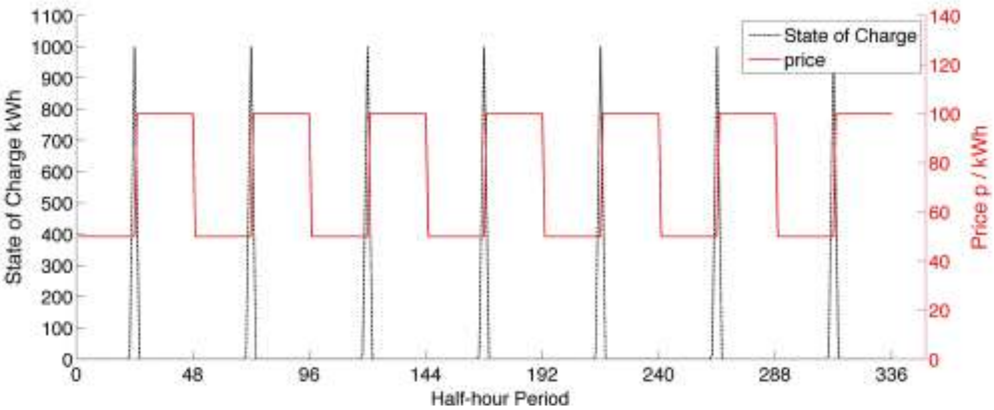


Figure 76 - State of Charge – time-dependent loss - `1902_cleaned_UK_crlf.txt`

The algorithm was then run without a time-dependent loss, but now with a saw shaped price file. This produced the results shown in Figure 77 and Figure 78 that charges the store with the cheapest energy at the beginning of the saw pattern, and discharges the energy at the most expensive periods at the end of the saw pattern. This is as expected. The difference in the changing value of the price compared to a flat price period, such as in the square wave, seemed to benefit the algorithm as it did not choose to charge and discharge energy within the same flat price period.

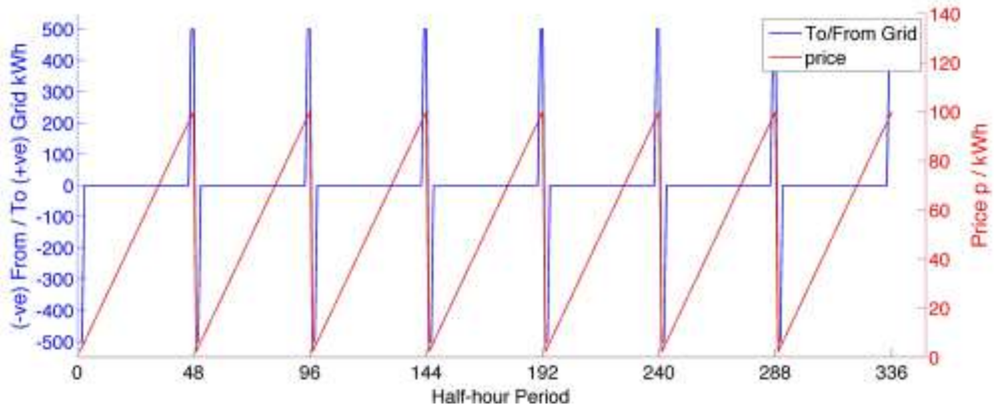


Figure 77 - Output to grid - `1901_cleaned_UK_crlf.txt`

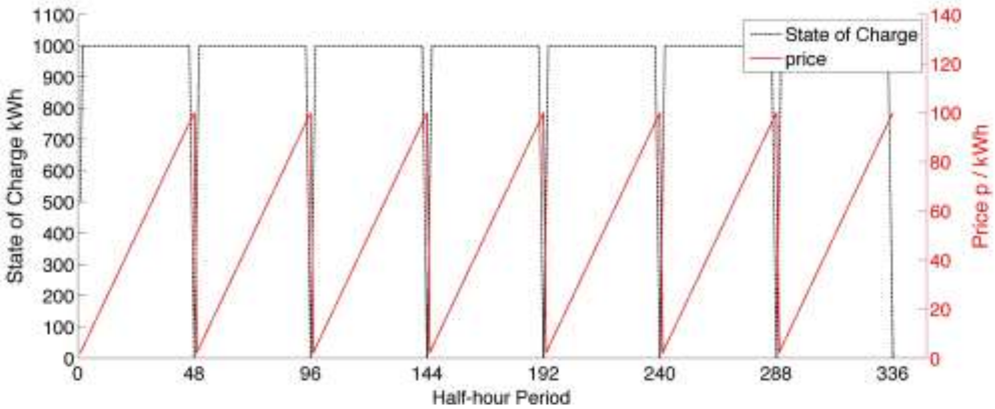


Figure 78 - State of Charge - `1901_cleaned_UK_crlf.txt`

The algorithm was then run again without a time-dependent loss and with a saw shaped price file, but this time with the output efficiency set to 30%. This produced the results shown in Figure 79 and Figure 80 that charges the store with the cheapest energy at the beginning of the saw pattern, and still discharges the energy at the most expensive periods at the end of the saw pattern. The difference between this result and the previous saw result is that the output power is restricted to 30% of the Energy Limit Out of the store *i.e.* 30% of 500 = 150kWh per period, which is clearly shown. This is as expected.

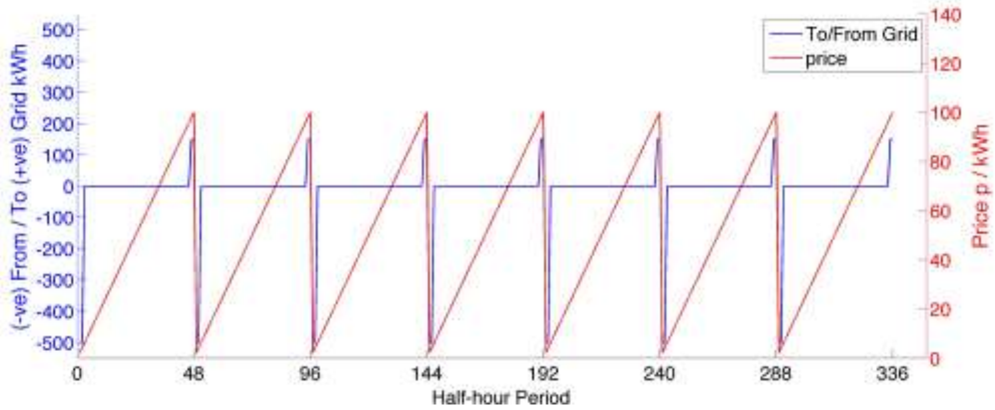


Figure 79 - Output to grid - `1901_cleaned_UK_crlf.txt`

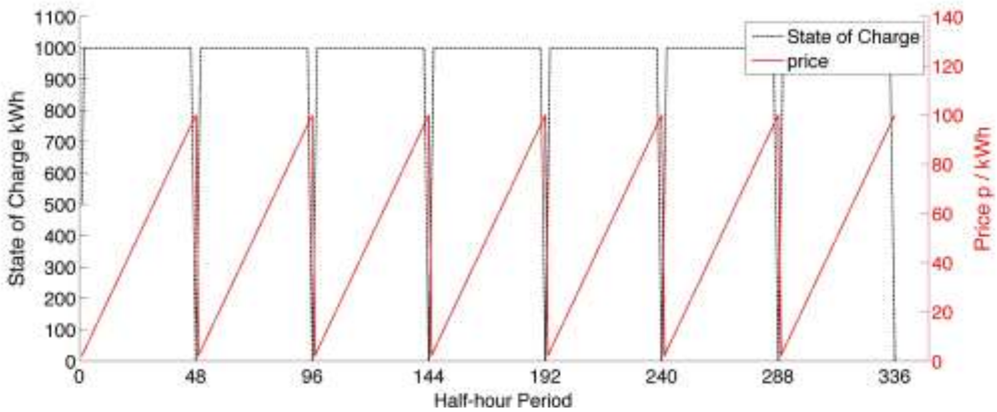


Figure 80 – State of Charge - `1901_cleaned_UK_crlf.txt`

time-dependent loss and with a

The algorithm was then run again without a
reverse saw shaped price file. This produced the results shown in Figure 81 and Figure 82 that charges the store with the cheapest energy at the lowest part of the saw pattern, and discharges the energy at the most expensive periods of the saw pattern.
This is as expected.

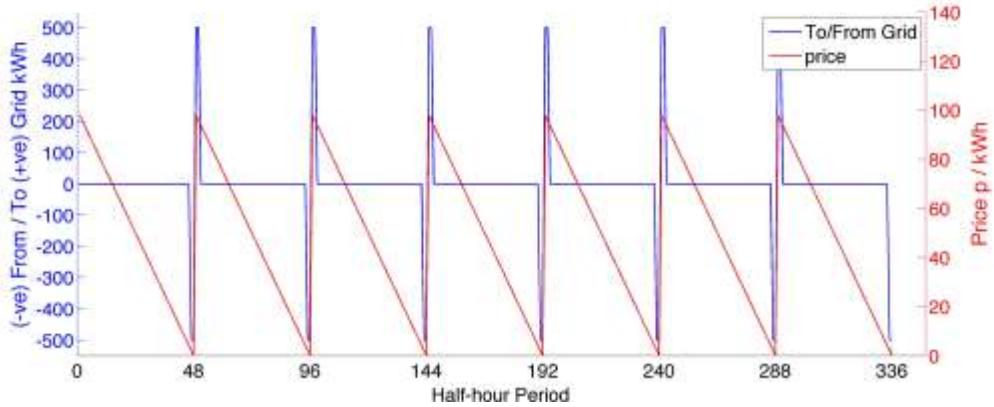


Figure 81 - Output to grid - `1903_cleaned_UK_crlf.txt`

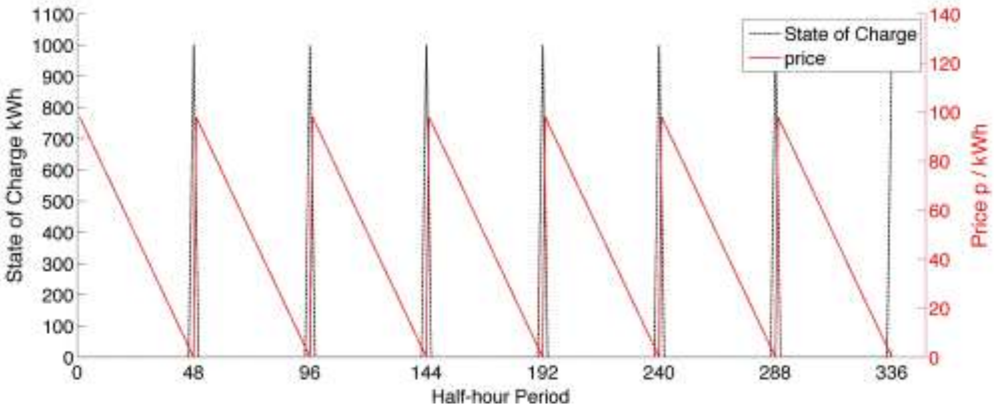


Figure 82 – State of Charge - `1903_cleaned_UK_crlf.txt`

time-dependent loss and with a sine shaped price file. This produced the results shown in Figure 83 and Figure 84 that charges the store with the cheapest energy at the lowest part of the sine pattern, and

The algorithm was then run again without a
discharges the energy at the most expensive periods of the sine pattern. This is as expected.

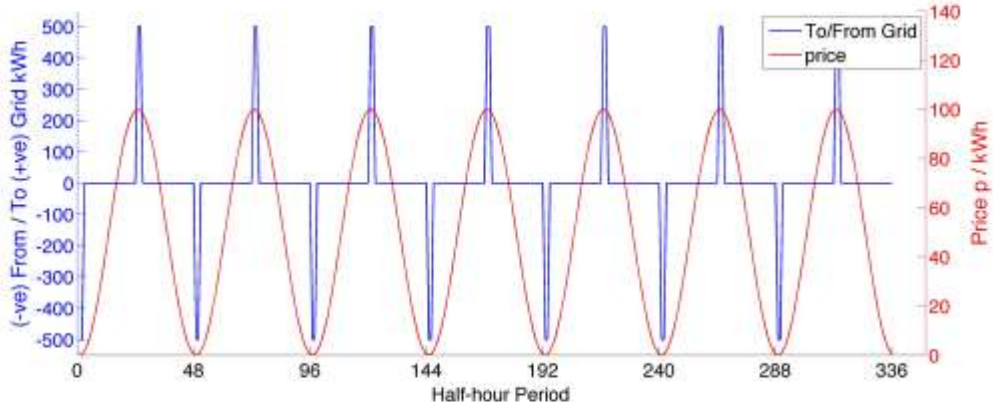


Figure 83 - Output to grid - `1904_cleaned_UK_crlf.txt`

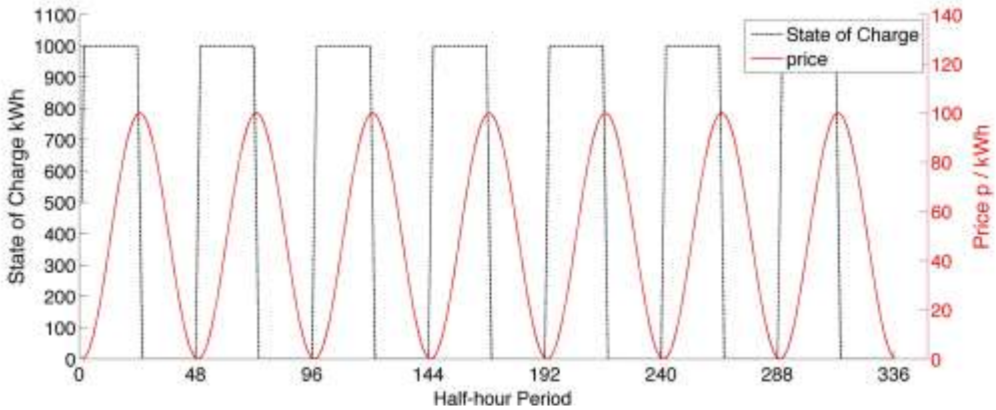


Figure 84 – State of Charge - `1904_cleaned_UK_crlf.txt`

time-dependent loss and with a sine shaped price file, but this time with the input efficiency set to 30%. This produced the results shown in Figure 85 and Figure 86 that charges the store with the cheapest energy at the lowest part of the sine pattern, and discharges the energy at the most expensive periods of the sine pattern. The charging is shown take a greater number of

The algorithm was then run again without a
periods than the 100% input efficient example in order to fill the store. This is as expected.

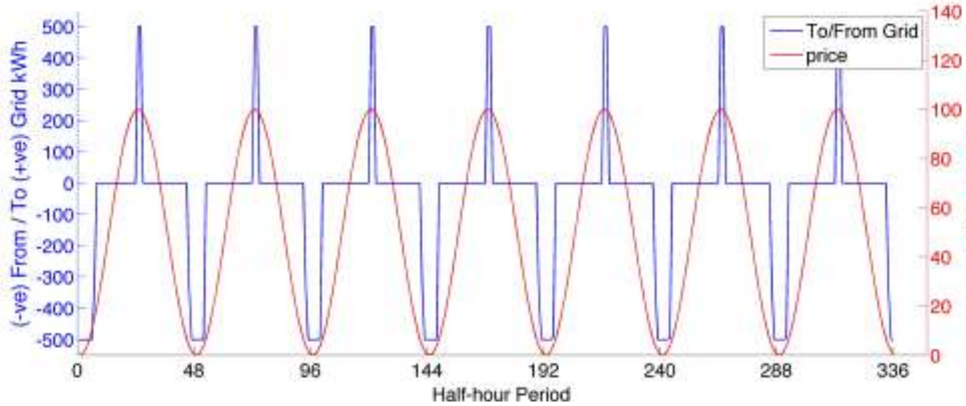


Figure 85 - Output to grid - `1904_cleaned_UK_crlf.txt`

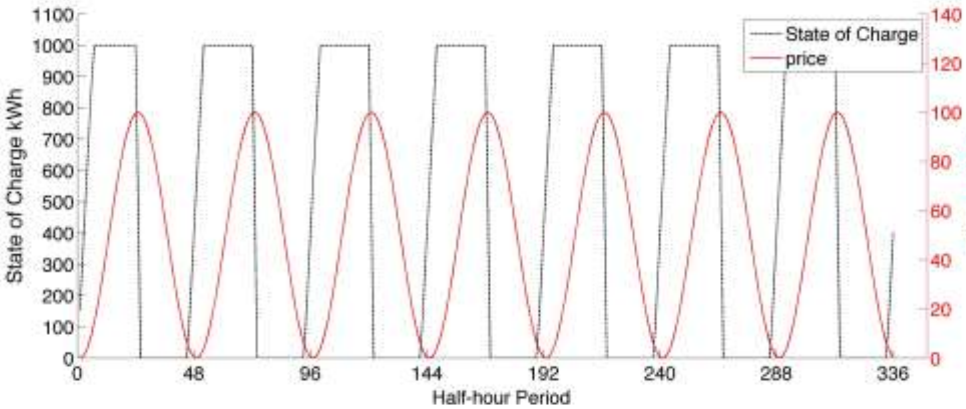


Figure 86 - Output to grid - `1904_cleaned_UK_crlf.txt`

The algorithm was then run again with no losses and with the 2005 price file. This produced the results shown in Figure 87 and Figure 88 that fully charges/discharges the store many times per 48 period. It is felt that the algorithm is overly sensitive to even slight price variations as there is no efficiency loss.

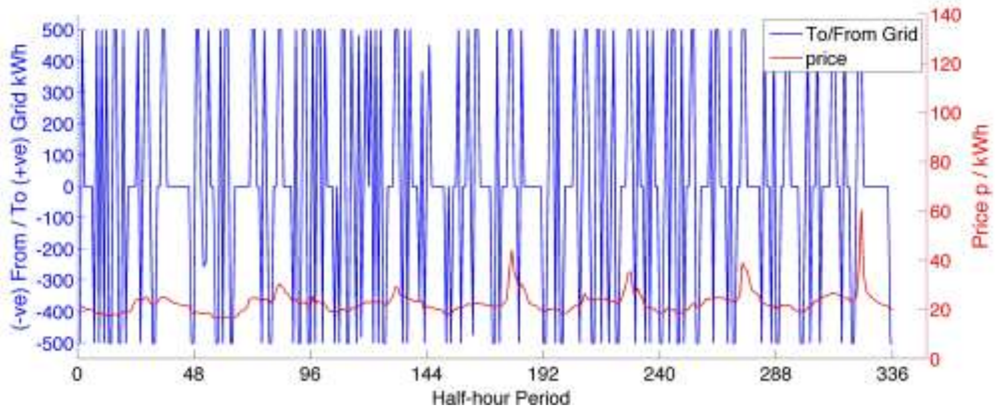


Figure 87 - Year 2005 – 100% 1000kWh

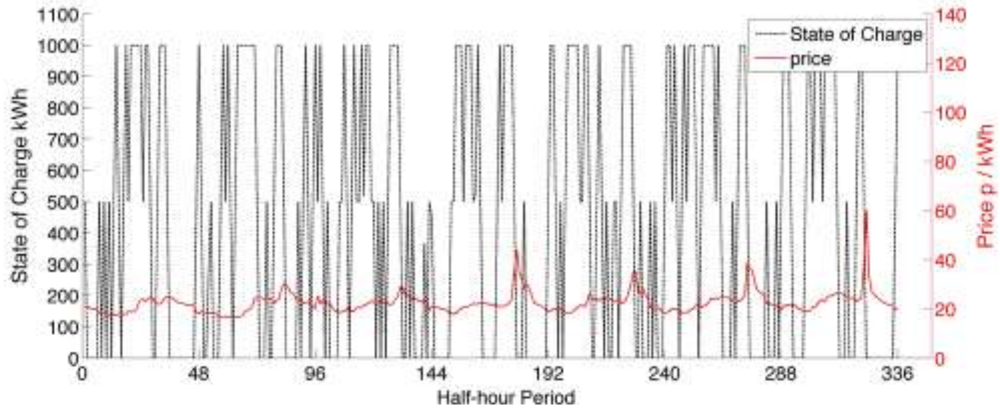


Figure 88 - Year 2005 – 100% 1000kWh

The algorithm was then run again with the 2005 price file, and an
100% and an `eta_out` of 30% (giving a 30% round-trip efficiency). This produced the results shown in Figure 89. The model did not store or release any energy during

eta_in of

the first 7 days of 2005 as the price differentials were not great enough to cover the fixed efficiency losses.

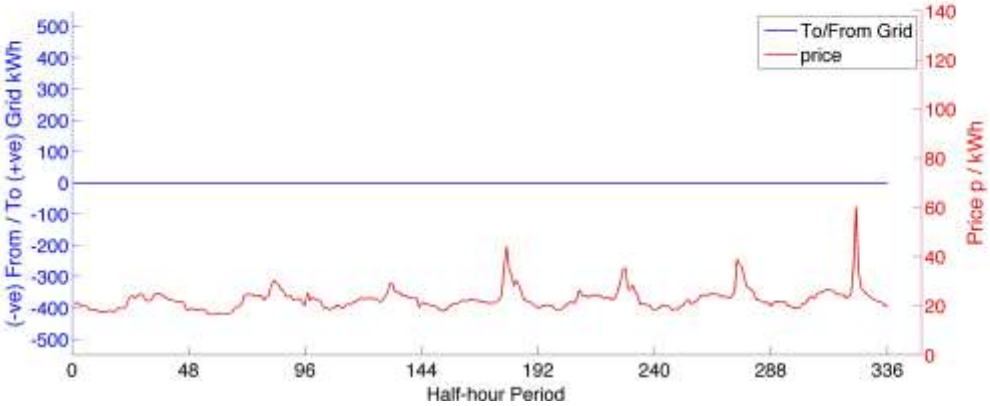


Figure 89 - Year 2005 – eta_in = 100%, eta_out = 30%, 1000kWh capacity

eta_in of trip

efficiency). This produced

The algorithm was then run again but with the **2006** price file, and an

30% and an eta_out of 100% (giving a 30% roundthe results shown in Figure 90. The model only stored and released energy on the few occasions that covered the fixed efficiency losses. At time periods 105, 106, 202 and 204 the model stores 107.6, 150, 93.01 and 149.39 kWh of energy from a gridinput of 358.6, 500, 310.04 and 497.98 kWh respectively. At time period 227 the model sells 500 kWh of stored energy back to the grid. This gives further confidence that the model is working as expected, as the fixed efficiencies in and out are working as expected.

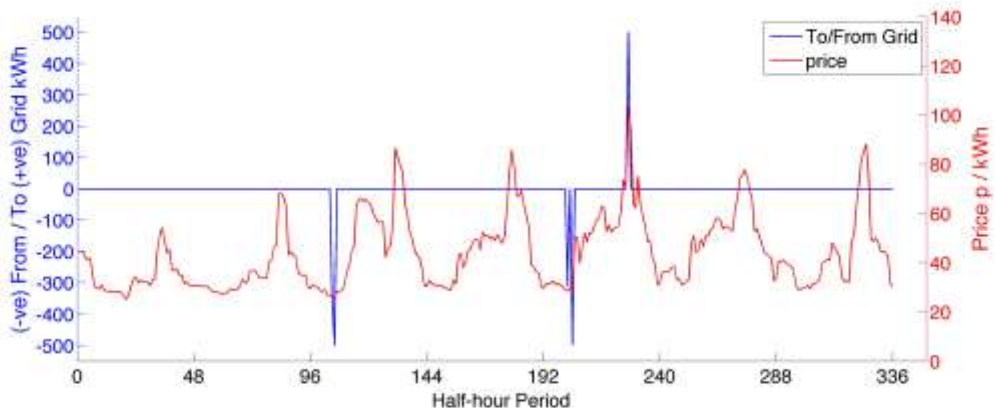
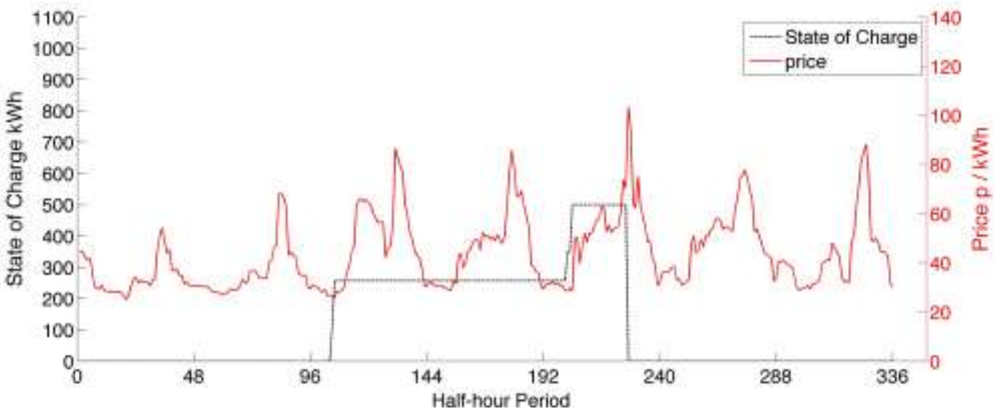


Figure 90 - Year 2006 – eta_in = 30%, eta_out = 100%, 1000kWh capacity



eta_in of

Figure 91 - Year 2006 – eta_in = 30%, eta_out = 100%, 1000kWh capacity

eta_in of trip

efficiency). This produced

The algorithm was then run again but with the **2008** price file, and an 100% and an eta_out of 30% (giving a 30% roundthe results shown in Figure 92 and Figure 93. The model only stored and released energy on the few occasions that covered the fixed efficiency losses. Thus the model was able to fully charge the store using energy at periods 13 and 14 from a grid energy input of 500 kWh at each period (which was all stored). The store was then fully discharged at time periods and 131 and 132, but due to an eta_out of 30% the amount of energy sold back to the grid was only 150 kWh for each period. This gives further confidence that the model is working as expected, as the fixed efficiencies in and out are working as expected.

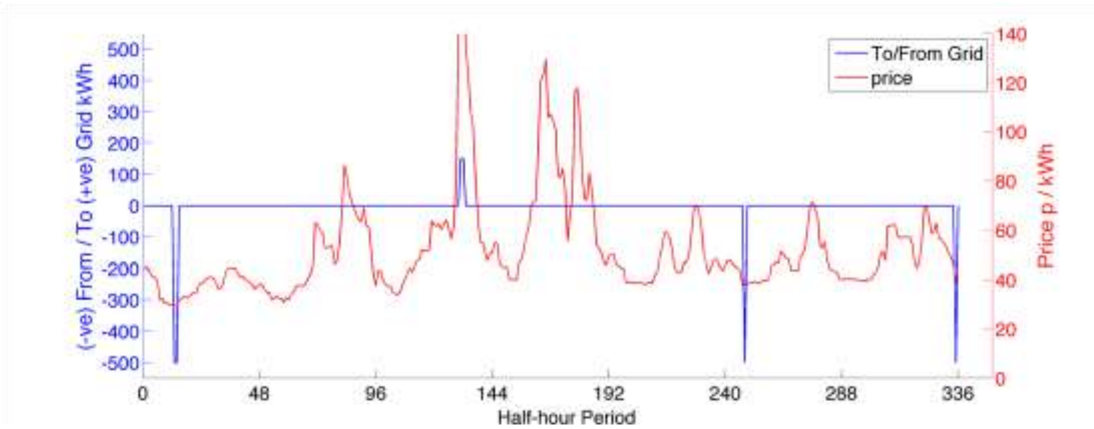


Figure 92 - 2008 – eta_in = 100%, eta_out = 30%, 1000kWh capacity

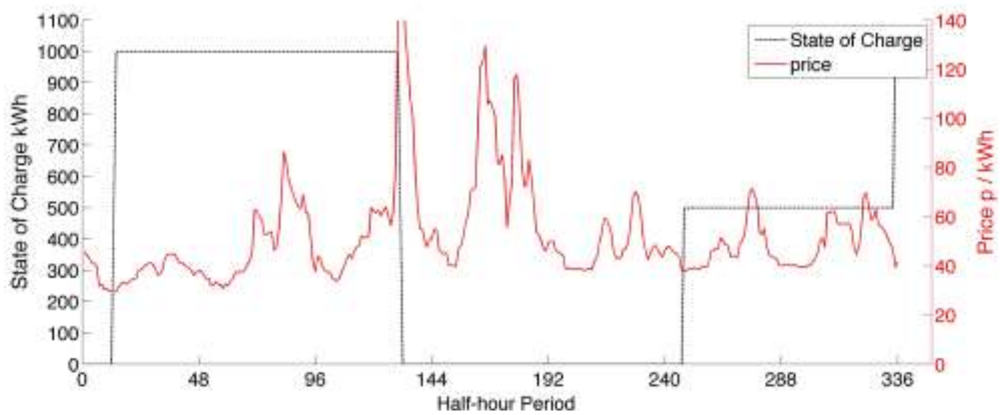


Figure 93 - 2008 – eta_in = 100%, eta_out = 30%, 1000kWh capacity

The algorithm was then run again but with the **2009** price file, and an 30% and an eta_out of 100% (giving a 30% roundthe results shown in Figure 94 and Figure 95. The model only stored and released energy on the few occasions that covered the fixed efficiency losses. The model chose to forego selling the stored energy at the peak at period 180, in order to maximise revenue by selling all the stored energy at periods 227 and 228. This gives further confidence that the model is working as expected, as the underlying algorithm is choosing situations that maximise revenue.

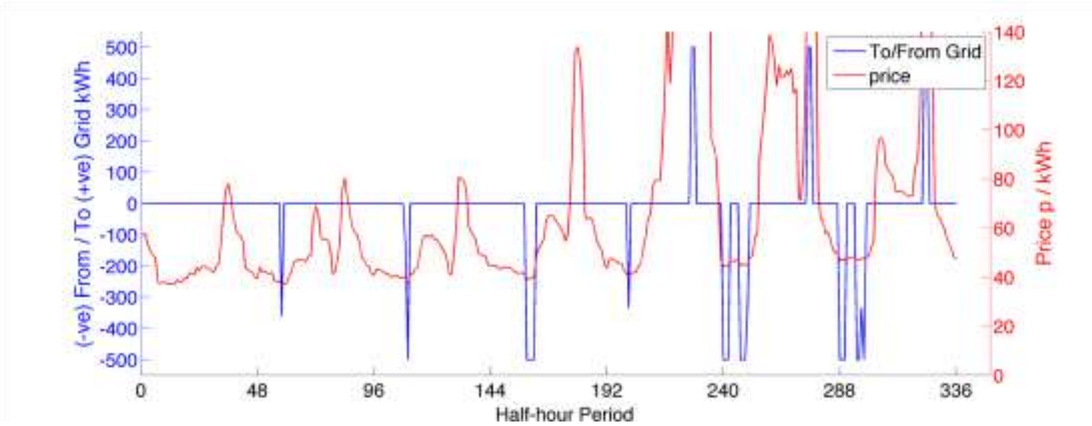


Figure 94 - 2009 - eta_in = 30%, eta_out = 100%, 1000kWh capacity

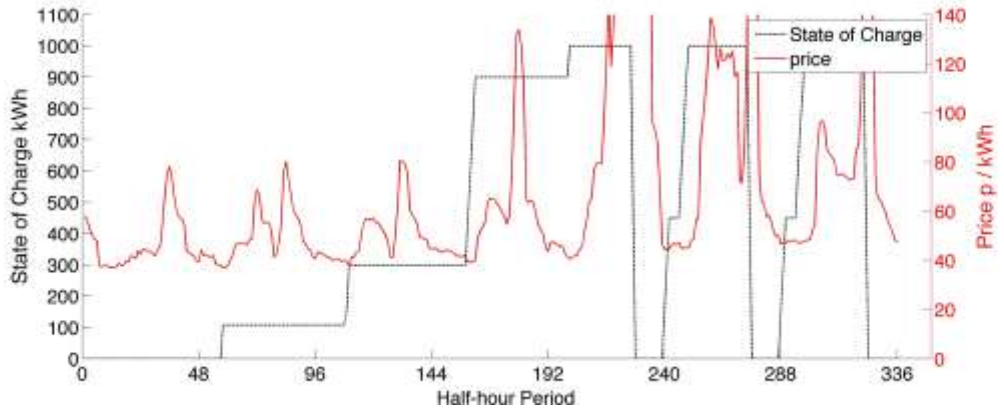


Figure 95 - 2009 - eta_in = 30%, eta_out = 100%, 1000kWh capacity

`eta_in` of trip

efficiency). This produced

7.15 Validation of random walk

In order to validate the random walk nature of the algorithm, a series of ten runs were undertaken with similar input variables, but with a different random seed starting point for the random number sequence used by the algorithm. Using a similar starting point for the random number sequence used by the Fortran code resulted in a similar stream of random numbers, and thus a similar random walk, and a similar end result. This was helpful throughout the debugging process, and can easily be changed to result in a different random seed by the use of the Fortran code `CALL RANDOM_SEED` before the start of the main iteration loop.

The ten similar runs had the input variables detailed below:

```
 (time independent) round trip efficiency =          0.7500
  (time independent) efficiency in (1=100%) =         0.8660
(time independent) efficiency out (1=100%) =          0.8660
                        max capacity (kWh) =      10000.0000
                       Power Limit In (kW) =       1000.0000
                      Power Limit Out (kW) =       1000.0000
              storage time constant (hours)  =     1.000E+30
                          number of trials =       100000000
                                 step_size =             500
                    nearest neighbour Bias =         48.0000
                                    market =              UK
                                      year =            2008
                               Old Revenue =          0.0000
                               new Revenue =        975.6252
                    Original energy output =          0.0000
                         New energy output =     -11138.7374
                               Flags total =               0
                            total cpu time =         30.3324
```

They all had a storage capacity of 10,000 kWh, a power limit in and out of 1000 kW, and a round-trip efficiency of 75% with no time-dependent losses. They only used price data for the first 7 days of 2008, and used 100 million iterations. The CPU time on the High Performance Computer was 30.3324 seconds.

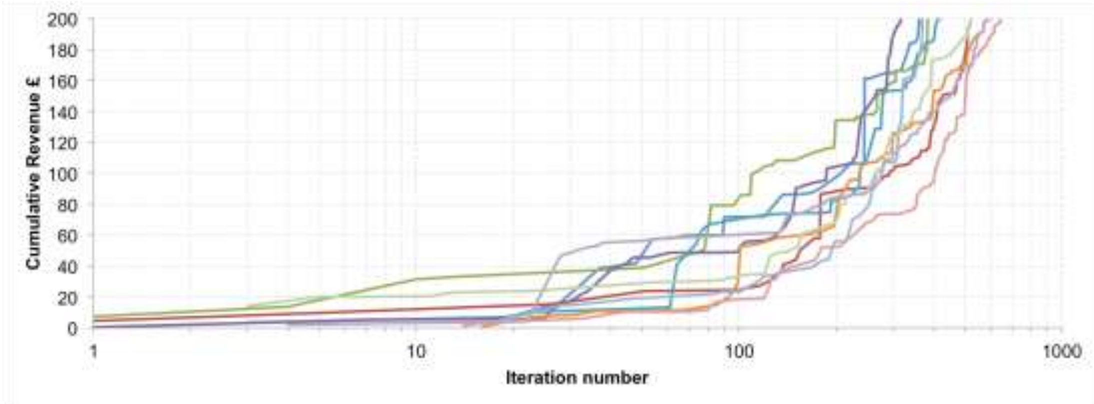


Figure 96 - Cumulative Revenue versus iterations showing 10 different random paths – partial graph

Figure 96 contains ten differently coloured lines showing the first 1000 iterations performed in the ten separate runs. The x-axis is $\log_{10}$, and the y-axis is normal. It can be seen that the lines exhibit different pathways of increasing revenue versus the number of iterations, and also the size of the jumps in revenue can be seen to change between different iterations within the same run.

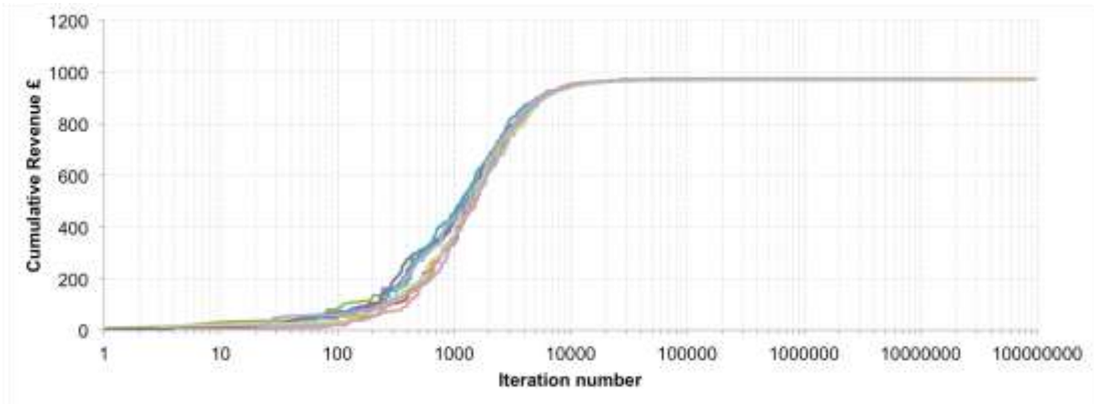


Figure 97 – Cumulative Revenue versus iterations showing 10 different random paths – full graph

Figure 97 shows the full 100 million iterations using the $\log_{10}$ x-axis. Regardless of the starting point and pathway, the ten differently coloured lines converge on a similar end result of £975.62. It is interesting to note the s-shaped nature of this semi-log plot, where the bulk of the iterations that increase the revenue amount are concentrated at the initial stage of the process; it seems more probable that iterations at the earlier stages of the run will be able to increase revenue than those at the end stages of the run. These results indicate that the algorithm is indeed nondeterministic and uses a random walk methodology to trend towards a final result.

Some thought was given to an automatic method to stop the algorithm before the end of the iterations once the revenue increase had plateaued, but a satisfactory method was never found, and it was also thought helpful to be able to compare different runs with the knowledge that they had been allowed the same number of iterations. It was decided to use a billion iterations for every standard run using a years worth of data due to the resource available at the High Performance Computer. Each run of a billion iterations took approximately 2.5 hours on an individual CPU node.

With the results from the validation of the model, it was thought that the model was behaving as expected, and therefore a degree of confidence could be attributed to the results from using actual historical data. The amount of time and effort in reaching this point was a significant part of the effort for this work, as time and again it would seem that the model had some difficulty with a particular set of input conditions that would require a detailed understanding of why the algorithm was not behaving as expected.

Once the debugging was satisfactory, the process of performing many different runs was also investigated.

7.16 Automation of different runs

The Fortran program was originally scripted and debugged to run as a standalone program that was run from a shell script with associated price and time files. In the initial debugging phase different storage device parameters were entered via the keyboard against screen prompts from the program; this was superseded by piping an input file to the complied file using a shell script. This made it much easier to keep a record of the input variables of any particular run.

With access to the High Performance Computer (HPC), it was possible to consider running the program with different input values (for different runs) as standalone jobs, which were submitted to the queuing system for the HPC. The HPC is a fantastic resource to use for raw computing power, which allowed for the completion of many more runs than using a desktop PC. The Bash shell scripts also allow a flexible and powerful means of controlling the entire process, although the intricate nature of the data formatting expected for the programs, and the syntax of Bash shell scripts and Fortran were a steep learning curve.

After much thought and discussion, it was decided that a flexible but powerful method to allow for the submission of several runs (jobs) to the HPC would be to organise a set of master files that could be copied into new folders with the executable file, and then this executable file would be submitted as a job to the HPC headnode for execution. Therefore, most of the data files that the executable file requires were placed in the same folder as the executable file. The drawback to this approach was the duplication of data files (and the use of server hard disk space), but the advantage of having a specific set of data contained within each folder was thought to outweigh this. The price and time files were not copied to each folder as a compromise to save space, and were accessed from a particular folder on the HPC server. The pathway to these files is hardcoded into the Fortran program and the correct pathway is critical to the correct running of the program.

A particular programming and syntax issue was found with the main Fortran program in setting a `PARAMETER` value at the beginning of the code. The `PARAMETER` value for the number of half-hour periods in a non-leap year (17520) is different from the number of half-hour periods in a leap year (17568). A valid method of changing this `PARAMETER` value from outside the code (dependent on the year) was never found, so a workaround of using two distinct Fortran files with the different `PARAMETER` value hardcoded into the file was used. These two distinct main program files are called `full_grid_normal.f90` and `full_grid_leap.f90`, and are copied into sub-folders to be run as separate instances. The coding of these files is ostensibly the same, but differ in the `PARAMETER` value of the number of half-hour periods in the year. The flexibility of the Bash script programming environment also allowed for the keyboard input to be replaced by an automated method to read one line of input data from a `master_input.txt` file, which itself was created in excel or

Matlab and then excel. This allowed for the creation of many different runs of input to be created in a logical manner. However, the file preparation for Unix has to take account of the different carriage return and line feed methods between the different operating systems of Apple, Windows and Unix (see Appendices 3 & 4).

8 Results and Discussion

8.1 UK market prices - varying power limits in/out and round trip efficiencies 2005 – 2011

It was decided a reference time series and storage device would be helpful to compare several of the different input variables, and therefore an initial set of results were calculated to compare the revenue between different years for a variation in the power limit in and out. This was in order to choose a reference year for the price input. For these initial calculations the storage device capacity was chosen as 100,000 kWh (100 MWh) to suggest a small bulk energy storage device. The terminology ‘pump’ and ‘turbine’ for the power limit in and power limit out are used throughout the results and discussion sections as it relates to hydro-pumped storage technology, although other terms would be more suitable to other technologies. The following six Figures (Figure 98-Figure 103) show the results of the 100,000 kWh device with different round-trip efficiencies (with input efficiency = output efficiency), using a Power Limit In and Out of 12,500 kW, 25,000 kW, 50,000 kW, 100,000 kW, 200,000 kW and 400,000 kW; equivalent to full charging or discharging over 16, 8, 4, 2, 1 and 0.5 of a time period(s) (30 minutes) respectively. The input of 400,000 kW (Figure 103) was run as a check, with the ability to fully charge or discharge the storage device in half of one time period, which should output a similar upper boundary value to the run when the storage device could be fully charged or discharged over one time period (Figure 102). The results showed that there was no additional revenue benefit from being able to oversize the pump or turbine in order to charge/discharge the storage device in less than a time period – this was as expected.

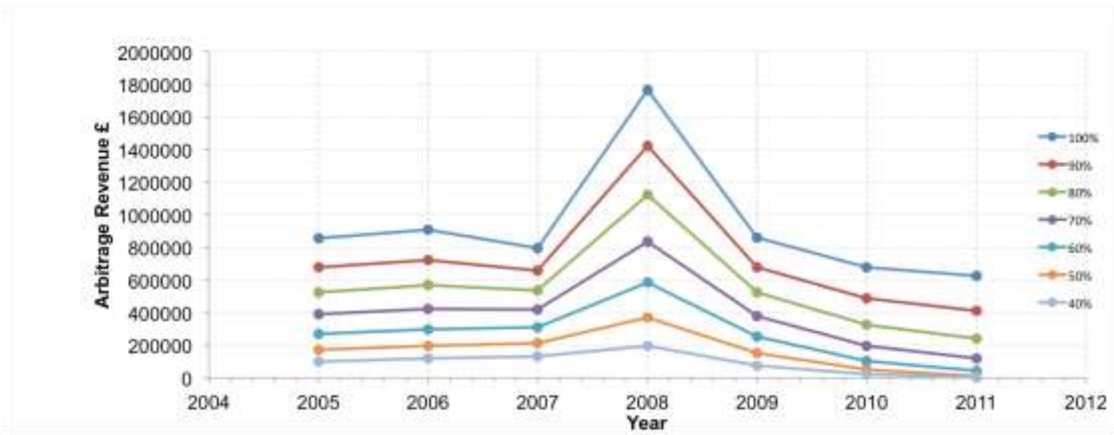


Figure 98 – Arbitrage revenue years 2005-2011 for different round-trip efficiencies. Cap_max 100,000 kWh – Power Limit In and Out 12,500 kW, no time-dependent loss

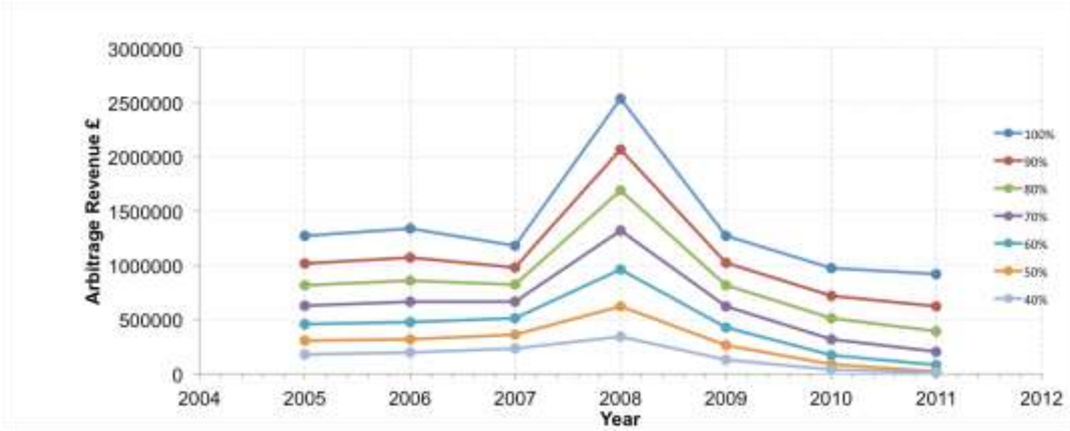


Figure 99 - Arbitrage revenue years 2005-2011 for different round-trip efficiencies. Cap_max 100,000 kWh – Power Limit In and Out 25,000 kW, no time-dependent loss

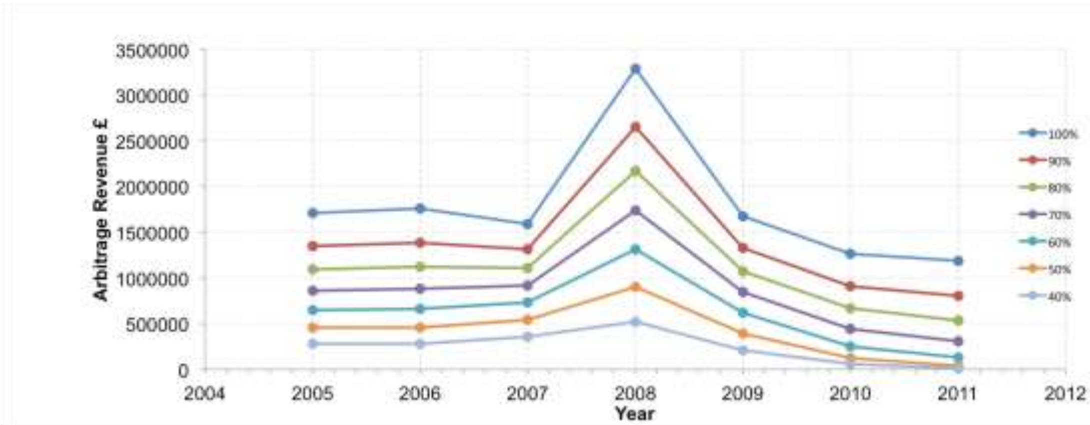


Figure 100 - Arbitrage revenue years 2005-2011 for different round-trip efficiencies. Cap_max 100,000 kWh – Power Limit In and Out 50,000 kW, no time-dependent loss

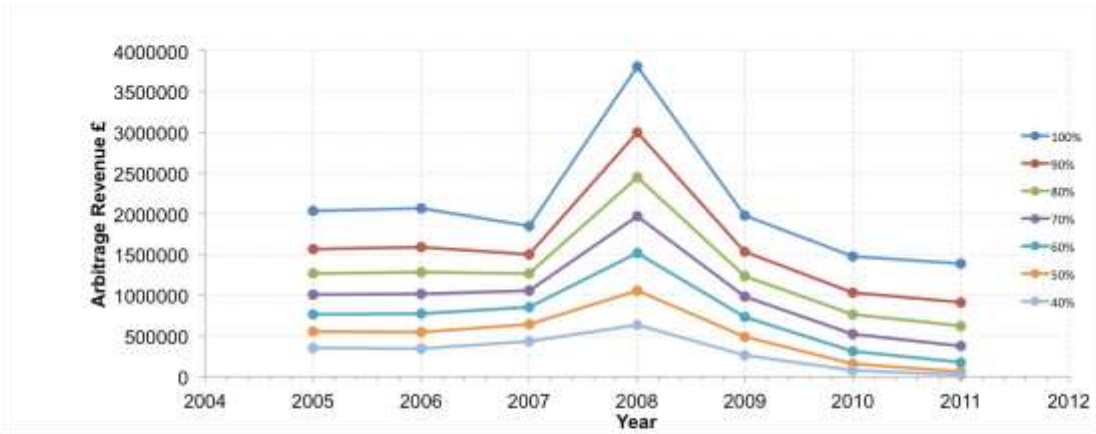


Figure 101 - Arbitrage revenue years 2005-2011 for different round-trip efficiencies.

Cap_max 100,000 kWh – Power Limit In and Out 100,000 kW, no time-dependent loss

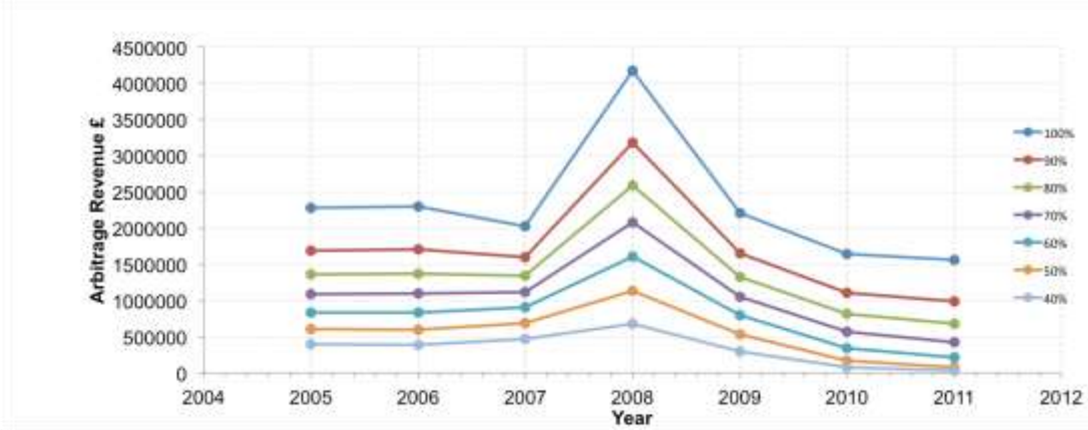


Figure 102 - Arbitrage revenue years 2005-2011 for different round-trip efficiencies. Cap_max 100,000 kWh – Power Limit In and Out 200,000 kW, no time-dependent loss.

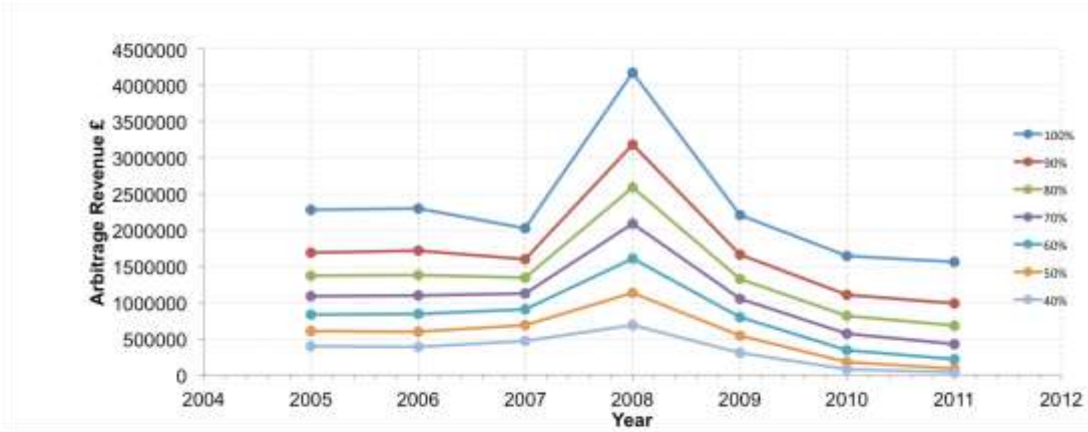


Figure 103 - Arbitrage revenue years 2005-2011 for different round-trip efficiencies. Cap_max 100,000 kWh – Power Limit In and Out 400,000 kW, no time-dependent loss

After considering the results from these preliminary model runs, the time series price data of 2009 was chosen as the reference year, as the level of annual arbitrage revenue was similar to 2005, 2006 and 2007, in all variations of the Power Limit In and Out; it was also the most recent year of price data to give this result.

8.2 Discussion of the variation in yearly revenues

The results in Figure 98 to Figure 103 show that there is a significant variation in the arbitrage value between different years. This seems to be regardless of the storage scheme power to capacity ratios or even the round-trip efficiencies and is therefore considered to be a function of the underlying price file variations between the years.

Years 2005, 2006, 2007 and 2009 have similar levels of revenue, whereas 2008 is a stand out year having almost double the arbitrage revenue of the previous years. 2010 is approximately two thirds of the 2009 value and 2011 is even less than 2010. This yearly variation driven by the underlying spot price structure will be of great concern to any organisation considering operating a bulk electrical energy storage device in the UK market due to the variation in yearly revenues from arbitrage. Storage operators have no control over the underlying spot prices, and thus, they would be exposed to the annual fluctuations in overall arbitrage revenue between different years.

This variability in revenue may also increase the cost of capital associated with a bulk storage project, as it can be viewed as a riskier set of future cash flows rather than a wind farm for example. This variability in arbitrage revenue is also likely to be a driving force as to why existing pumped storage operators provide other services in the UK such as bidding into the Short Term Operating Reserve Requirement market. These diverse revenue streams should help to smooth the yearly difference in revenue and it is thought that bulk electrical storage operators will focus on a weekly and day ahead basis to evaluate the condition of these diverse markets to provide the greatest potential revenue from using the store. The sub timeperiod movements in the aggregated output from the UK's pumped storage operators (Figure 116 on page 191) indicate that the timeframes for consideration for storage operators is at least as low as 5 minutes (if not even shorter). A default strategy could be to buy energy from the spot market between 11pm and 6am and to sell this back between 6am and 11pm with an increase in output between 4pm and 7pm in the evening. This potential default position would then be changed to meet the particular market conditions prevailing throughout a given day.

It was decided to investigate the impact on arbitrage revenue using the 2009 price data:

- By varying the size of the power limit in and power limit out with a particular capacity of a storage device.
- By varying the fixed efficiencies (both in and out)
- By varying the value of the time-dependent self-discharge variable compared to the round-trip efficiency

8.3 UK market prices - varying the power in/out ratio to the device capacity

Two sets of values for the round-trip efficiency were used to provide an understanding of varying the Power Limit In (the pump) versus the Power Limit Out (the turbine). The low value had a round-trip efficiency set to 45% (Figure 104), whereas the high value had a round-trip efficiency set to 75% (Figure 106), where the efficiencies in and out were both equal to the square root of the round-trip efficiency.

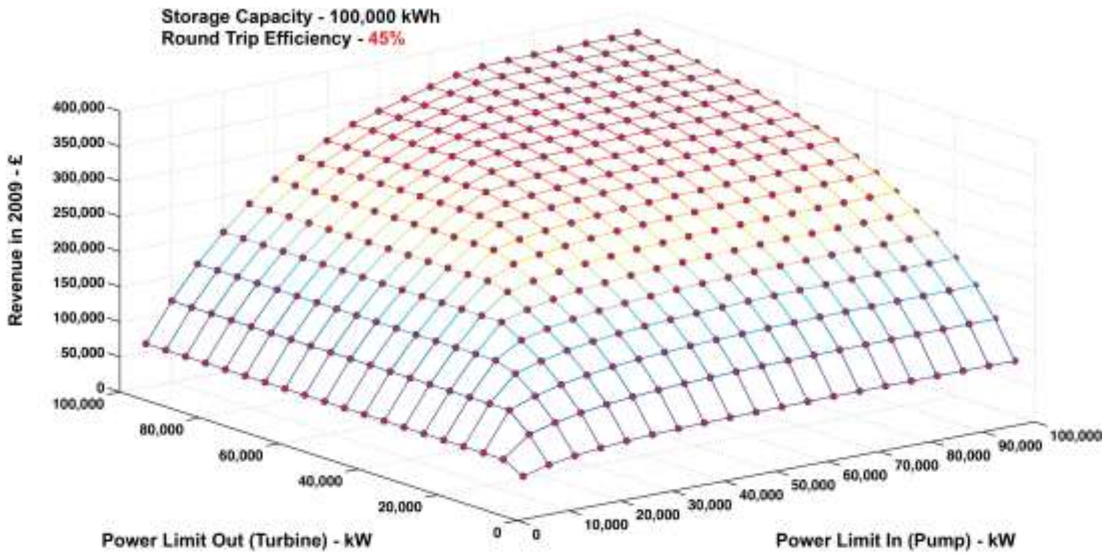


Figure 104 - Arbitrage revenue year 2009 for different Power Limit In and Out. Cap_max 100,000 kWh – Round-trip efficiency 45%, no time-dependent loss

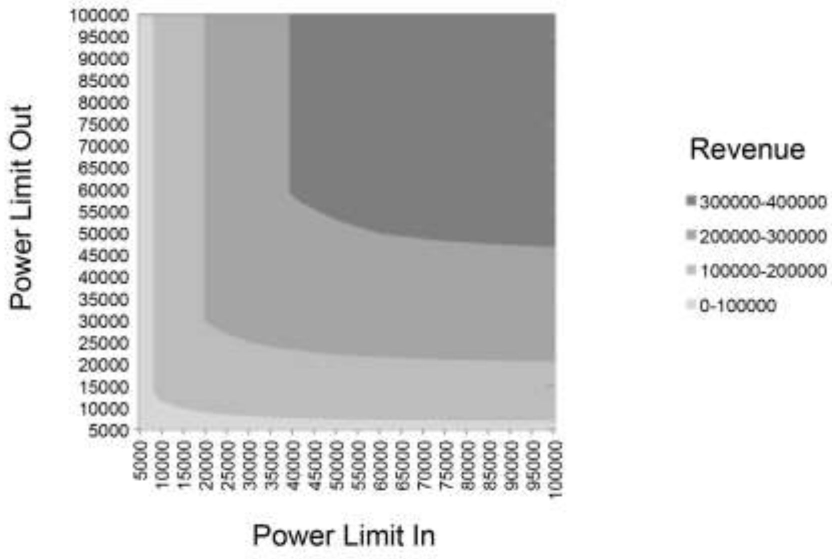


Figure 105 – 2D Contour plot of previous figure

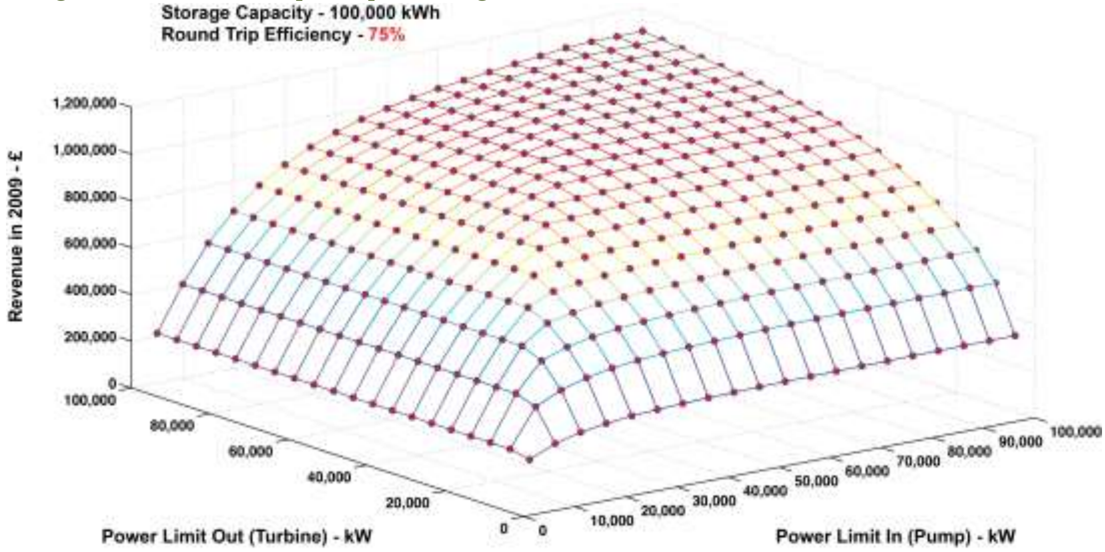


Figure 106 - Arbitrage revenue year 2009 for different Power Limit In and Out. Cap_max 100,000 kWh – Round-trip efficiency 75%, no time-dependent loss

8.4 Discussion of varying the power in/out ratio to the device capacity

Figure 98 to Figure 103 in the previous section show the arbitrage revenues whilst varying the Power Limit In/Out (but keeping PLI=PLO). The Figures show that more revenue is generated with a higher ratio of power rating to the storage scheme capacity, and as each data value in the spot price input file covers a timeframe of 30 minutes, increasing the discharging/charging power beyond that which can entirely empty/fill the storage system in 30 minutes does not generate any additional revenue. The ability of a storage scheme to fully charge and discharge over reduced time frames, gives the storage operator the ability to capture the price over those time frames, and as price spikes may only last for a few time periods, this is likely to explain the model's increase in revenue for an increased power rating ratio.

Figure 104 and Figure 105 show that this increase in the power rating ratio is nonlinear for a round trip efficiency of 45%. If one considers having access to capital to purchase a given number of either pumps or turbines, the results in this figure suggest that the greatest level of revenue capture would be possible if there is a similar level of pumps and turbines, with a bias towards an increase in the amount of turbines. This also seems to be shown in the results for the 75% round-trip efficiency in Figure

106 too, however, in the early increases of power rating ratios, the bias seems to favour the pumps rather than the turbines. This overall bias towards turbines is thought to be due to the short-lived nature of some of the peaks in the spot price, where a greater ability to sell energy during these periods equates to greater level of captured revenue. What is surprising is that there is not a greater bias towards the turbine side, given that lower prices tend to last for longer periods of time than price spikes. This is thought to be due to the model capturing small short lived 'dips' in the spot price as well as the short lived peaks too. In reality a storage operator would be limited by the size of the pump and the turbine by the sizes available in the market, and also whether the pump and turbine were intended to be the same device *e.g.* a reversible pump. Reality is also expected to differ from the model by operators not trying to capture each short-lived dip of a spot price, as this would have at least some cost in terms of increased maintenance, and may not be easily forecastable. The change in bias from turbine to pump at the lower power rating ratios also indicates the non-linear nature of a combination of the different input variables.

The results also show there is a greater revenue benefit for increasing the power rating ratio in order to fully charge or discharge in 4 hours (50,000 kW) than there is for increasing this further in order to fully charge or discharge below 4 hours in both the 45% and 75% round-trip efficiency runs. The Figures also show that there is also a large revenue benefit in increasing the round-trip efficiency from 45% up to 75%, which increases the revenue by a factor of nearly 3, and is further explored in the next section.

8.5 UK market prices - varying the fixed efficiencies

Two sets of values for the Power Limit In and Out were used to provide an understanding of varying the fixed efficiencies. The low value of PLI and PLO was set to 10,000 kW (Figure 107 and Figure 108), whereas the high value of PLI and PLO was set to 100,000 kW (Figure 109). The low value could fully charge or discharge the device over 20 time periods, whereas the high value was able to do so over 2 time periods. Each point varies the value of either efficiency by 2%.

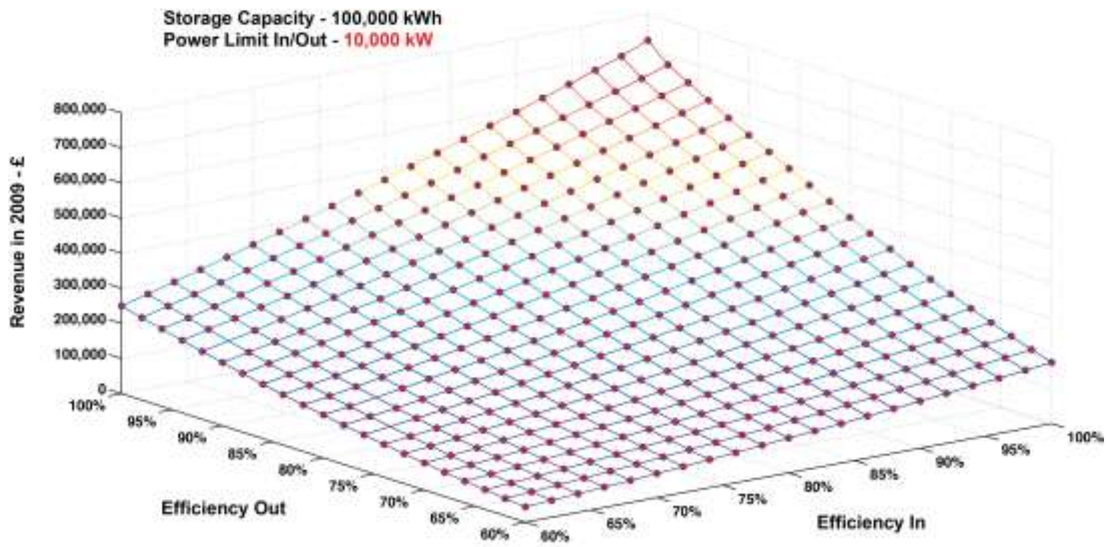


Figure 107 - Arbitrage revenue year 2009 for different fixed efficiencies In and Out. Cap_max 100,000kWh – Power Limit In/Out 10,000 kW, no time-dependent loss

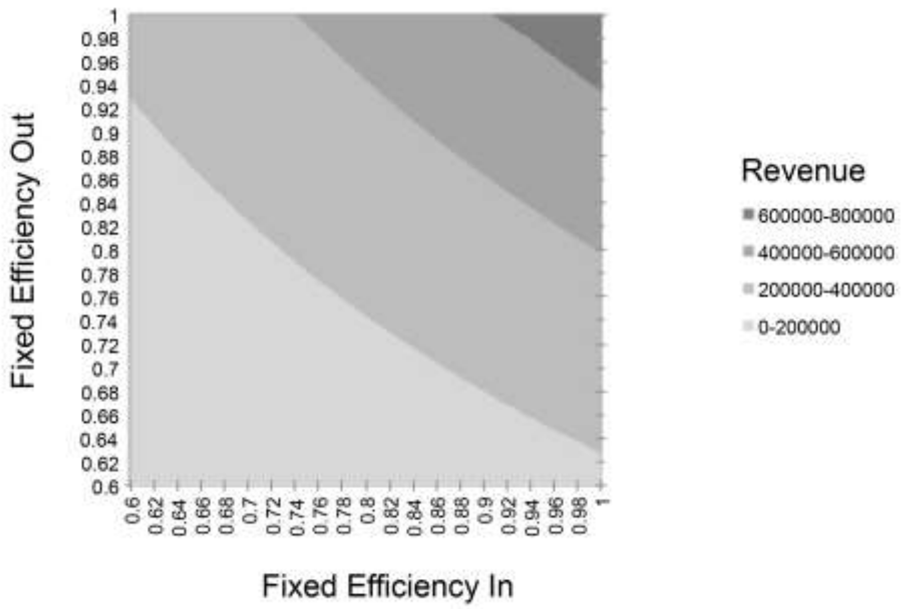


Figure 108 - 2D Contour plot of previous figure

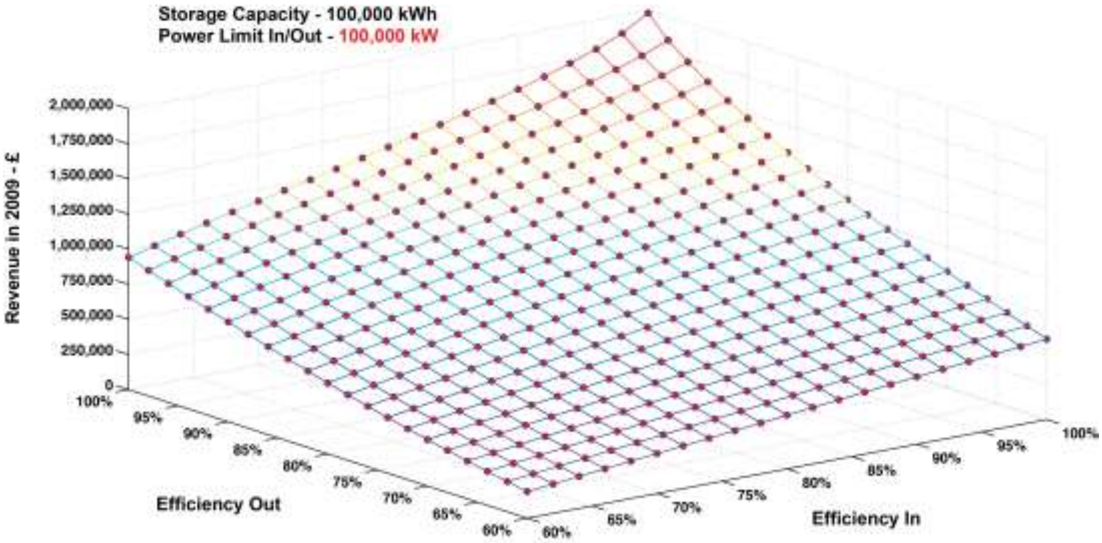


Figure 109 - Arbitrage revenue year 2009 for different fixed efficiencies In and Out. Cap_max 100,000 kWh – Power Limit In/Out 100,000 kW, no time-dependent loss

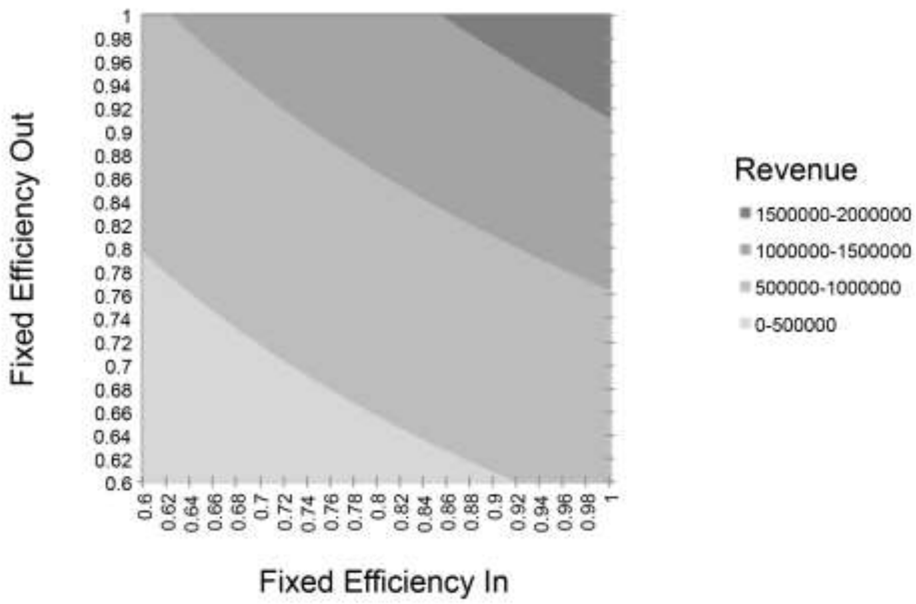


Figure 110 – 2D Contour plot of previous figure

8.6 Discussion of varying the fixed efficiencies

Figure 107 to Figure 110 show the arbitrage revenues whilst varying the fixed input and output efficiencies; each point varies the value of either efficiency by 2%. The Figures show that storage devices that have higher round-trip efficiencies will have greater upper boundary revenues than less efficient storage devices, given the same set of input conditions, which is as expected.

The increase in revenue is a non-linear function of the fixed input and output efficiencies, and visually seems to have a greater non-linear effect at a greater power rating ratio.

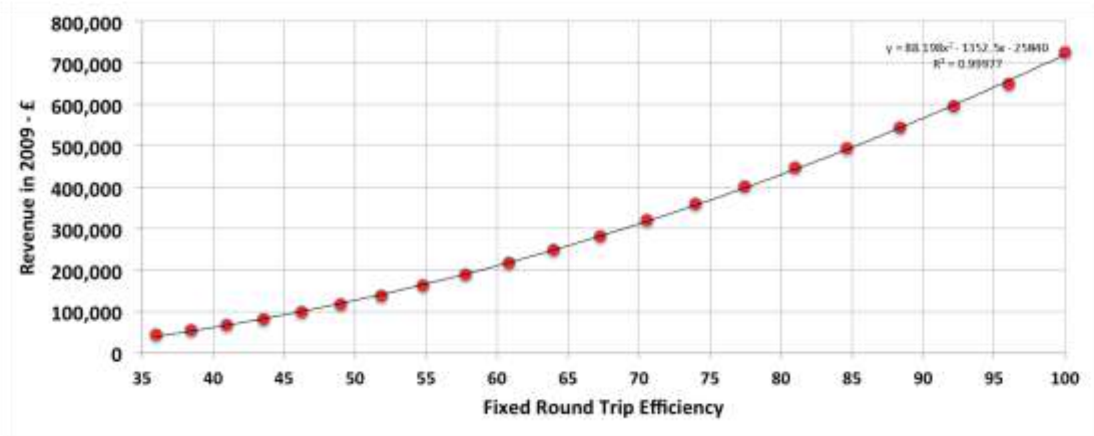


Figure 111 – Midline values of Fixed Round-trip Efficiency - Cap_max 100,000kWh – Power Limit In/Out 10,000 kW, no time-dependent loss, efficiency in = efficiency out.

Figure 111 shows the midline values of Figure 107 where the efficiency in and efficiency out values are equal, and is where the non-linear effect is most pronounced. The trend fitting line in Excel gives the following best-fit line of this data as a second order polynomial. This trend fitting line is used only to indicate the non-linear nature of the data, rather than an accurate representation of coefficient values.

$$y = 88.198x^2 - 1352.5x - 25840$$

$$R^2 = 0.99977$$

In simple terms, an increase in efficiency seems to provide an ever-increasing non-linear absolute financial benefit *e.g.* an increase of 5% round-trip efficiency from 80%

to 85% will have a greater absolute financial benefit than an increase from 40% to 45%. Indeed the increase of midline round-trip efficiency from 70% to 96% results in an approximate doubling of the revenue from arbitrage. However it should be noted that this result is subject to choosing the midline of results from the model and also the spot price data of 2009, and therefore this finding should be treated with some care.

What may be of more realistic interest if this finding is broadly correct is the suggested doubling of arbitrage revenue from 59% to 77%, which is a development range contemplated by cryogenic and pumped heat storage technologies.

The results are also skewed towards the fixed efficiency out, *e.g.* a storage scheme with efficiency in of **80**% and an efficiency out of **90**% has a higher arbitrage revenue than a storage scheme of efficiency in of **90**% and efficiency out of **80**% (both have a round-trip efficiency of **72**%). This is thought to be due to the ability of the model to sell more of the stored energy with the higher efficiency out value (given a finite storage capacity). This finding is analogous to, but subtly different from the bias to an increase in the power limit out discussed in the previous section.

8.7 UK market prices - varying the fixed efficiencies versus the timedependent efficiency

Two sets of values for the Power Limit In and Out were used to provide an understanding of varying the fixed efficiencies versus the time-dependent efficiency. The low value of PLI and PLO was set to 10,000 kW (Figure 112 and Figure 113), whereas the high value of PLI and PLO was set to 100,000 kW (Figure 114 and Figure 115). The low PLI/PLO value could fully charge or discharge the device over 20 time periods, whereas the high value was able to do so over 2 time periods. The fixed efficiencies in and out were both equal to the square root of the round-trip efficiency (the round trip efficiency in this case only includes the fixed efficiencies).

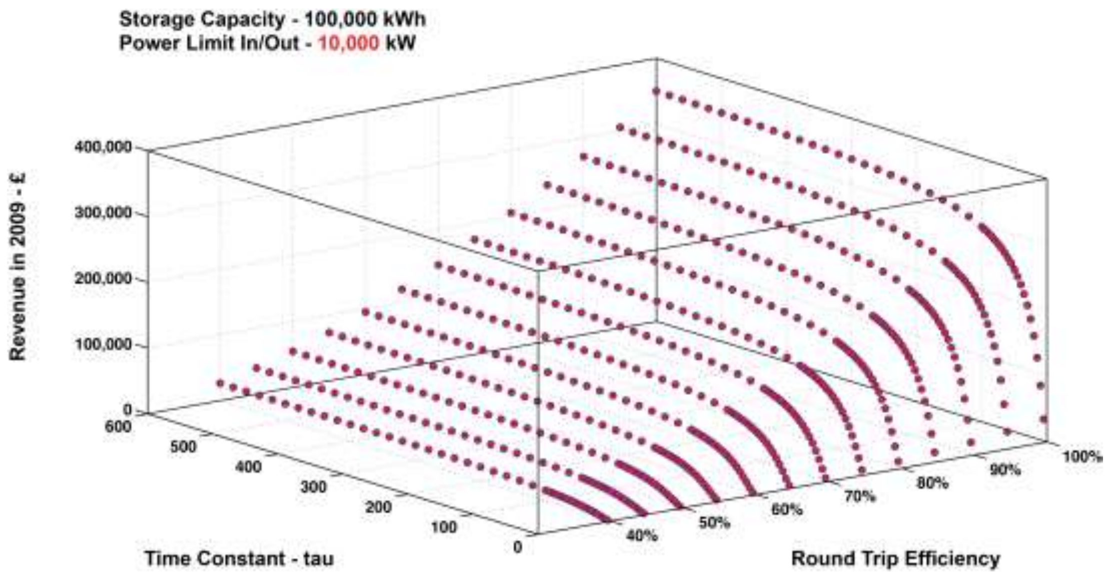


Figure 112 - Arbitrage revenue year 2009 for different round-trip efficiencies and different time constants (tau). Cap_max 100,000 kWh – Power Limit In/Out 10,000 kW

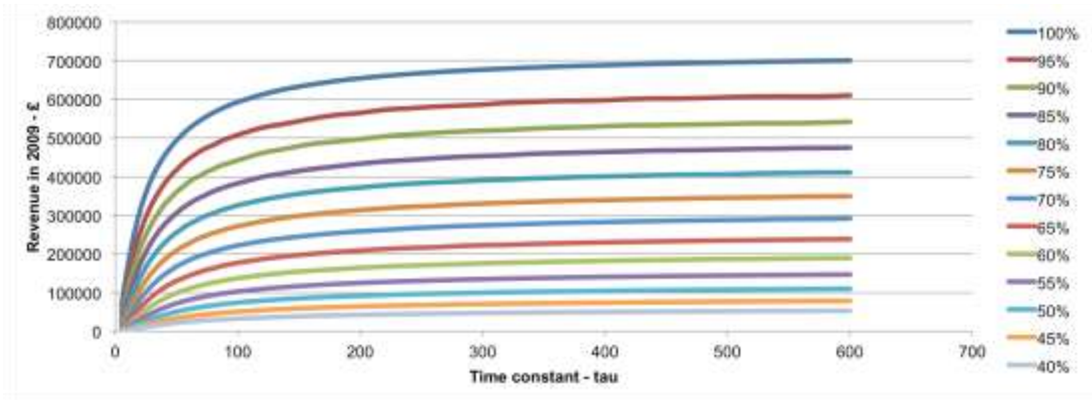


Figure 113 - Round-trip efficiency versus time-dependent efficiency, same values as previous figure

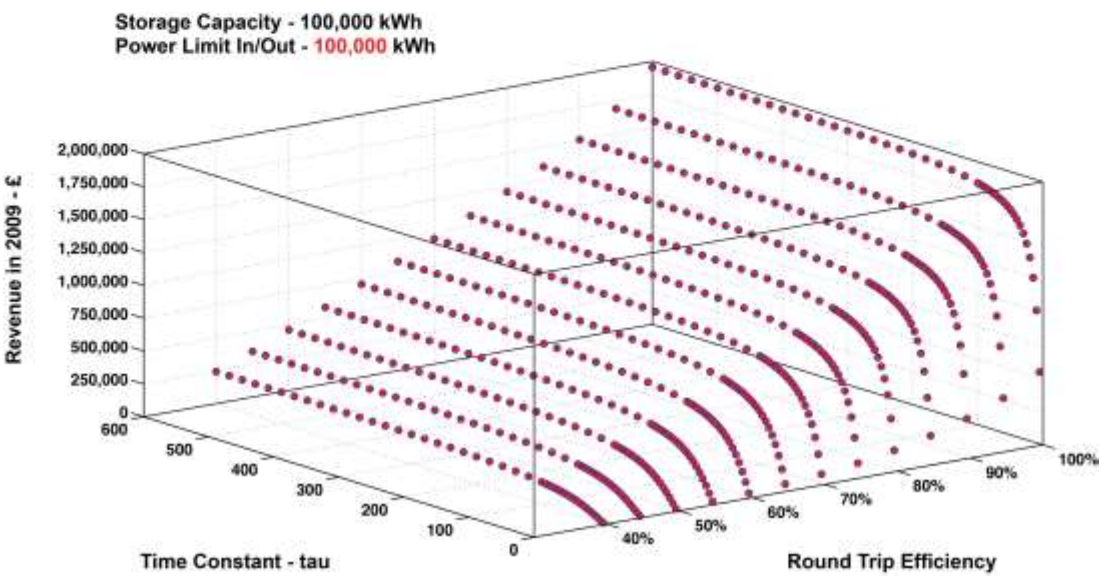


Figure 114 - Arbitrage revenue year 2009 for different round-trip efficiencies and different time constants (tau). Cap_max 100,000 kWh – Power Limit In/Out 100,000 kW

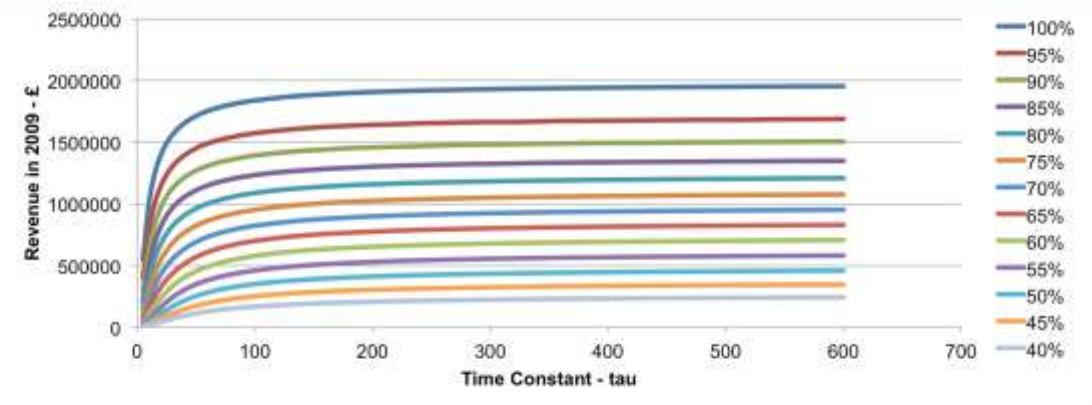


Figure 115 - Round-trip efficiency versus time-dependent efficiency, same values as previous figure

8.8 Discussion of varying the fixed efficiency versus the timedependent efficiency

Figure 112 and Figure 114 show the upper boundary values whilst varying the fixed efficiencies versus the time-dependent efficiency.

The model uses the formula: $exp^{\left(\frac{!_{!}\,!\,!_{!}}{!}\right)}$ to provide the self-discharge coefficient. When the value of the coefficient is equal to exp^{-1} *i.e.* when the time difference = the time constant, the value of the coefficient becomes 36.8%. Thus after a period of one time constant the store has self-discharged and now only has approximately 37% of its initial value. If the time constant is 100 time periods, it therefore takes 50 hours (one time-period = 30 minutes) for the storage device to lose approximately 63% of the energy it had at the start.

The model was run with the time constant (tau) ranging in value from 5 to 100 time periods with a step size of 5, and then from 100 to 600 time periods with a step size of 20.

The results show that there is a time-dependent effect at all round-trip efficiencies, with the effect being more pronounced at greater round-trip efficiencies. The trend in revenue at the 600 time period value (where a device would have lost 67% of the initial charge after 300 hours = 12.5 days) are clearly asymptotic towards the value of an infinite time constant or no self-discharge.

The nature of bulk energy storage and the markets it would intend to serve do point to technologies that will intrinsically have time-constants well above the 600 time period value, and so the results indicate that the reduction in revenue given a >600 time period value for the time constant that the time-dependent efficiency (selfdischarge) factor has a minor effect. There is even an argument that pumped-storage in the UK has in effect a negative time-constant at times when rainfall in the upper reservoir catchment area provides more energy than is input into the system using the pumps alone.

8.9 Comparison of grid data and model output for 6th and 7th January 2009

As a broad reality check, a snapshot of data from 2009 was arbitrarily chosen as the 6th and 7th of January. Aggregate data for 'pumped storage' connected to the transmission level was found on Elexon portal's website (Elexon, 2012), and has a granulation of 5 minutes. This is shown in Figure 116 along with the spot price. Figure 117 shows the model output for a 100,000 kWh device with 75% round-trip efficiency (efficiency_in = efficiency _out), no time-dependent loss, and a power limit in and out of 10,000 kW. Figure 118 shows the state of charge of Figure 117. The PLI/PLO value of 10,000 kW was chosen to represent the aggregate value for the UK's pumped storage devices so the model could fully charge or discharge in 20 time periods (10 hours). PLI/PLO was therefore set at 10% of the capacity of the storage device. From Table 13 the sum of the output of the UK's four existing pumped storage schemes is 2828 MW, and the sum of their storage capacities is 27,600 MWh. An average PLI/PLO for the UK's schemes is therefore ~10%, however, in reality this is a non linear figure, as Foyers pumped storage scheme only has 3.6 hours worth of capacity at full power, whereas Cruachan has over 22 hours at full power.

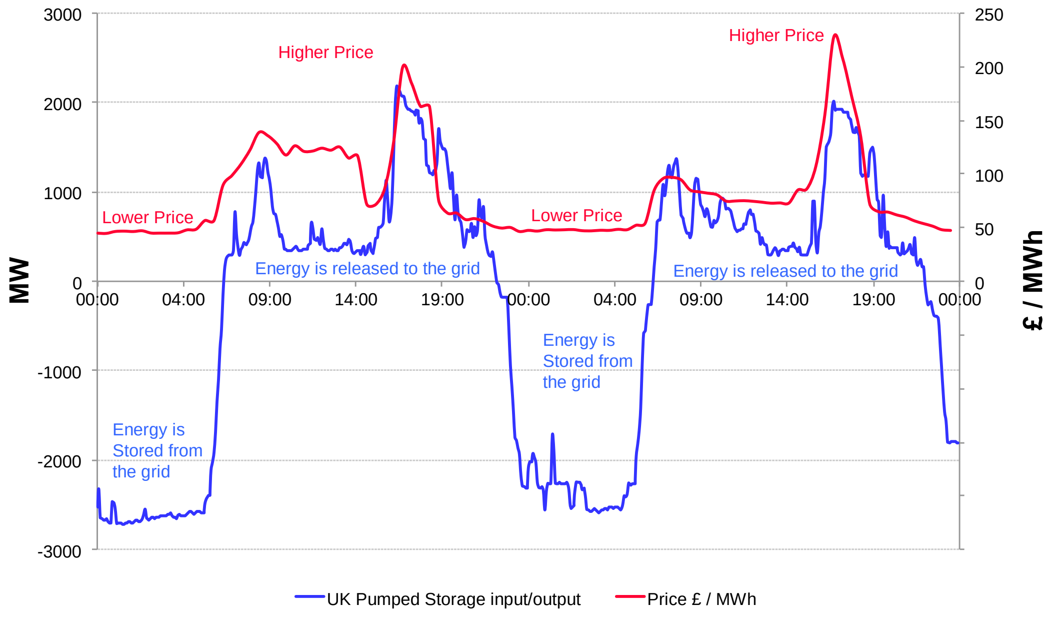


Figure 116 – Grid data from elexonportal.co.uk for aggregated output for UK pumped storage schemes

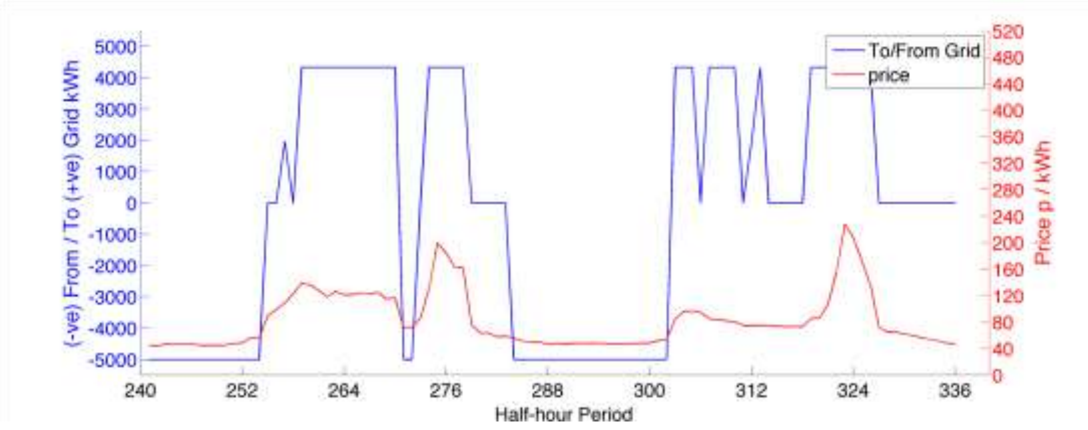


Figure 117 – 100,000 kWh device with 10,000 kW Power Limit In and Out, 75% round-trip efficiency, no time-dependent loss. 6th and 7th January 2009

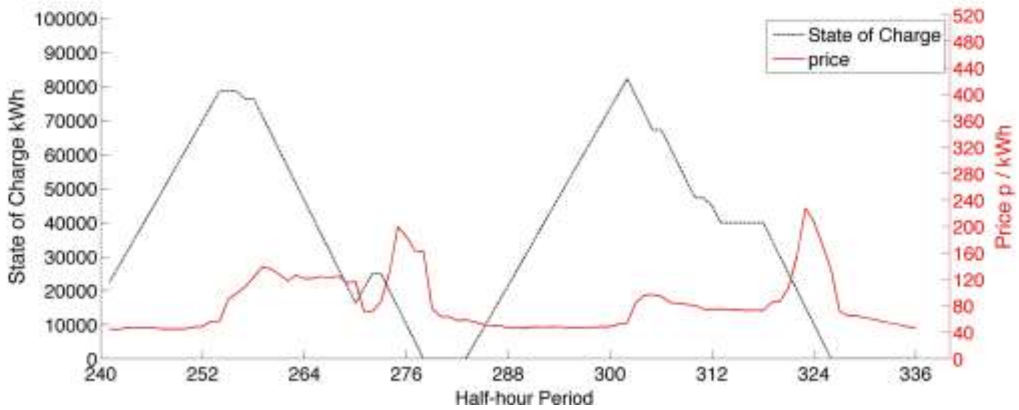


Figure 118 – State of Charge. 100,000 kWh device with 10,000 kW Power Limit In and Out, 75% round-trip efficiency, no time-dependent loss. 6th and 7th January 2009

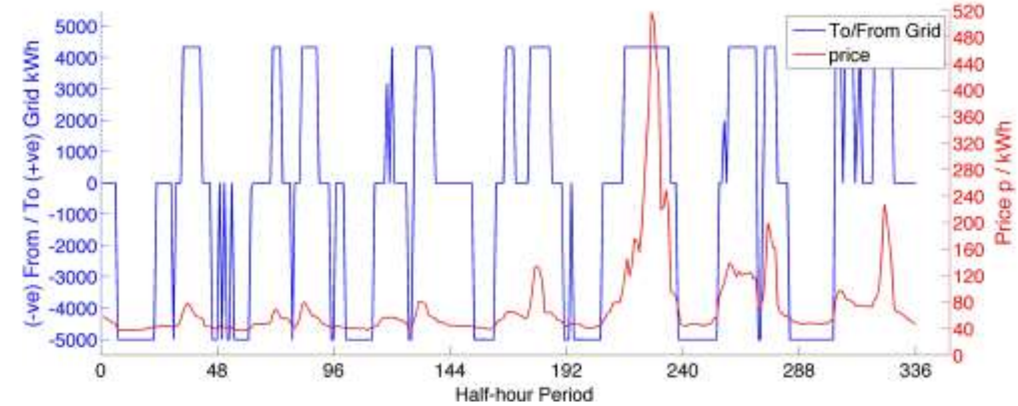


Figure 119 - 100,000 kWh device with 10,000 kW Power Limit In and Out, 75% round-trip efficiency, no time-dependent loss. 1st - 7th January 2009

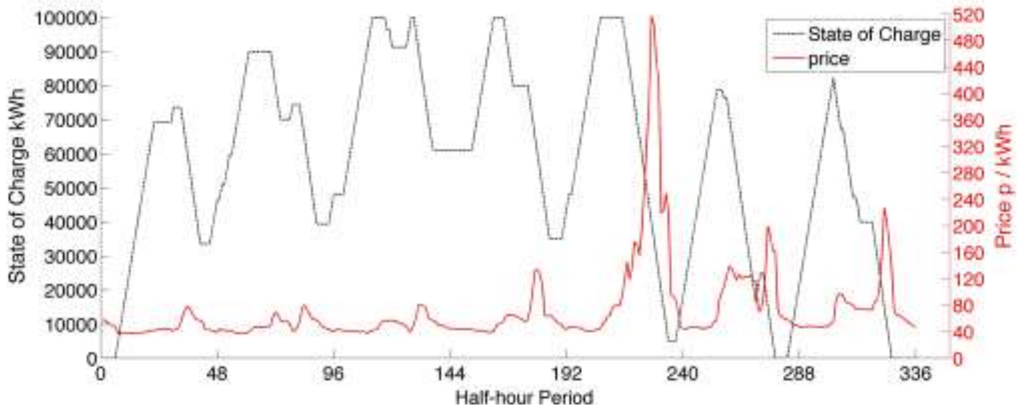


Figure 120 – State of Charge. 100,000 kWh device with 10,000 kW Power Limit In and Out, 75% round-trip efficiency, no time-dependent loss. 1st - 7th January 2009

Figure 119 and Figure 120 show the model output for the same device but for the first 7 days of 2009.

In order to show the difference of having a greater power limit in and out in comparison to the capacity of the device, Figure 121 and Figure 122 show the same results as the Figure 119 and Figure 120, with the only difference being that the power limit in and out value has increased from 10,000 kWh to 15,000 kWh. The time taken to fully charge or discharge the device has reduced from 20 time periods (10 hours) to 13.3 time periods (6.6 hours). This difference can be seen as a greater rate of change (a steeper ascent/descent of the black line) of the State of Charge – this was as expected.

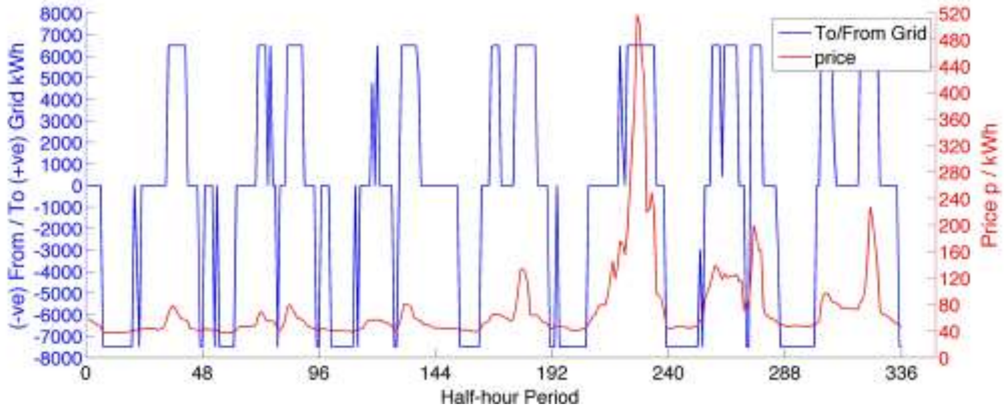


Figure 121 – 100,000 kWh device with 15,000 kW Power Limit In and Out, 75% round-trip efficiency, no time-dependent loss. 1st - 7th January 2009

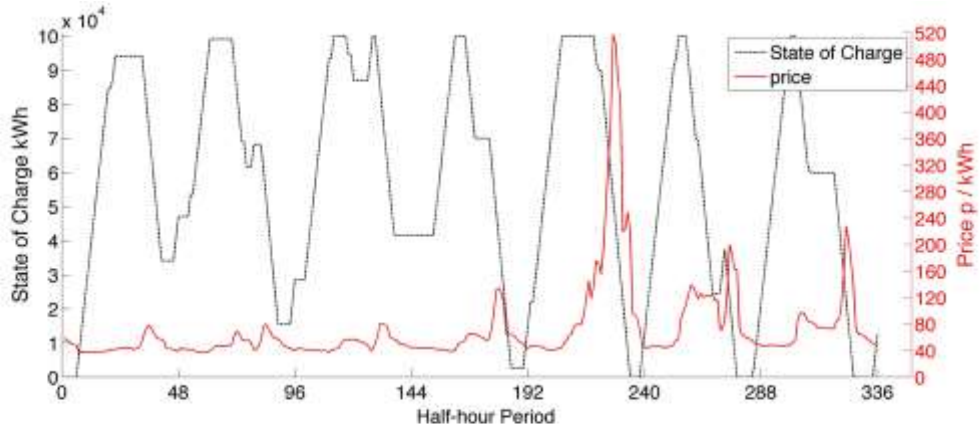


Figure 122 – State of Charge. 100,000 kWh device with 15,000 kW Power Limit In and Out, 75% round-trip efficiency, no time-dependent loss. 1st - 7th January 2009.

8.10 Impact of the diurnal nature of the price file structure

Figure 117 is the model's result of the actual aggregated values for pumped storage input/output shown in Figure 116. The data used for the model has a granularity of a 30-minute time-period, whereas the granularity of the data for Figure 116 has a granularity of a 5-minute time period. There seems to be a broad correlation between the times of charge and discharge with some of the smaller peaks even being picked out by the model. As mentioned previously, the time-series price data only changes every 30 minutes, so the higher frequency changes seen in the actual input/output from the aggregated pumped storage data must be due to other considerations, especially the quick spikes of power to or from pumped storage that have a value of approximately 500 MW.

Comparing Figure 120 to Figure 122 it can be seen that the greater power in/out available to charge/discharge the storage scheme in Figure 122 allows the storage scheme to be fully charged and fully discharged more often *i.e.* it is able to use the full depth of discharge available more often. This has an obvious benefit to capturing a greater amount of the available revenue, and thus leads to a higher annual revenue as shown in Figure 104 to Figure 106.

The output schedules of the model of which Figure 116 to Figure 122 are typical, seem to favour arbitrage cycles of at least a diurnal nature in order to maximise the revenue from time-shifting. In essence, the model seems to favour a dispatch schedule that tends to mimic the period of the underlying price file, and if this happens to be diurnal in nature, the schedule will tend to be diurnal in nature too. This is an important consideration for policy makers to be aware of regarding the greater encouragement of bulk energy storage – indeed – if the only payment mechanism for stimulating investment in bulk storage is through the spot market – then storage operators will tend to follow the period of the underlying price structure, and this may or may not be a desirable timeframe for storage. Policy makers may also need to take account of the other markets from which energy storage devices can derive revenue streams, *e.g.* balancing and black start markets, as provision of one service may preclude or disrupt the provision of a similar service to a different market.

8.11 How the model can be modified to evaluate the impact of imperfect foresight on the arbitrage revenue.

Thus far, the model has been used with historical electrical spot prices, but in reality operators would not be able to forecast prices perfectly. An important question is therefore how close an operator may come to capturing the upper boundary value obtained by perfect foresight. Sioshansi et al., (2009) attempted to do this by 'backcast' optimising using the previous two weeks of price data (which would then be known in reality to a storage operator) to provide the operational schedule for the following two weeks. Even with this basic approach, it was found the schedule was able to capture 85-90% of the theoretical maximum arbitrage value. Sioshansi et al. suggest this 'no-foresight backcasting approach' represents a lower bound of arbitrage value that could almost certainly be improved closer to the theoretical upper-boundary by more detailed load and price forecasting. A similar type of approach may be able to be attempted using this modelling framework, but would a partial rewrite of code to provide a breakdown of each year into 26 consecutive two-week periods that can then be aggregated over the year. This in itself would be an interesting comparison to see the difference between optimising over a years worth of data versus aggregating the values over shorter optimisation periods *e.g.* what impact does the beginning and end of the optimisation window have on the upper boundary figure.

Other methods to consider the impact on revenues from imperfect foresight were considered *e.g.* changing the price input files to have a random 'noise' superimposed; changing the variance but keeping the average price the same, and changing the average price but keeping the variance the same. However, the approach by Sioshansi et al. was thought to provide greater insight.

Given that even the basic nature of Sioshansi et al.'s approach is able to capture between 85 – 90% of the theoretical upper-boundary, it is felt that the values of the upper-boundary presented in this work appear to be a reasonable approximation. The upper-boundary values will intrinsically always be greater than the arbitrage value able to be captured by storage operators in reality, not only due to imperfect foresight, but also due to planned maintenance and other operational downtime.

Knowing the maximum theoretical revenue available to storage devices in historical markets is thought to be a useful addition to the general knowledge base on storage, especially the difference between annual revenues. It can act as the benchmark that forecasting techniques and scheduling can be measured by.

9 General Discussion

9.1 The requirement for increasing bulk storage

In terms of the amount of storage available to provide security of supply to any network – it is important to make a distinction between storage that works on a cycling timeframe of less than 48 hours (less than hundreds of GWhours of storage), and storage that is at a strategic level (TWhours of storage) that may be hoped never to be used at all. The former will have a system benefit in terms of balancing the electrical network on a day-to-day, and on shorter timeframes depending on the technology. The latter will also have a system benefit on longer timeframes at a considerable cost, and the benefit could be argued to be a social benefit to the system as a whole. In order to provide stored energy to the system in the eventuality that renewable energy generation is not able to provide primary energy for extended periods of time (5+ days), strategic level storage could be thought of as an insurance against this eventuality. Having the stored energy available for these periods would seem to preclude their use at certain times of year from being utilised on a day-today basis as there would be little point in having strategic storage if it is not available when it is actually required. This seems little different than the current strategic stores of fossil fuel energy that are increased and decreased throughout the year depending on the statistical likelihood of meeting the system's needs. If a greater level of strategic post-conversion electrical energy storage is to be considered it is therefore likely that it is partly funded through separate mechanisms than the revenues derived from the market based time-shifting of energy. These stores of energy are currently and historically in the form of coal, gas and nuclear fuel stocks, which may well continue to be used if low-carbon abatement technologies allow.

Even though replacing fuel storage with rechargeable storage on a similar scale would be environmentally as well as financially unacceptable, an increase in postconversion rechargeable storage can be examined.

Fossil fuels are energy dense, cost effective stores of energy, but their major drawbacks in terms of UK energy policy include the greenhouse gas emissions from combustion, and an increasing future reliance on imported fuels, as the indigenous production of fossil fuels reduces. Also, given that the supply of fossil fuels is finite, they are ultimately likely to become more expensive, and therefore less attractive as stores of energy. The UK has set long-term targets of an 80% reduction in CO2 emissions by 2050 (below 1990 levels), and a 34% reduction by 2020. These targets can be set against the findings of the European power plant database (Kjärstad & Johnsson, 2007) that provides a snapshot of current plant, plant in construction, and planned generation plants in the UK as of May 2006. The paper has a time horizon out to 2050 and notes that *'70% of the planned capacity is natural gas combined cycles (14 GW gas versus 20 GW in total), although the actual commissioning of some of these plants is highly uncertain. Moreover, 85% of all coal plants are older than 30 years, indicating that natural gas will become even more dominant if the current trend remains'*. If this current trend of investing in natural gas plants continues as the UK's indigenous oil and gas reserves deplete, the UK will become more heavily dependent on fossil fuel imports, which has implications for energy security for the UK. Indeed, a scenario analysis published by (Bhattacharyya, 2009) indicated that the *'UK is likely to face greater gas vulnerability in the future due to increased gas dependence in electricity generation and higher import dependence.'* This remains a significant problem for UK energy policy that cannot be hedged against in the market over the long-term.

The view of whether increased amounts of electrical energy storage would be an advantage to the network is dependent on the future UK energy generating mix, its interconnectivity with larger European grids, the future load profile of the UK, and the legislative status of renewables. These are all largely unknown at this point in time – but the benefit of rechargeable storage to different generating technologies can be considered. At some future increased level of non-dispatchable renewable energy capacity, it is likely that supply will be greater than demand in certain periods. The options of dealing with this excess supply are to increase the demand to meet supply, to curtail (reduce) the excess supply, or to store the excess energy (equivalent to increasing the demand). This reduction in curtailment is one of the largest sources of possible system benefit (as suggested by Strbac et al., (2012), as the energy lost to renewable generation curtailment in an earlier period could well offset fossil fuel based generation at a later time, with the associated fuel costs.

Dinorwig hydro-pumped storage scheme (~10GWh) was initially built by the Central Electricity Generating Board (CEGB - the UK's monopoly state energy provider) when the nuclear build program was expected to increase through the 1970's and 1980's. The increased electricity demand that was forecast did not materialise and the expected nuclear build program was scaled back. Dinorwig was built to provide a balancing service in the event that the output from a large nuclear power station was reduced at short notice, and to provide a rechargeable storage scheme in order to store off-peak electricity, which allowed baseload generators such as nuclear to remain in a steady state output matched to their highest efficiencies. There is some hope that the 3rd generation of nuclear power plants will have an increased operability in order to load follow (WNA, 2012). On the other hand, if future nuclear plants are utilised as inflexibly as historical plants, then electrical energy storage offers a method to increase the system flexibility.

Significant research effort is being devoted to the development and deployment of carbon capture and storage (CCS) for fossil fuel generating technologies. Dependent on the technology and design of the plant, post combustion CCS plants can be designed to quickly reduce the steam requirements for the carbon capture process, which would have the effect of providing a reserve output to the grid, albeit at the expense of increased carbon emissions for periods of time. Large amounts of bulk electrical energy storage are unlikely to be beneficial to fossil fuel plants with CCS, if their operability is equal to or even enhanced from the current generation of fossil fuelled plants, indeed, *'In the medium to long term it seems likely that flexible operation of most or all fossil plants could become virtually obligatory in many plausible lower carbon electricity generation mixes in many jurisdictions'* (Chalmers et al., 2009). An overview of the technologies, and likely benefits and disadvantages to operability of coal-fired plants with CCS is provided by (Chalmers & Gibbins, 2006; Chalmers & Gibbins, 2007; Chalmers, Lucquiaud, Gibbins, et al., 2009). The best route for policy makers to encourage this flexibility in CCS generation is unclear and also requires consideration, but if CCS allows the continued use of fossil fuels to provide pre-conversion storage to the UK network, then it will be important that greater flexibility is designed from the outset.

A large increase in wind generation is planned in the UK; the eventual amount is unclear, but if the 2020 legal commitment requires 15% of the UK's energy demand to be provided by renewable generators (DECC policies, 2013), the increase will be significant. The combination of variable renewable generation and electrical energy storage can provide a higher degree of certainty to the predicted output from their combined output. The market structure in the UK requires electrical generators to provide values for the amount they are able to supply to the network on a 30 minute rolling period basis. Every 24-hour period is divided into 48 rolling half hour blocks that generators can potentially aim to supply within, with the closing gate for bids being 60 minutes before the time period in question. If generators are not able to provide the predicted level of output for a particular timeframe, they will suffer financial penalties. Wind farm operators thus have to predict the available output from their wind turbines for the half hour block starting at least 60 minutes into the future. Electrical energy storage allows a wind farm operator the ability to balance a predicted output (60 minutes in the future) and thus reduce the amount of potential financial penalties. Scottish and Southern Energy will undoubtedly use part of their proposed new pumped storage scheme at Coire Glass in this manner if it passes planning and if they decide to construct it. The amount of electrical energy storage required can be optimised for a given timeframe, *i.e.* a 30-minute timeframe will require less storage than a 120-minute timeframe. A paper by Bathurst & Strbac, (2003) describes an algorithm to maximise value added with this type of postconversion storage. In a paper by Apt (2007) the power spectral density of the output of wind turbines was analysed using real data over a period from 2001 – 2004.
The output was shown to follow an $f^{-2/3}$ Kolmogorov spectrum over the frequency range 30s to 2.6 days. A conclusion was that any 'fill-in' power to compensate for the variable output of wind generators should have the ability to fluctuate its output in a similar manner. Linear generators such as a gas generator follow a Kolmogorov spectrum with a different value. It is likely that a combination of different storage

technologies (fuel cells, batteries, electrochemical capacitors, and bulk storage) would be better able to provide the ‘fill-in’ power, than one particular technology alone.

It should be borne in mind that as the size and topology of the network have a large influence on the benefit that any storage system can provide (Lund & Paatero, 2006), that different parts of the network will undoubtedly require different solutions. Large-scale electrical energy storage has been discussed as a backup for wind generation on a weekly scale (as weather patterns with low wind speeds can dominate over weekly rather than daily periods), which would require storage in the 100s of GWh - TWh range rather than the GWh range as exists now. This level of storage may well be required if fuels become less able to provide this service, perhaps because of limited CCS deployment.

The scale of present-day stocks of fossil fuels is heavily influenced by the length and nature of their supply chains, coupled with their variability in price. It can be argued that a move towards renewable energy generators removes or reduces the price variability of energy inputs, and also changes the risks associated from long supply chains of fossil and nuclear fuels to the risks associated with the variability of the weather. If the current combined level of pre and post-conversion is demonstrably adequate due to the high level of security of supply that the UK enjoys, it is thought that the different renewable energy supply chains (*e.g.* wind, solar, tidal, wave and biomass) would require reduced levels of combined storage. As many coal fired power plants in the UK are forced to close due to the Large Combustion Plant Directive. Text from National Grid’s seven year statement in 2011 states - *‘This affects some 12 GW of coal and oil-fired generating plant which will therefore now close by 1st January 2016. However, the exact timing of these closures is a commercial matter for plant owners, taking into account factors such as other environmental restrictions and the state of repair of the plants. Consequently, it is not possible to predict with certainty the precise timing of the impact of the LCPD on generation capacity, particularly if a replacement station is planned to be constructed on the same site.’*(National Grid SYS, 2011). As fossil fuel plants close, the need for a stockpile of fuel associated with that power plant will also disappear. It is therefore expected that there will be TWhours less of pre-conversion stores of coal available to the UK network after 2016. The absolute value of this change is not thought to provide a great deal of insight in and of itself but does indicate the changing nature of the UK electrical system. There will come a point however, when the levels of stores of primary energy and the generators available to convert these stores to electricity does require a fundamental change in the nature and operation of the combined (pre and post-conversion) level of energy stores available to the network.

As previously mentioned, the level of combined storage required will be influenced by many variables, not only the nature of the energy inputs (fuels or renewable energy), but also the type of generators, the type and level of balancing and ancillary services to be provided, the demand profiles, and the network topography. As a multi variant problem at a network level, it is complex to determine what an appropriate level of combined storage would be for a particular future UK network. Complex modelling using a combination of WASP, CGEN and MARKAL models can provide an ability to test various scenarios, giving valuable knowledge to policy makers (UKERC, 2009), however, models are a simplification of reality and programmed to analyse a particular set of problems. Energy storage has not been historically well represented and catered for in these suites of models. Recent work carried out by Strbac et al., (2012) for the carbon trust provides a high level assessment of the system benefits of increased post-conversion electrical energy storage within future UK networks and is a solid start in analysing the amount and system benefits of storage. Interesting findings include a difference in the type of storage preferred in different broad locations in the UK, such as a preference for centralised large storage in Scotland, and smaller distributed storage in the South East of England. If the variables are reduced to the level of individual generators (*e.g.* wind farms or even wind turbines), with known network constraints, statistical patterns of supply and demand, and well-understood market price variables, there is the potential to undertake an investment appraisal with these reduced set of variables for this distinct part of the network. This is indeed happening, and provides the rationale behind private sector investments in post-conversion storage not only in the UK but also around the world *e.g.* Coire Glass and bulk storage developments in Switzerland and Germany.

If policy makers decided that large-scale network electrical energy storage was to be encouraged within the existing market framework in order to promote a greater benefit to the market as a whole, then consideration should also be given to ownership and access by third parties. It should be noted that even though all the UK hydro-pumped storage schemes were built by the vertically integrated state-owned network operators before market liberalisation, that upgrading and a ~10% increase in the capacity of Dinorwig has taken place under unbundled and private market conditions. The existing hydro-pumped storage schemes are thus under private ownership, with no access rights for third parties, but do provide a benefit to the market as a whole in terms of load levelling and ancillary services.

If CCS can provide low-carbon use of the chemical energy contained in fossil fuel stocks, in the short to medium term it may not be desirable to replace these stores of fuels with greater levels of electrical energy storage, but it would be wise to use this time period to explore other methods of network flexibility including storage, and to increase market knowledge and participation before it does indeed become essential. It is difficult to imagine TWhours of post-conversion storage being built in the UK's liberalised electricity market for weekly storage of renewable energy if dispatchable low-carbon generating technologies can continue to use the stored energy available in fuels. It is assumed that in the future UK liberalised electricity market there will still be a finite limit to the amount and types of balancing and ancillary services required, and if these are secured by low-carbon generating technologies using fossil or nuclear fuels, that there will be a reduced requirement for further large scale postconversion storage schemes to be built. However, due to the expected increase of non-dispatchable generating plant, there is equally likely to be an increased requirement for more rechargeable storage in order to accept energy if demand drops below supply, overcome local network constraints, provide additional balancing services, and provide increased network flexibility and resilience. Demand side management and greater interconnectivity can also increase system flexibility and security, and storage does not have the right to dominate as a tool to help match supply and demand. Equally however given the size of the challenge of transitioning to a future low-carbon network these other methods should not be allowed to dominate either, as it is expected that all available tools should have a role to play. The transformation of electrical energy to a different energy vector *e.g.* electrical energy to heat or fuel could provide a degree of welcome flexibility as discussed in Blarke & H. Lund, (2008), and to be demonstrated by Aberdeen City's Hydrogen Hub and bus project (SHFCA, 2012). Ultimately the market frameworks to provide this needed flexibility will determine whether these different methods are complementary or competitive, and whether the required learning can happen at a rate to provide a smooth and orderly transition at an acceptable cost. The acceptable cost issue is highly important, as the end-users will end up paying for the transition one way or another, and after decades of cheap fossil fuels have ended (at least for UK customers) there is more discussion about the fairness of how profits are distributed along the energy supply chain. Full transparency of costs would be helpful in building public trust, but the precedence for this does not seem encouraging in a disparate market of private entities using commercial confidentiality to reduce transparency.

The sheer size of the stores of energy historically provided by pre-conversion fuel stockpiles in the TWh range point to the challenge of replacing them with postconversion storage of a similar level. However, if the long-term goal is to be independent of fossil fuels – then the storage role currently carried out by fossil fuels will require replacement. A new appropriate level of storage will have to be found where the size and location will be driven by future needs and markets, rather than the energy equivalents of historical fossil fuel stockpiles, which are driven by price variability and the perceived risks associated with long supply chains. It is therefore felt that the historical TWh level of stored energy will not be required to provide for security of supply to the network – but the future network will have to be smarter to allow for this reduction to take place. The role of future networks to provide greater levels of information exchange, possibly not just through price mechanisms is an outcome that is welcome, and as this seems to be the general direction of travel for the introduction of smart meters, it is viewed as an enabling foundation to allow for such things as a reduction in the overall level of stored energy required by the network.

It would be however be perspicacious to continue research into low-carbon fuels for large-scale strategic storage that is not dependent on fossil or nuclear fuels *e.g.* hydrogen or some other low-carbon synthetic fuel.

If renewables output is stored in periods of low demand and then supplied to the market in periods of high demand, storage could potentially reduce emissions by substituting for fossil fuel based electricity generation. Furthermore, the greater the penetration of non-dispatchable renewable generation requires a greater need to invest in supply and demand flexibility to accommodate the variability of renewables output, although in an integrated system what matters here is variability of the aggregation of renewables output, not that of individual technologies or sites, unless particular network constraints are an issue.

Of course, the incentive to invest in storage capacity in the UK is also going to be related to the ease with which electricity can be imported to and exported from the UK, and hence the degree of integration with the EU and elsewhere. A link of sufficient scale to Norway, for example, would give access to its hydro capacity, and a link of sufficient scale to European markets would increase the UK market's effective size. Nonetheless, there seems little doubt that storage capacity in the UK could, in principle at least, and in conjunction with renewables generation, be used to reduce UK emissions.

Electrical energy storage also offers potential benefits in terms of security of supply, irrespective of the source of primary energy. The ability of storage to not only supply energy to a network, but also to take energy from a network provides additional stability to a network that is greater than an equivalent sized generator or block of demand alone can provide. Interconnectors can also provide this bidirectional functionality, but they are dependent on generation or demand being available at the other end of the interconnector to provide the desired flexibility.

Overall, due to the orders of magnitude difference between existing levels of postconversion electrical energy storage in the UK and the pre-conversion chemical and atomic energy contained within fossil fuel and nuclear stocks, it is expected that preconversion storage of these fuel stocks will continue to be seen as the dominant factor in a strategy to improve security of supply in the short to medium term.

The decarbonisation of transport systems globally is seen as a method for the rapid decarbonisation of the energy system as a whole. Electrification of transport would provide an additional demand on the electrical network, which could be favourable in terms of flexibility and resilience, dependent on how the extra demand is integrated. Indeed, the potentially large increase of peak demands from electrical vehicles on the distribution grid is an area of concern that is being actively researched *e.g.* (Perujo & Ciuffo, 2010), and embedded smaller scale storage throughout the distribution network could also well form part of the solution to managing distribution network demands to increase the resilience of the system.

Electrical energy storage *per se* is historically costly, and many storage technologies are currently far from commercial viability. However, to the extent that storage can, in principle, contribute to reducing emissions and enhancing security of supply, there may be a case for greater government involvement. As for renewables, this could potentially take the form of legally binding targets (as applied in the case of EU oil reserves), the equivalent of a Renewable Obligation Certificate or Feed In Tariff based on supplies to the grid from stored renewable generation.

The EU currently mandates minimum reserves of petroleum products and the storage of these transport fuels provides an insurance policy against sudden shocks to supply or demand, which would have an undesirable political effect if shortages were to happen. Would this be feasible to mandate at a European level for a minimum level of post-conversion storage within each electrical market? This would have a considerable cost, but also a considerable benefit in terms of security of supply to the wider European energy system. To put this into some perspective the UK's postconversion electrical energy stores have a combined capacity of 27.6 GWh, which is less than 30 minutes of peak electrical demand (in raw energy terms). If legislation were to be considered to bring this up to one hour of some measure of peak demand – then this would be a phenomenal driver for the uptake of electrical energy storage.

The spot market price is influenced by a multitude of variables, but a major factor is the marginal cost of the next generating plant that offers to sell energy through the spot market. Peaking plants that only operate for a reduced set of hours of the year have to capture enough revenue in those hours to cover the annualised cost of running the plant plus the other financial aims of operating the plant. Peaking plants therefore submit bids that are much greater than the average spot price, which causes the super peaks in the spot price charged by a provider of last resort. A storage device operating through the spot market may also act to smooth the variability between demand and supply and by doing so increase the overall reliability of the system. While this may be of a wider social benefit to the system, there is no mechanism by which the storage operator is currently paid for these benefits through the spot market.

Different electrical spot markets will have different price profiles caused *inter alia* by the nature of the generating devices, the marginal cost of electrical energy produced by these devices, the demand profile, and the interconnectivity of the market to other markets. Different spot markets will therefore have different underlying price structures; the more variable the spot market price the more likely that electrical energy storage will have the opportunity to generate greater revenue through time-shifting. Spot markets with flatter price profiles (such as Norway) do not provide the same market opportunity for bulk energy storage as more volatile markets such as the UK and the Netherlands. It would be an interesting exercise to compare the results of different markets to the body of work carried out by Connolly et al., (2011).

10 Conclusions

10.1 Conclusions: UK energy stores of energy

10.1.1 Pre-conversion stores of fuels are the overwhelming stores of energy (over 99.9%) available to the UK electrical network

Storage has always been a key element of electrical networks that has historically been dominated by the pre-conversion stocks of stored energy available from fuels. The decarbonisation challenge facing the UK electricity sector should be viewed not only as a generating challenge, but also as a storage challenge. As the percentage of non-dispatchable low-carbon generators increases in the future UK electrical generating mix, the importance of flexible generation technologies and flexible demand side strategies to balance the network will also increase in importance.

In particular, the problem of excess supply looms large, which requires a rechargeable storage solution or flexibility to increase demand from a different market (either locationally or even a different energy vector). Electrical energy storage can offer benefits to both the supply side and the demand side of the network; the challenge lies in determining the best type, location and scale of this storage. It is thought that the drivers for the large stockpiles of fossil fuels lie within the inherent risks associated with international supply chains and price volatility. As the energy network changes to a system whose primary energy is based on, to a much greater extent, indigenous renewable sources with much shorter supply chains and less (or no) price volatility for the fuel, then the total amount of energy contained within pre and post-conversion stores of energy can conceivably be reduced, as the risks will change from the risks inherent in long supply chains to the risks associated with renewable energy resources.

However, due to the present mix of fuel storage versus rechargeable storage available to the UK network (over 99.92% contained in fuels vs. under 0.08% rechargeable storage), combined levels of storage are likely to continue to be dominated by stored fuels for the short to medium term, with the hope that carbon abatement technology and strategies can be scaled up to reduce the greenhouse gas emissions from their continued use. The challenge for new power plants that use fossil fuels with CCS or nuclear fuel is to have an increased operability that will allow renewable generating plant to supply low-carbon electricity when available.

10.1.2 Distributed storage

Distributed rechargeable storage at the small and medium scale (kWh-MWh) could also be a key enabling technology to allow demand side strategies to be even more flexible, as well as providing increased resilience throughout the network. Indeed, rather than existing controllable demands being seen as competition to the increase of distributed storage, it is conceivable that distributed storage would simply become part of a greater flexible demand and thus allow demand side management to become more effective *e.g.* the future demand from electric vehicles.

10.1.3 Synthetic fuels

If in a future world that has an increased average price and perhaps coupled with increased price volatility of fossil fuels, the manufacture of synthetic fuels that can be produced using excess energy could provide weekly or even interseasonal storage without the use of conventional fuels. The carbon footprint of these synthetic fuels will be determined by the primary energy input and the type of fuel *e.g.* if carbon based fuels – where did the carbon come from. Due to the energy density of fuels compared to any post-conversion storage technology, it is difficult to envisage TWh of stored energy being possible without the use of fuels.

10.1.4 Policy direction for energy storage in the UK

Given uncertainties about the flexibility of operation of future CCS and nuclear plants, concerns about security of supply of both nuclear and fossil fuels, the obvious current dominance of pre-conversion fuels within the network, increased price movements, and the possibility of synergy between the electrical network and the transport and heat networks it would be judicious for policy makers to give serious consideration to the potential role for significantly increased levels of postconversion electrical energy storage to increase system flexibility and resilience. An increase in recent reports covering this area do point to greater consideration by esteemed organisations such as the Low-carbon Innovation Coordination Group (LCICG, 2012), the Royal Academy of Engineering (RAEng, 2012), the Centre for Low-carbon Futures (CLCF, 2012), the Energy Research Partnership (ERP, 2011), and the Carbon Trust (Strbac et al., 2012). These reports have formed part of the background to increased funding in the wide area of energy storage and network flexibility by the Engineering and Physical Sciences Research Council as well as learning by doing pilot projects involving storage funded through the DNO's LowCarbon Network Fund (OFGEM, 2012a).

10.1.5 Storage Research Challenges for the UK

Many of the challenges for storage research remain, in addition to major material development, integration and cost challenges, serious questions require further consideration such as:

- the amount and location of where energy storage should be incorporated into the UK's energy transmission and distribution grids
- the balance between different energy storage technologies
- and indeed how a greater market for energy storage could be developed.

Increased research and development funding is helpfully not only being focused at the large-scale centralised level, but also at the distributed level, as modular storage in the 10 - 100 kWh range is viewed as potentially both benefitting distributed storage and domestic demand side strategies, and also meeting the storage needs of passenger vehicle transport. The continuing research and development of storage technologies in this range thus not only holds out breakthroughs of building a resilient distributed storage capacity throughout the electrical network, but would also help the aim of decarbonising transport using electric vehicles.

Research into heat storage for space heating/cooling and hot water requirements is also a hugely important area, although not discussed in this work. Further exploration of the costs and benefits of various heat storage technologies, with a greater understanding of the societal costs and benefits would allow a fuller understanding of policy options.

10.2 Conclusions: the arbitrage model

The method presented in this work provides an objective tool with which to compare storage systems through the provision of a single value for the maximum achievable revenue for the time-shifting of electrical energy in historical markets. In essence the model provides the optimal solution for the schedule of operation for a storage device that yields the upper boundary of revenue available from energy arbitrage. The model has the ability to simulate systems of various types, through the parameters of discharging and charging power limits, input efficiency, output efficiency, a self-discharge rate and maximum storage capacity. The input to the model is a discrete time-series for the market index price that the storage system operates under, which is taken to be the spot market price that the storage operator would have been able to access. A storage operator would therefore not have been able to derive greater revenue than this upper-boundary figure from arbitrage alone. For a full techno-economic assessment, other costs would need to be included, such as the capital and operation/maintenance costs of the storage systems, as well as analysis of other potential sources of revenue such as the ancillary services markets.

10.2.1 Variation of the power in and out ratio to overall storage capacity

The results of varying the power limit in and the power limit out (Figure 104 – 106) versus the over all capacity (how quickly the store can charge and discharge) were surprising in that there was not a greater bias towards the discharging side, given that lower prices tend to last for longer periods than price spikes. The results suggest a combination of charging and discharging power limits that are roughly equal gives the best revenue *i.e.* the pumps have a similar power rating to the turbines. This may in part be due to the set-up of the model capturing small short lived 'dips' in the spot price as well as the short lived peaks too, and may be an indication that the model can be overly sensitive to price variations, as long as the round trip efficiency is covered by the price increase. In reality a storage operator would be limited in choice of the combination of the size of the pump and the turbine by the sizes available in the market, and also whether the pump and turbine were intended to be the same device *e.g.* a reversible pump.

The results also suggest there is a greater revenue benefit for increasing the power rating ratio in order to fully charge or discharge in 4 hours than there is for increasing this further in order to fully charge or discharge below 4 hours in both the 45% and 75% round-trip efficiency runs.

10.2.2 Non-linear nature of changing the fixed efficiencies in and out

The results showed that increases in efficiencies seemed to provide an everincreasing non-linear absolute financial benefit *e.g.* an increase of 5% round-trip efficiency from 80% to 85% will have a greater absolute financial benefit than an increase from 40% to 45%. Indeed the increase of round-trip efficiency from 70% to 96% results in an approximate doubling of the revenue from arbitrage, although this may be particular to the 2009 price data used for these results. A more interesting suggestion if this finding is broadly correct is the doubling of arbitrage revenue from increasing the round trip efficiency from 59% to 77%, which is a development range contemplated by several developing storage technologies including cryogenic and pumped heat storage.

The results are also skewed towards the fixed efficiency out, *e.g.* a storage scheme with efficiency_in of **80**% and an efficiency_out of **90**% has a higher arbitrage revenue than a storage scheme of efficiency_in of **90**% and efficiency_out of **80**% (both have a round-trip efficiency of **72**%). This is thought to be due to the ability of the model to sell more of the stored energy with the higher efficiency_out value (given a finite storage capacity).

10.2.3 Self-discharge does not significantly impact revenue for bulk electrical energy storage

The difficulty and complexity of including a time-dependent loss into the algorithm was considered against the insights gained by this inclusion. The results suggest that self-discharge is not particularly significant in terms of a reduction in the annual upper-boundary value. This is thought mainly to be due to the tendency for energy storage devices to follow the underlying cycles of the price data in the market (and in many markets the most pronounced cycle is a daily cycle); in the UK market this is certainly true, with a peak and off-peak time during each day. In order to maximise the revenue, the algorithm therefore tends towards charging and discharging the store on a daily basis. The second point of consideration is in terms of the characteristics of potential bulk energy storage technologies, where the timedependent rate of loss within the store over a daily cycle would have to be largely insignificant. Therefore, considering the time taken to develop the algorithm with the inclusion of a self-discharge variable compared to the insights gained from its inclusion, it may not have been necessary to include this level of complexity. However, the path taken in the course of development of the algorithm would have been unlikely to take the route of a non-deterministic random walk based approach had the time-dependent variable not been included. The knowledge gained from tackling this thorny issue has resulted in a flexible algorithm that may possibly be able to be utilised for other purposes. The lesson for other researchers investigating the upper-boundary of value for storage arbitrage may well be that a simpler programming method can be used e.g. (Sioshansi et al., 2009).

10.2.4 Annual variation in upper boundary value

The variation in the annual upper boundary figures from 2006 – 2011 in the Great British electrical energy market is significant (Figure 98-103). Although Sioshansi et al., (2009) looked at data covering different years (2002 – 2007), in a different electrical market (PJM region in the USA), and using a different optimisation method, they equally showed that the variation between differing years was significant. It is expected that the variable nature of a future revenue stream from bulk electrical energy storage in any market will be viewed as a riskier proposal from an investment perspective. Bulk storage projects are capital intensive projects, which suggests that they are particularly sensitive to the borrowing costs for capital, *e.g.* any increase in borrowing costs brought about by the unknown nature of future arbitrage revenue streams will have a damaging effect on the profitability of the project. Independent operators of bulk energy storage therefore require a robust analysis of expected future prices, and thus expected future revenues from arbitrage. This is monstrously tricky task even on a quarterly ahead basis, so it would seem somewhat of a leap of faith to have confidence in the price profile of electrical spot markets decades into the future; this price profile determines the revenue opportunities that storage arbitrage seeks to capture. Given the revenue variation in the years presented in this work (which corroborates work by Sioshansi et al., (2009), it would seem that independent storage operators require to mitigate this inherent risk by accessing other markets that can provide a more stable source of revenue, *e.g.* ancillary services markets. An interesting investment case may be able to be made by a generator with a fleet of differing generator technologies *e.g.* coal, gas, renewables, where additional value may be able to be captured across (but internally to) the business by helping to provide greater operational flexibility to differing technologies.

10.2.5 Future market landscape for storage

The development and deployment of energy storage is essential as part of a sustainable and low-carbon energy future. This itself is crucially dependent on a more detailed techno-economic analysis for both policy makers and potential investors alike, and the time-shifting model presented here provides focussed but valuable insights.

It is my firm belief that future energy networks will benefit greatly from having access to greater levels of electrical energy storage, as they eventually transition away from the use of fossil fuels to provide primary energy, and thus move away from their intrinsic nature as stores of energy. However, the type, the location and the cost of these storage devices are unknown. The development path for energy storage technologies at some point requires a vibrant market to allow growth and learning for all parties involved, from the system operator, distributed network operator, the regulators, the lenders, and also customers who will ultimately have to pay the price of a secure energy system. It is my hope that policy makers have the foresight to create these markets in a manner that enhances the development of storage in the short to medium term, so that the energy system as a whole benefits from this learning experience in the long term.

The results of the UK Energy Market Reform are as yet unclear in terms of the specific benefit to energy storage investment, with a hope that the capacity mechanism part of the reform would provide a better landscape for storage investment. However, it may well turn out that demand side management and new peaking plants are better able to capture this revenue stream than new investments in energy storage. It would indeed be helpful for energy storage development if part of the capacity mechanism was ring-fenced for low-carbon devices (such as electrical energy storage rather than fossil fuel peaking plants), or indeed a different market mechanism altogether. Storage developers ultimately require a functioning market for their technologies that is not wholly dependent on demonstrator projects for their revenue and thus continued development and deployment.

In much the same manner as renewable generation has benefitted from policies promoting access to protected market shares for some time, with the aim to provide a wide learning experience for all parties in order to meet long-term aspirations, I feel that storage may benefit from similar consideration. The upper-boundary values calculated by this modelling framework may also help inform policy makers to the nature of incentives they may need to offer storage operators if they wish to encourage investment in bulk electrical energy storage devices.

11 Suggestions for future work

There were several avenues of research that were considered but not undertaken due to the timeframes involved in development of the model and completion of this work. These could be conveniently grouped under future work and include:

- How the model can be modified to investigate whether the assumption of a ‘price taker’ is robust. - This could be attempted by investigating the relationship between price and demand, and then changing the price input file to incorporate the additional load at times of charging, and by reducing the generation required by the rest of the market at times of discharging. There may be some difficulty with this approach however, given the zero or even negative price of electricity that may be attributable to wind energy that would otherwise be curtailed.

- How the model can accommodate network constraints.- This would be very location specific, but changing the inputs to the model to use a time series for the power limit in and the power limit out, rather than a single value used in this work, may provide the ability to investigate network constraints further.

- How the model can accommodate changing device parameters. – Electrochemical storage devices change their efficiency and capacity parameters dependent on the rate of charge/discharge, temperature and history of use. This additional layer of complexity may not be tractable with this programming method.

- How the model can be modified to evaluate the impact of imperfect foresight on the results. The approach by Sioshansi et al., (2009) seems a sensible approach to modify the model. Rather than having the model optimise over a year (as now), the model could be recoded to optimise over a two-week period, which are then aggregated over an annual basis. The method uses the previous two weeks of historical price data (which would be known by a storage operator) to optimise, in order to provide the operational schedule for the following two weeks. Essentially this method presupposes that the following two weeks of prices are the same as the previous two weeks of prices. Given this basic approach, this can be considered as providing a lower bound to the arbitrage value able to be captured by a storage operator, as in reality, a storage operator would have a more complex method of forecasting the price of electrical energy.

- Using the model to compare various storage technologies in different markets, in order to gain an idea of their comparative attractiveness as an investment. – The price files from differing markets could be used as input to the model and the results compared.

- Using the output of the model to provide duration curves for charging, discharging and state of charge of the storage device – The output files could be changed to provide this data, which can then be analysed and presented in graphical format.

- Using the model to provide insights into different operational strategies e.g. if the store always bought energy between 03:00 and 06:00 and always sold the energy back between 17:00 and 20:00, how much revenue would this capture compared to the optimum? - The Power Limits In (PLI) and Power Limits Out (PLO) single value in this work could be changed to a matrix that has different PLI and PLO values throughout the day and year.

- Investigating when the revenue aggregating to the upper boundary figure is captured; is it biased by the revenue from several price superpeaks, is there much greater revenue at certain times of year? – Investigation of the optimal operation schedule and associated revenue on an hourly, daily, or seasonal basis.

- Using the model to provide insights into seasonal storage, *e.g.* what would the model outputs be given a set of conditions of a theoretical storage system with a capacity at least and 1000 times greater than the power limits in or out (full charge/discharge over almost 42 days). - Changing the PLI and PLO ratio to the storage capacity would provide some insights into this.

- Developing the model to take energy data in order to consider where storage would be optimally placed on a network to provide the greatest level of benefit to the system. (wholly dependent on the ability to access robust and credible energy data at a distributed level). - Investigation of code rewrite to provide inputs from several network flows.

- If used in conjunction with the carbon intensity for different generators, the overall CO_2 production in electrical networks with and without storage may be able to be estimated. If feasible, this could then be used to calculate any net CO_2 savings resulting from the use of energy storage in an electrical network, *e.g.* when wind energy at a time of low demand is used to offset more CO_2 intensive peaking plant at a later time. - Investigation of code rewrite to provide additional functionality.

- Providing a more user-friendly interface for the model so that others may use the model without the learning overhead that is intrinsic to the current version. - Investigation of interfaces with the High Performance Computing environment.

The algorithm has already been extended in order to compare the increased revenues available from using storage with renewable energy generation suffering from different levels of curtailment, although this is particularly network dependent.

Overall, the model seems to be a flexible and powerful tool that can be coded in different ways to provide insights into other areas of interest.

12 References

2006/67/EC (2006) COUNCIL DIRECTIVE 2006/67/EC. Available from: <http://www.energy.eu/directives/l_21720060808en00080015.pdf> [Accessed 26 February 2013].

AEA (2011) *AEA Biomass Report*. Available from: <http://bit.ly/YUxZYm> [Accessed 26 February 2013].

Allan, G., Eromenko, I., McGregor, P. & Swales, K. (2010) The regional electricity generation mix in Scotland: A portfolio selection approach. *Working Papers*. Available from: <http://ideas.repec.org/p/str/wpaper/1010.html> [Accessed 26 February 2013].

Anderegg, W.R.L., Prall, J.W., Harold, J. & Schneider, S.H. (2010) Expert credibility in climate change. *Proceedings of the National Academy of Sciences*. Available from: <http://www.pnas.org/content/early/2010/06/04/1003187107.abstract> [Accessed 26 February 2013].

Apt, J. (2007) The spectrum of power from wind turbines. *Journal of Power Sources*, 169 (2), pp.369–374.

Ausubel, J. & Marchetti, C. (1996) Elektron: electrical systems in retrospect and prospect. *Daedalus*. Available from: <http://www.jstor.org/stable/20027374> [Accessed 21 August 2012].

Bathurst, G.N. & Strbac, G. (2003) Value of combining energy storage and wind in short-term energy and balancing markets. *Electric Power Systems Research*, 67 (1), pp.1–8.

BERR (2007) *The Fuel Security Code*. Available from: <http://bit.ly/YyIS3Q> [Accessed 26 February 2013].

Bertoletti, P., Cavaliere, A. & Tordi, A. (2008) The Regulation of Access to Gas Storage with Capacity Constraints. *economia.unipv.it*. Available from: <http://bit.ly/127Mn5B> [Accessed 26 February 2013].

Bhattacharyya, S.C. (2009) Fossil-fuel dependence and vulnerability of electricity generation: Case of selected European countries. *China Energy Efficiency*, 37 (6), pp.2411–2420.

Blarke, M.B. & Lund, H. (2008) The effectiveness of storage and relocation options in renewable energy systems. *Renewable Energy*, 33 (7), pp.1499–1507.

BMReports (2013) n e t a | Electricity Summary Page [Internet]. Available from: <http://www.bmreports.com/bsp/bsp_home.htm> [Accessed 20 February 2013].

Carrasco, J.M., Franquelo, L.G., Bialasiewicz, J.T., Galvan, E., Guisado, R.C.P., Prats, M.A.M., Leon, J.I. & Moreno-Alfonso, N. (2006) Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey. *Industrial Electronics, IEEE Transactions on*, 53 (4), pp.1002–1016.

CCA (2008) *Climate Change Act 2008 (UK: The Stationary Office Limited) chapter 27*. Available from: <http://www.legislation.gov.uk/ukpga/2008/27/contents> [Accessed 26 February 2013].

CCC (2013) Carbon Budgets [Internet]. Available from: <http://www.theccc.org.uk/carbon-budgets> [Accessed 26 February 2013].

CCC (2010) Fourth Carbon Budget [Internet]. Available from: <http://www.theccc.org.uk/reports/fourth-carbon-budget> [Accessed 26 February 2013].

CCC (2011) Renewable Energy Review [Internet]. Available from: <http://www.theccc.org.uk/reports/renewable-energy-review> [Accessed 26 February 2013].

CDIAC (2011) Top 20 Emitting Countries by Total Fossil-Fuel CO2 Emissions for 2008 [Internet]. Available from: <http://cdiac.ornl.gov/trends/emis/tre_tp20.html> [Accessed 5 January 2012].

Chalmers, H. & Gibbins, J. (2007) Initial evaluation of the impact of postcombustion capture of carbon dioxide on supercritical pulverised coal power plant part load performance. *The 6th European Conference on Coal Research and its Applications*, 86 (14), pp.2109–2123.

Chalmers, H. & Gibbins, J. (2006) Potential for synergy between renewables and carbon capture and storage. Available from: <http://www.co2capture.org.uk/Publications/Chalmers.pdf> [Accessed 26 February 2013].

Chalmers, H., Lucquiaud, M., Gibbins, J. & Leach, M. (2009) Flexible Operation of Coal Fired Power Plants with Postcombustion Capture of Carbon Dioxide. *Journal of Environmental Engineering*, 135 (6), pp.449–458.

CLCF (2012) *Research Reports | Centre for Low Carbon Futures*. Available from: <http://www.lowcarbonfutures.org/sites/default/files/Pathways_energy_storage.pdf> [Accessed 25 February 2013].

Connolly, D., Lund, H., Finn, P., Mathiesen, B.V. & Leahy, M. (2011) Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage. *Energy Policy*, 39 (7), pp.4189–4196.

Crampes, C. & Moreaux, M. (2010) Pumped storage and cost saving. *Energy Economics*, 32 (2), pp.325–333.

Darling, S.B., You, F., Veselka, T. & Velosa, A. (2011) Assumptions and the levelized cost of energy for photovoltaics. *Energy & Environmental Science*, 4 (9), pp.3133–3139.

DECC Coal (2011a) *2011 Digest of UK Energy Statistics - ISBN 9780115155277 - Chapter 2 Solid fuels and derived gases*. Available from: <http://bit.ly/13OUIXk> [Accessed 26 February 2013].

DECC Coal (2011b) *Historical coal data: coal production, availability and consumption 1853 to 2011*. Available from: <http://bit.ly/XY4R05> [Accessed 26 February 2013].

DECC ET (2012) *DECC Energy Trends ISSN 2040-6029*. Available from: <http://bit.ly/XY2Ukh> [Accessed 26 February 2013].

DECC GHG (2013a) *2011 final UK figures: Statistical release*. Available from: <http://bit.ly/Y7kR0b> [Accessed 26 February 2013].

DECC GHG (2013b) UK Greenhouse Gas emissions - 2011 final UK figures: Data tables [Internet]. Available from: <http://bit.ly/Yz0PiW> [Accessed 26 February 2013].

DECC Hydro (2010) *England and Wales Hydropower Resource Assessment*. Available from: <http://bit.ly/127SiHZ> [Accessed 26 February 2013].

DECC policies (2013) Increasing the use of low-carbon technologies - Policies - Inside Government - GOV.UK [Internet]. Available from: <http://bit.ly/VvUNOY> [Accessed 26 February 2013].

DECC PV (2013) Weekly solar PV installation and capacity based on registration date - Statistical data sets - Inside Government - GOV.UK [Internet]. Available from: <http://bit.ly/WfSbHF> [Accessed 26 February 2013].

DEFRA (2012) 2012 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. Available from: <http://bit.ly/ZLCkRK> [Accessed 26 February 2013].

DERA (2012) Reserves, Resources and Availability of Energy Resources 2011 - ISSN: 2193–5319 [Internet]. Available from: <http://bit.ly/XdGTRs> [Accessed 26 February 2013].

DUKES 2.1.1 (2011) *Digest of UK Energy Statistics 2.1.1*. Available from: <http://bit.ly/WcUeg2> [Accessed 26 February 2013].

DUKES 2.6 (2013) *Digest of UK Energy Statistics 2.6*. Available from: <http://bit.ly/15gqJdc> [Accessed 26 February 2013].

DUKES 3.1.1 (2011) *Digest of UK Energy Statistics 3.1.1*. Available from: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65781/dukes3_1_1.xls> [Accessed 26 February 2013].

DUKES 4.1.1 (2011) *Digest of UK Energy Statistics 4.1.1*. Available from: <http://bit.ly/YzOyuH> [Accessed 26 February 2013].

DUKES 4.5 (2011) *Digest of UK Energy Statistics 4.5*. Available from: <http://bit.ly/YVycdG> [Accessed 26 February 2013].

DUKES 5.1.1 (2011) *Digest of UK Energy Statistics 5.1.1*. Available from: <http://bit.ly/WoiyG1> [Accessed 26 February 2013].

DUKES 5.10 (2010) *Digest of UK Energy Statistics 5.10*. Available from: <http://bit.ly/YUAHwS> [Accessed 26 February 2013].

DUKES 5.6 (2013) *Digest of UK Energy Statistics 5.6*. Available from: <http://bit.ly/Yyxcyi> [Accessed 26 February 2013].

DUKES A.1 (2011) *Digest of UK Energy Statistics A.1*. Available from: <http://bit.ly/YyvuwE> [Accessed 26 February 2013].

Dunn, B., Kamath, H. & Tarascon, J.-M. (2011) Electrical Energy Storage for the Grid: A Battery of Choices. *Science*, 334 (6058), pp.928 –935.

EC (2009a) European Renewable Energy Directive (2009/28/EC) [Internet]. Available from: <http://bit.ly/X8xpZf> [Accessed 26 February 2013].

EC (2009b) The EU climate and energy package - Policies - Climate Action - European Commission [Internet]. Available from: <http://ec.europa.eu/clima/policies/package/index_en.htm> [Accessed 12 January 2012].

Elexon (2012) ELEXON Portal - Historic Generation by Fuel Type [Internet]. Available from: <http://bit.ly/15Ni1EH> [Accessed 26 February 2013].

Elexon ETA (2012) Electricity Trading Arrangements - beginners guide v2.0 [Internet]. Available from: <http://bit.ly/XzPDCi> [Accessed 26 February 2013].

EMO (2009) *Energy Markets Outlook - ISBN: 9780102963137*. DECC. Available from: <http://bit.ly/XzQ8wq> [Accessed 26 February 2013].

ERP (2011) energystorage | Energy Research Partnership [Internet]. Available from: <http://bit.ly/XDNPp0> [Accessed 26 February 2013].

EU/0363 (2009) *COM/2009/0363 FIN*. Available from: <http://bit.ly/VL4BF8> [Accessed 26 February 2013].

EUK (2010) Energy UK [Internet]. Available from: <http://www.aepuk.com/aboutelectricity/electricity-market/> [Accessed 10 June 2010].

Figueiredo, F.C. & Flynn, P.C. (2006) Using diurnal power price to configure pumped storage. *Energy Conversion, IEEE Transactions on*, 21 (3), pp.804–809.

Google Public Data Explorer (2013) Google Public Data Explorer [Internet]. Available from: <http://www.google.com/publicdata/directory> [Accessed 19 February 2013].

Graves, F., Jenkin, T. & Murphy, D. (1999) Opportunities for Electricity Storage in Deregulating Markets. *The Electricity Journal*, 12 (8), pp.46–56.

Gross, R., Heptonstall, P., Leach, M., Anderson, D., Green, T. & Skea, J. (2007) Renewables and the grid: understanding intermittency. *Energy*, 160 (1), pp.31–41.

Grubb, M. (2004) Kyoto and the Future of International Climate Change Responses: From Here to Where? *International Review for Environmental Strategies (IRES)*, 5 (1), pp.15–38.

Grubb, M., Butler, L. & Twomey, P. (2006) Diversity and security in UK electricity generation: The influence of low-carbon objectives. *Energy Policy*, 34 (18), pp.4050–4062.

GSE (2012) GSE Storage Map [Internet]. Available from: <http://www.gie.eu.com/index.php/maps-data/gse-storage-map> [Accessed 6 February 2012].

HMG PA (2010) *HM Government 2050 Pathways Analysis*. Available from: <http://bit.ly/13eaL5p> [Accessed 26 February 2013].

Hulme, M. (2009) *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity - ISBN:9780521727327*. Cambridge University Press.

Hunt, G.W. & Technols, G.N.B. (1999) Valve regulated lead/acid battery systems. *Power Engineering Journal [see also Power Engineer]*, 13 (3), pp.113–116.

IEA (2011) IEA Press Release [Internet]. Available from: <http://www.iea.org/newsroomandevents/pressreleases/2011/june/name,20309,en.html> [Accessed 20 February 2012].

IEA (2012) MARKAL [Internet]. Available from: <http://www.ieaetsap.org/web/Markal.asp> [Accessed 26 February 2013].

IEA (2010) *Power Generation from Coal*. Available from: <http://www.iea.org/ciab/papers/power_generation_from_coal.pdf> [Accessed 26 February 2013].

Infield, D.G. (1984) A study of electricity and central electricity generation [Internet]. Available from: <http://bit.ly/V5BvRG> [Accessed 26 February 2013].

IPCC (2007a) *Climate Change 2007: Synthesis Report*. Available from: <http://bit.ly/DkgSJ> [Accessed 26 February 2013].

IPCC (2011) *IPCC - Intergovernmental Panel on Climate Change*. Available from: <http://www.ipcc.ch/organization/organization.shtml> [Accessed 2 January 2012].

IPCC (2007b) *IPCC - Reports*. Available from: <http://bit.ly/dKvFUO> [Accessed 26 February 2013].

Kjärstad, J. & Johnsson, F. (2007) The European power plant infrastructure—Presentation of the Chalmers energy infrastructure database with applications. *Energy Policy*, 35 (7), pp.3643–3664.

Korpaas, M., Holen, A.T. & Hildrum, R. (2003) Operation and sizing of energy storage for wind power plants in a market system. *International Journal of Electrical Power & Energy Systems*, 25 (8), pp.599–606.

Lannen, N. (2010) New Pumped Storage Proposals. Available from: <http://bit.ly/WqBzrq> [Accessed 26 February 2013].

LCICG (2012) Working together - Technology Focus Areas - Electricity Networks & Storage - LCICG | Low Carbon Innovation Co-ordination Group [Internet]. Available from: <http://www.lowcarboninnovation.co.uk/document.php?o=15> [Accessed 25 February 2013].

Leiserowitz, A., Maibach, E., Roser-Renouf, C., Smith, N. & Hmielowski, J.. (2011) Climate Change in the American Mind: Americans' Global Warming Beliefs and Attitudes in November 2011. Available from: <http://environment.yale.edu/climate/files/ClimateBeliefsNovember2011.pdf > [Accessed 26 February 2013].

Lu, N., Chow, J.H. & Desrochers, A.A. (2004) Pumped-storage hydro-turbine bidding strategies in a competitive electricity market. *Power Systems, IEEE Transactions on*, 19 (2), pp.834–841.

Lund, P. & Paatero, J. (2006) Energy storage options for improving wind power quality. *Nordic Wind Power Conference*. Available from: <http://paatero.arkku.net/pub/conf_2006_NWPC_Espoo.pdf> [Accessed 26 February 2013].

Maeda, H. (2005) The Global Nuclear Fuel Market – Supply and Demand 20052030. WNA Market Report. Annual Symposium 2005. [Internet]. Available from: <http://www.world-nuclear.org/sym/2005/pdf/Maeda.pdf> [Accessed 26 February 2013].

Maly, D.K. & Kwan, K.S. (1995) Optimal battery energy storage system (BESS) charge scheduling with dynamic programming. *Science, Measurement and Technology, IEE Proceedings* -, 142 (6), pp.453–458.

Mathiesen, B.V. & Lund, H. (2009) Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. *Renewable Power Generation, IET*, 3 (2), pp.190–204.

Mokrian, P. & Stephen, M. (2006) A stochastic programming framework for the valuation of electricity storage - 26th USAEE/IAEE North American Conference, September 24-27. Available from: <http://www.iaee.org/en/students/best_papers/PedramMokrian.pdf> [Accessed 26 February 2013].

National Grid (2012a) *2-52 Week Ahead Data (NDFW,TSDFW,OCNMFW,OCNMFW2) Last Updated at 2012-07-12 13:45:00*. Available from: <http://www.bmreports.com/bsp/BMRSSystemData.php?pT=WEEKFC#> [Accessed 16 July 2012].

National Grid (2012b) *National Grid: Future Requirements*. Available from: <http://bit.ly/YAVJ5B> [Accessed 26 February 2013].

National Grid (2011a) *National Grid: Gas Ten Year Statement 2011*. Available from: <http://bit.ly/XZ9SIH> [Accessed 26 February 2013].

National Grid (2012c) *National Grid: Operational documents - Gas Demand and Supply Forecasting Methodology*. Available from: <http://bit.ly/Wgvint> [Accessed 26 February 2013].

National Grid (2011b) *National Grid: Storage information - National Grid 2011/12 Safety Monitor and Firm Gas Monitor Requirements*. Available from: <http://bit.ly/ZGTAbk> [Accessed 26 February 2013].

National Grid (2009) *National Grid: Storage information - Preliminary Safety & Firm Monitor Requirements 2009/10*. Available from: <http://bit.ly/13RCdBo> [Accessed 26 February 2013].

National Grid (2012d) *NG: Data Explorer*. Available from: <http://marketinformation.natgrid.co.uk/gas/DataItemExplorer.aspx> [Accessed 26 February 2013].

National Grid (2012e) *Overview of BETTA market structure*. Available from: <http://www.nationalgrid.com/uk/sys_06/chap10/images/fig10-1.gif> [Accessed 26 February 2013].

National Grid SYS (2011) *National Grid: 2011 National Electricity Transmission System (NETS) Seven Year Statement*. Available from: <http://bit.ly/XB2X6h> [Accessed 25 February 2013].

National Grid-Services (2012) *National Grid: Services*. Available from: <http://www.nationalgrid.com/uk/Electricity/Balancing/services/> [Accessed 26 February 2013].

Neuhoff, K., Boyd, R., Grau, T., Barquin, J., Echabarren, F., Bialek, J., Dent, C., von Hirschhausen, C., Hobbs, B.F., Kunz, F., Weight, H., Nabe, C., Papaefthymiou, G. & Weber, C. (2011) Renewable Electric Energy Integration Quantifying the Value of Design of Markets for International Transmission Capacity. Available from: <http://www.diw.de/documents/publikationen/73/diw_01.c.387959.de/dp1166.pdf> [Accessed 16 July 2012].

Newberry, D. (1998) Freer Electricity Markets in the UK: A Progress Report. *Energy Policy*, 26 (10), pp.743–749.

NFA (2008) Scottish Hydro Resource Study [Internet]. Available from: <http://bit.ly/YykLyd> [Accessed 26 February 2013].

NPP (2007) The Nobel Peace Prize 2007 [Internet]. Available from: <http://www.nobelprize.org/nobel_prizes/peace/laureates/2007/> [Accessed 2 January 2012].

NREAP (2009) UK National Renewable Energy Action Plan - Department of Energy and Climate Change [Internet]. Available from: <http://bit.ly/14tHPE3> [Accessed 26 February 2013].

OFGEM (2005a) BETTA Factsheet [Internet]. Available from: <http://bit.ly/128SXcg> [Accessed 26 February 2013].

OFGEM (2005b) BETTA User Guide [Internet]. Available from: <http://bit.ly/15gVsHj> [Accessed 26 February 2013].

OFGEM (2012a) Low carbon networks fund [Internet]. Available from: <http://www.ofgem.gov.uk/networks/elecdist/lcnf/pages/lcnf.aspx> [Accessed 26 February 2013].

OFGEM (2012b) Network Innovation Competition [Internet]. Available from: <http://www.ofgem.gov.uk/Networks/nic/Pages/nic.aspx> [Accessed 26 February 2013].

Oreskes, N. & Conway, E.M. (2010) *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming - ISBN 978-1408824832*. 1st ed. Bloomsbury Press.

OVG (2010) *The Offshore Valuation*. Available from:

<http://www.offshorevaluation.org/> [Accessed 26 February 2013].

Perujo, A. & Ciuffo, B. (2010) The introduction of electric vehicles in the private fleet: Potential impact on the electric supply system and on the environment. A case study for the Province of Milan, Italy. *Energy Policy*, 38 (8), pp.4549–4561.

Pirani, S., Stern, J. & Yafimava, K. (2009) The Russo-Ukrainian gas dispute of January 2009: a comprehensive assessment. Available from: <http://bit.ly/XZ51ar> [Accessed 26 February 2013].

POYRY (2011) 232_Report_Analysing the technical constraints on renewable generation_v8_0 [Internet]. Available from: <http://bit.ly/128RBOv> [Accessed 26 February 2013].

RAEng (2012) News and Publications - List of Publications - Royal Academy of Engineering [Internet]. Available from: <http://bit.ly/13lnrXR> [Accessed 26 February 2013].

Risk.net (2012) Which way for Europe's gas storage markets? - Risk.net [Internet]. Available from: <http://www.risk.net/energy-risk/feature/1931594/europe-sgas-storage-markets> [Accessed 6 February 2012].

Scottish Government (2011) 2020 Routemap for Renewable Energy in Scotland - ISBN 978 1 78045 271 5 [Internet]. Available from: <http://www.scotland.gov.uk/Publications/2011/08/04110353/0> [Accessed 26 February 2013].

Scottish Power (2006) Scottish Power Press Release [Internet]. Available from: <http://www.scottishpower.com/ PressReleases_632.htm>.

SHFCA (2012) News Article - Aberdeen Hydrogen Hub & Bus Project Announced by First Minister Alex Salmond [Internet]. Available from: <http://www.shfca.org.uk/news_article/334/> [Accessed 26 February 2013].

Short, J.A., Infield, D.G. & Freris, L.L. (2007) Stabilization of Grid Frequency Through Dynamic Demand Control. *Power Systems, IEEE Transactions on*, 22 (3), pp.1284–1293.

Sinden, G. (2007) Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand. *Energy Policy*, 35 (1), pp.112–127.

Sioshansi, R., Denholm, P. & Jenkin, T. (2011) A comparative analysis of the value of pure and hybrid electricity storage. *Energy Economics*, 33 (1), pp.56–66.

Sioshansi, R., Denholm, P. & Jenkinłdots, T. (2009) Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects. *Energy Economics*. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0140988308001631>.

SoSTI (2006) Energy statement of need for additional gas supply infrastructure. Available from: <http://bit.ly/ZGQ5ll> [Accessed 26 February 2013].

Stansberry, P. (2011) US Shifts to Gas Export Role [Internet]. Available from: <http://jutiagroup.com/20110913-porter-stansberry-u-s-shifts-to-gas-exportrole/> [Accessed 26 February 2013].

Stern, J. (2004) UK gas security: time to get serious. *Energy Policy for a Sustainable Energy Future*, 32 (17), pp.1967–1979.

Strbac, G., Aunedi, M., Pudjianto, D., Djapic, P., Teng, F., Sturt, A., Jackravut, D., Sansom, R., Yufit, V. & Brandon, N. (2012) Energy Storage Systems in the UK Low Carbon Energy Future: Strategic Assessment - Carbon Trust [Internet]. Available from: <http://bit.ly/RUAabN> [Accessed 26 February 2013].

Swift-Hook, D.T. (2010) Grid-connected intermittent renewables are the last to be stored. *Renewable Energy*, 35 (9), pp.1967–1969.

UK_Energy_Bill (2012) *Bill 135 2012-13, (as Amended in Public Bill Committee)*. Available from: <http://services.parliament.uk/bills/2012-13/energy.html> [Accessed 26 February 2013].

UKERC (2009) UKERC2050 Report [Internet]. Available from: <http://www.ukerc.ac.uk/support/tiki-index.php?page=ukerc2050homepage> [Accessed 26 February 2013].

UNEP (2010) United Nations Environment Programme. The Emissions Gap Report: Are the Copenhagen Accord pledges sufficient to limit global warming to 2°C or 1.5°C? In: *Technical summary*. UNEP website. Available from: <http://www.unep.org/publications/ebooks/emissionsgapreport/pdfs/The_EMISSIONS_GAP_REPORT.pdf> [Accessed 26 February 2013].

UNFCCC (2005a) Clean Development Mechanism (CDM) [Internet]. Available from: <http://unfccc.int/kyoto_protocol/mechanisms/clean_development_mechanism/items/2718.php> [Accessed 26 February 2013].

UNFCCC (2009) Copenhagen Accord [Internet]. Available from: <http://unfccc.int/documentation/documents/advanced_search/items/3594.php?rec=j&priref=600005735#beg> [Accessed 26 February 2013].

UNFCCC (2005b) Emissions Trading [Internet]. Available from: <http://unfccc.int/kyoto_protocol/mechanisms/emissions_trading/items/2731.php> [Accessed 26 February 2013].

UNFCCC (2005c) Joint implementation [Internet]. Available from: <http://unfccc.int/kyoto_protocol/mechanisms/joint_implementation/items/1674.php> [Accessed 26 February 2013].

UNFCCC (2005d) KYOTO PROTOCOL [Internet]. Available from: <http://unfccc.int/essential_background/kyoto_protocol/items/1678.php> [Accessed 26 February 2013].

UNFCCC - Article 3: Principles (2013) FULL TEXT OF THE CONVENTION, ARTICLE 3 [Internet]. Available from: <http://unfccc.int/essential_background/convention/background/items/1355.php> [Accessed 19 February 2013].

UNFCCC - Parties & Observers (2013) UNFCCC - Parties & Observers [Internet]. Available from: <http://unfccc.int/parties_and_observers/items/2704.php> [Accessed 19 February 2013].

UPO (2009) UK 'now a net gas importer' - Upstreamonline.com [Internet]. Available from: <http://www.upstreamonline.com/live/article202201.ece> [Accessed 26 February 2013].

Urgaonkar, R., Urgaonkar, B., Neely, M.J. & Sivasubramaniam, A. (2011) Optimal Power Cost Management Using Stored Energy in Data Centers [Internet]. Available from: <http://arxiv.org/abs/1103.3099v2> [Accessed 26 February 2013].

Walawalkar, R., Apt, J. & Mancini, R. (2007) Economics of electric energy storage for energy arbitrage and regulation in New York. *Energy Policy*. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0301421506003545>.

WB-WDIa (2013) Historical CO2 - World Bank, World Development Indicators - Google Public Data Explorer [Internet]. Available from: <http://bit.ly/UGWPww> [Accessed 26 February 2013].

WB-WDIb (2013) Historical CO2 per capita - World Bank, World Development Indicators - Google Public Data Explorer [Internet]. Available from: <http://bit.ly/11UILDZ> [Accessed 26 February 2013].

WB-WDIc (2013) Historical Per Capita kWh - electricity World Bank, World Development Indicators - Google Public Data Explorer [Internet]. Available from: <http://bit.ly/WWcwjK> [Accessed 26 February 2013].

WCA (2012) coal reserves, coal exploration - World Coal Association [Internet]. Available from: <http://www.worldcoal.org/coal/where-is-coal-found/> [Accessed 26 February 2013].

Weber, E.U. & Stern, P.C. (2011) Public understanding of climate change in the United States. *American Psychologist;American Psychologist*, 66 (4), pp.315–328.

Weron, R. (2010) An empirical comparison of alternate regime-switching models for electricity spot prices. *Energy Economics*. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0140988310000885>.

Weron, R. (2006) *Modeling and forecasting electricity loads and prices: a statistical approach - ISBN: 9780470057537*. Available from: <http://bit.ly/XYD8MM> [Accessed 26 February 2013].

Weron, R., Bierbrauer, M. & Trück, S. (2004) Modeling electricity prices: jump diffusion and regime switching. *Proceedings of the XVIII Max Born Symposium 'Statistical Physics outside Physics'*, 336 (1–2), pp.39–48.

Wilson, I.A.G., McGregor, P.G., Infield, D.G. & Hall, P.J. (2011) Grid-connected renewables, storage and the UK electricity market. *Renewable Energy*, 36 (8), pp.2166–2170.

WKP (2011a) Climatic Research Unit email controversy - Wikipedia [Internet]. Available from: <http://bit.ly/aWW33i> [Accessed 26 February 2013].

WKP (2011b) Copenhagen Accord - Wikipedia [Internet]. Available from: <http://bit.ly/5gRqxD> [Accessed 26 February 2013].

WKP (2011c) Criticism of the IPCC Fourth Assessment Report - Wikipedia [Internet]. Available from: <http://bit.ly/if3ls4> [Accessed 26 February 2013].

WKP (2011d) List of scientists opposing the mainstream scientific assessment of global warming - Wikipedia [Internet]. Available from: <http://en.wikipedia.org/wiki/List_of_scientists_opposing_the_mainstream_scientific_assessment_of_global_warming> [Accessed 26 February 2013].

WNA (2012) Advanced Nuclear Power Reactors | Generation III+ Nuclear Reactors [Internet]. Available from: <http://www.world-nuclear.org/info/default.aspx?id=528&terms=advanced> [Accessed 26 February 2013].

Youn, L.T. & Cho, S. (2009) Optimal Operation of Energy Storage Using Linear Programming Technique [Internet]. Available from: <http://www.iaeng.org/publication/WCECS2009/WCECS2009_pp480485.pdf> [Accessed 22 August 2012].

-

Appendix 1 Programming environments

Software Used on Apple Mac Macbook Pro 13”

- Mac OS X 10.6.8 – Snow Leopard
- Microsoft Excel for Mac 2011, Version 14.2.1
- Microsoft Word for Mac 2011, Version 14.2.1
- Cyberduck Version 4.0.1 (8510)
- X11, XQuartz 2.3.6 (xorg-server 1.4.2-apple56)
- GNU Bourne Again Shell, Bash 3.2
- Aquamacs Emacs based on GNU Emacs, Version 23.2.50.1
- Intel® Fortran Compiler, ifort, compiler for professional applications running on Intel® 64, Version 11.1, Build 20091130
- Apple® Textedit, Version 1.6 (264)
- Matlab Student Version 2009a
- Zotero

The use of the High Performance Supercomputer required the learning and use of several different programs and computer languages, as each had a particular benefit and disadvantage. Matlab was found to be of benefit to program and test particular snippets of code but the syntax between Matlab and Fortran can at times be confusing and problematic, however, there is a rich knowledgebase of problems and solutions on the internet which was widely accessed. Graphing of results was mostly carried out in Matlab, as m-files (Matlab program files) could be written to speed up the process of formatting and outputting graphs of a repeatable nature. More intricate one-off graphs were created using Microsoft Excel and output as a pdf file that were then further changed in Adobe Illustrator. The flexibility of this method (Excel and Illustrator) allows for far greater control of the style of the eventual graph and ability to easily add further notation if necessary. Matlab is a powerful programming environment, but Fortran and Bash scripting on the HPC was found to be much quicker in terms of running the code especially with hundreds of millions of iterations. Access to files on the HPC (downloading to a local environment and uploading to the server) was carried out using an Apple Mac based file transfer program called Cyberduck and editing of the files on the HPC was carried out locally using Aquamacs and Textedit through Cyberduck's environment. Files could therefore be worked on locally and were saved automatically to the HPC. This complicated pathway was found to be the most efficient method of debugging. Files would be changed using Aquamacs and Textedit (through Cyberduck), then the `master_input_shell.sh` bash script would be started through the command line in X11 using the command line `master_input_shell.sh &> outputoutput.txt`. The syntax of this command pipes any errors or screen outputs to the text file `outputoutput.txt`, which was found to be helpful in debugging. Once the Fortran files had finished running – an output folder of newly created output files was downloaded to the local machine. These files would then be used by Matlab to create graphs for viewing. This was also helpful to be able to visualise output results in order to debug the code. A shell script named `strip.sh` stripped the calculated upper boundary figure from the `upper_boundary.txt` file and appended it to the input data from the `master_input.txt` file. The input information for each run was thus available with the upper boundary figure in the `master_output.txt file`.

Appendix 2 Matlab file to process and analyse the raw Elexon market index data.

```
%change the year value of lines 6 and 18 to load a different year from
%2005-2010    clear, clc, load
mid_2005_2010.mat


number_of_days =  size(twod_mid_2009_cleaned,1);
  n = 0;    for i =
1:number_of_days




for j = 1:50
n=n+1;
    row_matrix(n) = twod_mid_2009_cleaned(i,j);

end
end

%a one dimensional row matrix has been prepared from the two dimensional
%matrix and includes the zero padding - each day is therefore made up of 50
%time periods with padding of zero values at time periods 49 and 50 other
%than the shortest day that has 4 time periods with zero values at time
%periods 47, 48, 49, and 50, and the longest day that has price values for
%all 50 time periods.
```

-

```
  n =
0;
for start_period = 1:1 %start period can be changed to determine variations


    for i = 0:number_of_days-1
                 for
j = 1:50
        if (start_period+((j-1)+(i*50))) >= 50 * number_of_days
row_temp(i+1,j) = 0;
        else row_temp(i+1,j) = row_matrix(start_period+((j-1)+(i*50)));
end         end              end          row_temp;


%the row_temp matrix now contains 365 or 366 rows of price values by 50
%columns that is governed by the starting period i.e. if the starting
%period is period 10, then the 1st column in row one of the row_temp matrix
%will be the price value of period 10 in day one, and the last price value
%in row one of the row_temp matrix will be the 9th time period price value
%of day 2. Basically each row of the row_temp matrix starts at the time
%period defined by the start_period, then continues to the start_period-1
%time period of the following day. This is to test the variation in the
%price uplift histogram by considering different 24 hour time periods e.g.
%00:00 - 24:00, and then 00:30 - 00:30 the following day. It is expected
%that there will be a low price uplift in the last day - especially when %the
start period changes to after the minimum price of the last day.


%the minimum and maximum prices on each row of the row_temp are found next,
%subject to the following constraints: all zero values are discounted as
%they are padding and not real prices, the maximum price has to happen
%at a future time period after the minimum price - as energy can only be
%sold once it has been stored. This may mean that the absolute max and min
%are not used - as the absolute max may happen before the absolute min.


for i = 1:number_of_days
         uplift
= 0;      m=0;
    for j = 1+m:50
         n
= 0;
       for k = 1+n:50
accept = 1;             if
row_temp(i,j)==0||row_temp(i
,k)==0; accept = 0;end
if n < m; accept = 0; end
           temp = 100*(row_temp(i,k)-row_temp(i,j))/row_temp(i,j);
temp2 = row_temp(i,k)-row_temp(i,j);



           if (temp > uplift) && (accept == 1)


               uplift = temp;


               uplift_matrix(i,1) = temp;
uplift_matrix(i,2) = temp2;
uplift_matrix(i,3) = j;                uplift_matrix(i,4)
= row_temp(i,j);                uplift_matrix(i,5) = k;
uplift_matrix(i,6) = row_temp(i,k);
uplift_matrix(i,7) = i;

end          n =
n + 1;
end      m = m +
1;     end
end


    %next line last value, should be 1 for % change in price, and 2 for the
    %absolute change in price
start_period_uplift_matrix(start_period,1:number_of_days)        =
uplift_matrix(1:number_of_days,1)';
  end
mean_start_matrix = mean(start_period_uplift_matrix,2);
%plot(mean_start_matrix); figure(gcf)
```

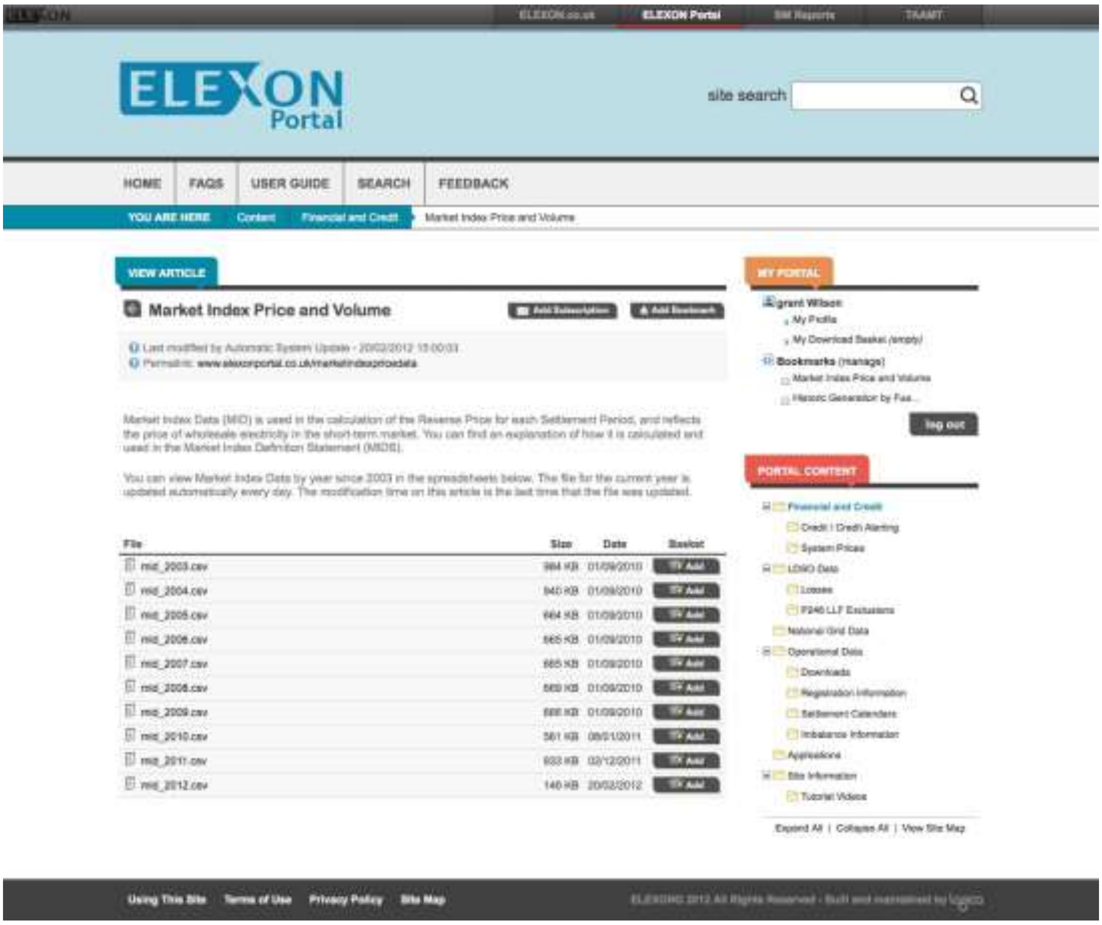
```
%line below provides the basis for the yearly price change histogram. Use a
%value of 1 for % change in price, and 2 for the absolute change in price
%hist(uplift_matrix (1:number_of_days),100); figure(gcf)


for i = 1:number_of_days


    time_period_diff(i) = uplift_matrix(i,5)-uplift_matrix(i,3);
lower_price_matrix(1,i) = uplift_matrix(i,4);
lower_price_matrixa(1,i) = uplift_matrix(i,3);
higher_price_matrix(1,i) = uplift_matrix(i,6);
higher_price_matrixa(1,i) = uplift_matrix(i,5);

end
%{
%code snippet produces a histogram of the number of days vs difference in
%time periods between higher and lower daily prices matrix_bins
= 1:48
hist(time_period_diff(1:number_of_days),matrix_bins); figure(gcf)
%}


%{
%code snippet produces a histogram of the number of days vs the percentage
%change in price
min_price_histogram = zeros(48,1); max_price_histogram
= zeros(48,1);
  for i =
1:number_of_days


    z = uplift_matrix(i,2);
    min_price_histogram(z) = min_price_histogram(z)+1;
z = uplift_matrix(i,4);
    max_price_histogram(z) = max_price_histogram(z)+1;

end %}


%code snippet produces a histogram of time periods the lower and
%higher prices happened - code needs changed to produce either lower or
%higher prices histogram


matrix_bins = 1:48;


%hist(lower_price_matrixa,matrix_bins); figure(gcf)


hist(higher_price_matrixa,matrix_bins); figure(gcf)
```

Appendix 3 Price File Preparation

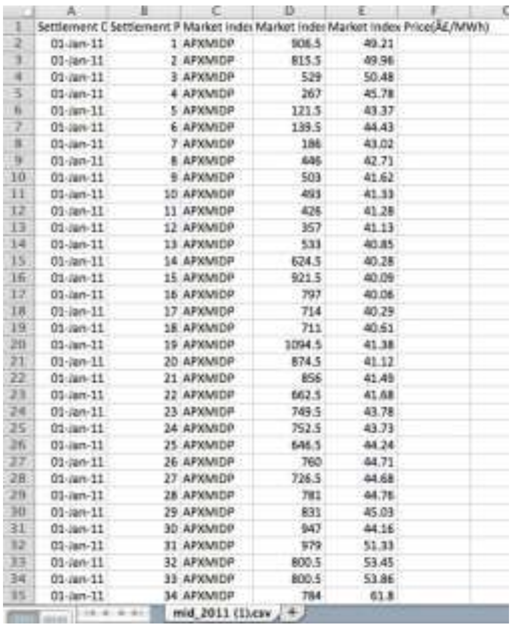
Data is downloaded from https://www.elexonportal.co.uk/ (previously https://www.bsccentralservices.com) - a login is required to access the data.

The data is under the ‘Market Index Data and Volume’ page, which itself is under the ‘Financial and Credit’ heading (*n.b.* not under ‘system prices’ which is also under the ‘Financial and Credit’ heading.)

-



The data is downloaded into as a comma separated value file and is opened in Excel.



	A	B	C	D	E	F
1	Settlement C	Settlement P	Market Index	Market Index	Market Index	Price(Â£/MWh)
2	01-Jan-11	1	APXMIDP	906.5	49.21	
3	01-Jan-11	2	APXMIDP	815.5	49.96	
4	01-Jan-11	3	APXMIDP	529	50.48	
5	01-Jan-11	4	APXMIDP	267	45.78	
6	01-Jan-11	5	APXMIDP	121.5	43.37	
7	01-Jan-11	6	APXMIDP	139.5	44.43	
8	01-Jan-11	7	APXMIDP	186	43.02	
9	01-Jan-11	8	APXMIDP	446	42.71	
10	01-Jan-11	9	APXMIDP	503	41.62	
11	01-Jan-11	10	APXMIDP	493	41.33	
12	01-Jan-11	11	APXMIDP	426	41.28	
13	01-Jan-11	12	APXMIDP	357	41.13	
14	01-Jan-11	13	APXMIDP	533	40.85	
15	01-Jan-11	14	APXMIDP	624.5	40.28	
16	01-Jan-11	15	APXMIDP	921.5	40.09	
17	01-Jan-11	16	APXMIDP	797	40.06	
18	01-Jan-11	17	APXMIDP	714	40.29	
19	01-Jan-11	18	APXMIDP	711	40.61	
20	01-Jan-11	19	APXMIDP	1094.5	41.38	
21	01-Jan-11	20	APXMIDP	874.5	41.12	
22	01-Jan-11	21	APXMIDP	856	41.49	
23	01-Jan-11	22	APXMIDP	662.5	41.68	
24	01-Jan-11	23	APXMIDP	749.5	43.78	
25	01-Jan-11	24	APXMIDP	752.5	43.73	
26	01-Jan-11	25	APXMIDP	646.5	44.24	
27	01-Jan-11	26	APXMIDP	760	44.71	
28	01-Jan-11	27	APXMIDP	726.5	44.68	
29	01-Jan-11	28	APXMIDP	781	44.76	
30	01-Jan-11	29	APXMIDP	831	45.03	
31	01-Jan-11	30	APXMIDP	947	44.16	
32	01-Jan-11	31	APXMIDP	979	51.33	
33	01-Jan-11	32	APXMIDP	800.5	53.45	
34	01-Jan-11	33	APXMIDP	800.5	53.86	
35	01-Jan-11	34	APXMIDP	784	61.8	

mid_2011 (1).csv

The 2011 csv data opens with the following columns:

Settlement Date

Settlement Period

Market Index Data Provider Id

Market Index Volume(MWh)

Market Index Price(£/MWh)

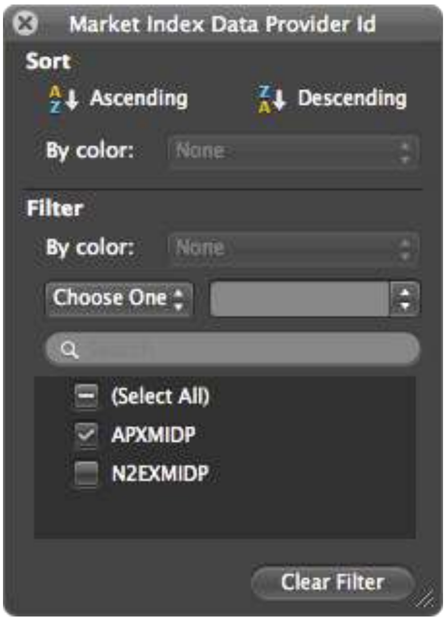
	A	B	C	D	E	F
4503	04-Apr-11	40	APXMIDP	1417	50.32	
4504	04-Apr-11	41	APXMIDP	1507.5	50.18	
4505	04-Apr-11	42	APXMIDP	1558.5	49.78	
4506	04-Apr-11	43	APXMIDP	2018.5	49.81	
4507	04-Apr-11	44	APXMIDP	2095	50.05	
4508	04-Apr-11	45	APXMIDP	2233.5	48.7	
4509	04-Apr-11	46	APXMIDP	2103	48.24	
4510	04-Apr-11	47	APXMIDP	1089.5	44.77	
4511	04-Apr-11	48	APXMIDP	441	43.91	
4512	05-Apr-11	1	APXMIDP	65	41.96	
4513	05-Apr-11	1	N2EXMIDP	0	0	
4514	05-Apr-11	2	APXMIDP	125.5	41.11	
4515	05-Apr-11	2	N2EXMIDP	0	0	
4516	05-Apr-11	3	APXMIDP	535	40.74	
4517	05-Apr-11	3	N2EXMIDP	0	0	
4518	05-Apr-11	4	APXMIDP	391	41.33	
4519	05-Apr-11	4	N2EXMIDP	0	0	
4520	05-Apr-11	5	APXMIDP	305.5	40.84	
4521	05-Apr-11	5	N2EXMIDP	0	0	
4522	05-Apr-11	6	APXMIDP	381.5	40.86	
4523	05-Apr-11	6	N2EXMIDP	0	0	
4524	05-Apr-11	7	APXMIDP	418.5	42	
4525	05-Apr-11	7	N2EXMIDP	0	0	
4526	05-Apr-11	8	APXMIDP	383.5	41.9	
4527	05-Apr-11	8	N2EXMIDP	0	0	
4528	05-Apr-11	9	APXMIDP	300.5	42.41	
4529	05-Apr-11	9	N2EXMIDP	0	0	
4530	05-Apr-11	10	APXMIDP	303.5	42.39	
4531	05-Apr-11	10	N2EXMIDP	0	0	
4532	05-Apr-11	11	APXMIDP	516.5	44.12	
4533	05-Apr-11	11	N2EXMIDP	0	0	
4534	05-Apr-11	12	APXMIDP	591	43.75	
4535	05-Apr-11	12	N2EXMIDP	0	0	
4536	05-Apr-11	13	APXMIDP	597.5	47.53	
4537	05-Apr-11	13	N2EXMIDP	0	0	

mid_2011 (1).csv

The 2011 csv data introduces a new Market Index Data provider from the 5th of April – namely N2EXMIDP – the Nordpool UK exchange - http://www.n2ex.com/aboutn2ex. This is in addition to the UKs existing Market Index Data provider APX Endex - http://www.apxendex.com

However, the N2EX data is highly sporadic, with only 193 data points out of a possible 13010 data points having a non-zero value. This may be due to bedding in of the new data stream.

The APX Endex data has therefore only been used for this work.



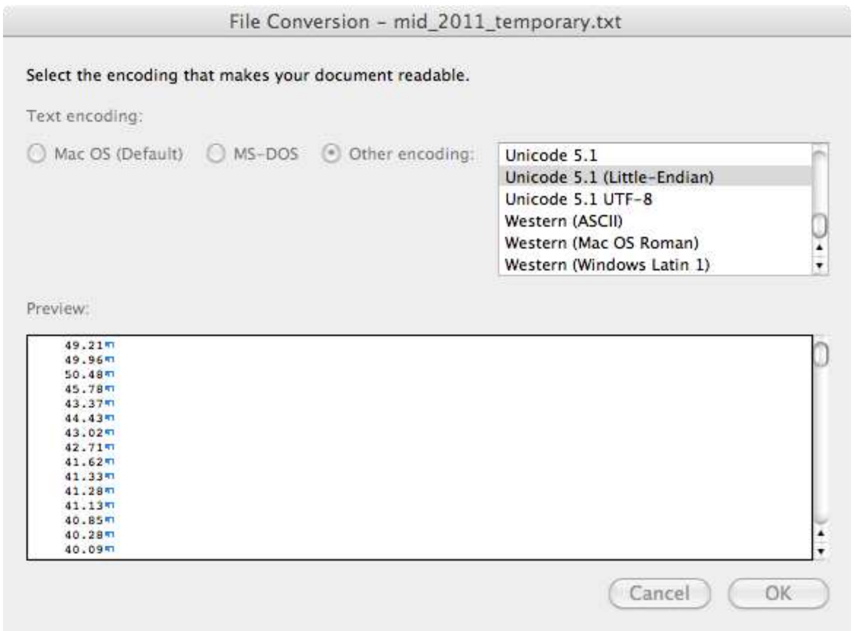
If all the columns are highlighted – then the filter function can be used – and the column 'Market Index Data Provider Id' can be filtered to only show the data values for 'APXMIDP'

The values in the Market Index Price(£/MWh) column are then highlighted and copied to a new worksheet.

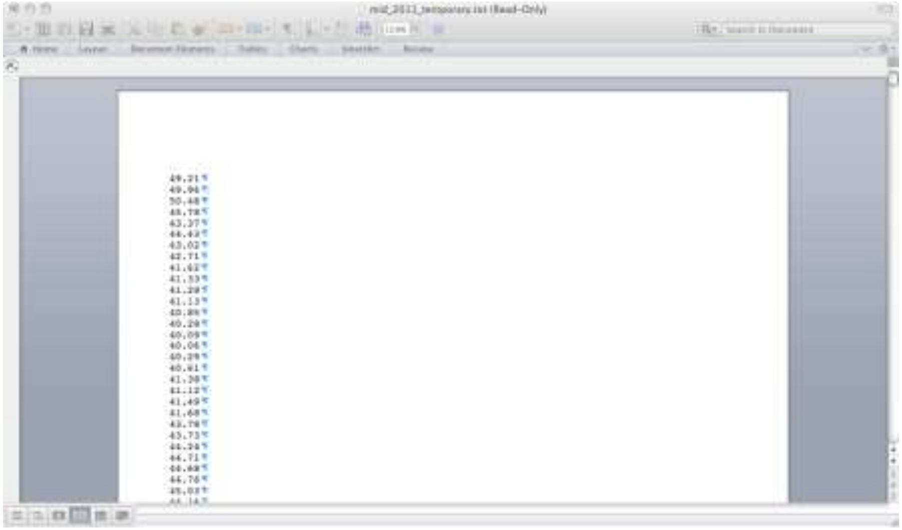
This new worksheet should now contain one column of 17520 price data points (for a non-leap year) or 17568 price data points for a leap year *i.e.* 2008. The units are £/MWh.

This one column excel worksheet should now be saved as **Unicode-16** text format using the save as menu option in Microsoft Excel.

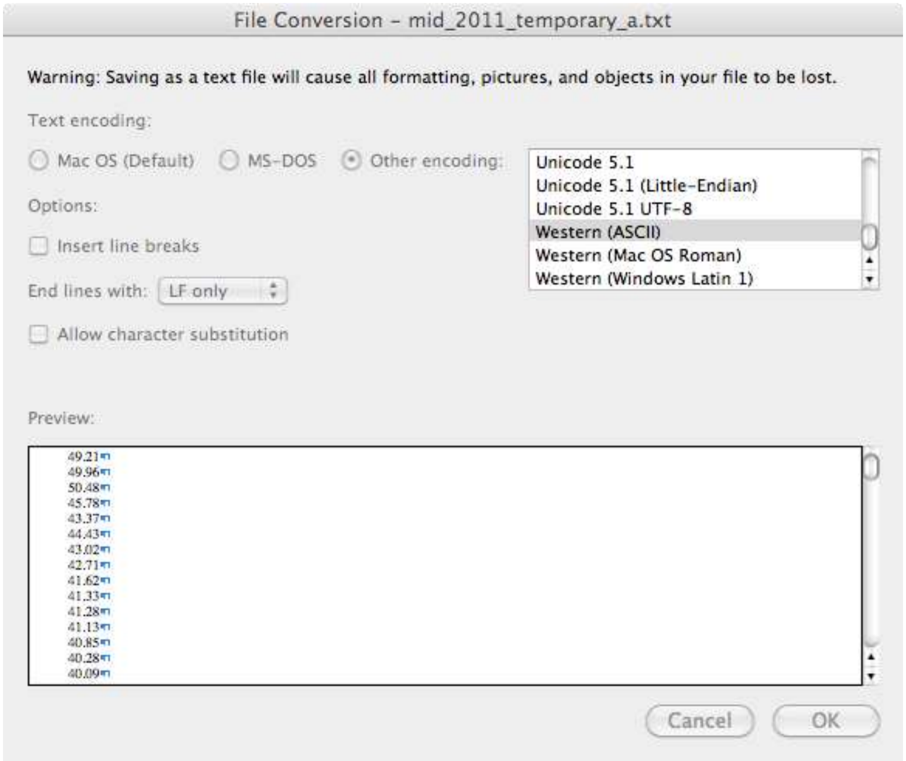
This **Unicode-16** text file should then be opened in Microsoft Word as a Unicode5.1 (Little-Endian) format.



There should now be a word file with one column of numbers (over 250 pages in length with font size set to 9) that looks similar to



The next stage is to export this file as a text file using the **Western (ASCII)** format under the **'Other encoding'** radio button. **'LF only'** must be chosen as a value in the drop down menu, and all other options disabled.



This saved file is now in a format ready to be uploaded to the High Performance Computer server and used by the Fortran program.

The need for this protocol derives from the differing nature of line endings in text files between the Apple Macintosh, Windows and UNIX operating systems. One text file is not immediately correctly readable by other operating systems, and if the price files are causing problems – then line endings should be checked first.

This year-long prepared master file, containing 17520 data points for a non-leap year and 17568 data points for a leap year, is then uploaded to the High Performance Computer (HPC) head node using a File Transfer Protocol (FTP) program such as Cyberduck. All runs of the program files use the master price input files – so this only requires to be undertaken once. A one year data file parsed using this method is approximately 100 kb in size.

The Fortran program expects each price data point to be on a different line, and also expects the last value to have a line feed after the value.

It should be noted that no additional linefeed or carriage return at the end of the file is required if this procedure is followed. If however, there is no line feed or carriage return at after the final data point value, the Fortran program will not execute.

The price files created to test the algorithm were located in the folder named '`TT`' and were given year names from `1900` to `1904` in order to reduce confusion with historical price files from years 2005 – 2011. For the UK market, these yearly price files using historical data were located in a folder named '`UK`'. The syntax of the scripting file for launching requires the name of the files to be the same as the filenames required in the scripting file *e.g.* `1904_cleaned_UK_crlf.txt` in order that the file was copied into a newly created folder, where the model code was subsequently launched. If the file or folder was incorrectly named or positioned in relation to the launch script a '`file not found`' error would occur.

Appendix 4 – Master Input File for Fortran program

The first step was to prepare a set of master files for the price files, the time files, and the shell programs required. The price file preparation is described in Appendix 2.

Once the HPC server is accessed, a new folder can be created, and several shell and program files are copied into the folder. A screenshot of a folder with the relevant files is shown below.

Filename	Size	Modified
master_input.txt	586 B	Today 12:52
master_input_shell.sh	3.8 KB	Today 12:10
full_grid_normal.f90	18.9 KB	Today 12:10
launch.sh	584 B	Today 12:10
strip.sh	1.4 KB	Today 12:10
full_grid_leap.f90	18.9 KB	Today 12:10

The names of these files are critical, as program shells access the files. These names therefore have to be identical to the names listed in the screenshot, or there will be errors finding the correct files.

A brief description of the files:

`master_input.txt` – text file with information in rows.

`master_input_shell.sh` – takes row-by-row data from master_input.txt file and creates new sub-folders and copies the relevant price files, time files and program files into these new sub-folders. It then compiles the program file as an executable file, and then submits this executable file to the HPC queuing system.

`full_grid_normal.f90` – is the Fortran code for a non-leap year, which needs compiled to become an executable file.

`launch.sh` – is a bash script shell to submit jobs to the HPC queuing system (it is called by the master_input_shell.sh shell script.

strip.sh – is a bash shell script that is run separately **after** all the jobs have completed. It strips the result from the output file of each of the jobs (each separate sub-folder), and puts it into a master_output.txt file along with the information from each row from the master_input.txt file.

full_grid_leap.f90 - is the Fortran code for a non-leap year, which needs compiled to become an executable file.

The master_input.txt file is created as follows:

The excel spreadsheet file master_input_excel_template.xlsx file is opened in Microsoft Excel spreadsheet program (Version 14.1.4 Excel for Mac 2011), and has 11 columns containing relevant information.

The 11 column headings are detailed in row one in order to help the user interface. The 11 column headings are (in order) eta_in, eta_out, Cap_max, PLI, PLO, tau, numtrials, step_size, nn_bias, market, and year. Each row contains the information required by the master_input_shell.sh file in order for it to copy relevant files into a sub folder. It is therefore critical that each row has all the information required and a value in each column. A partially completed row, or a data value in a column outside of the initial 11 columns will produce an error when running further files.

	A	B	C	D	E	F	G	H	I	J	K
1	eta_in	eta_out	Cap_max	PLI	PLO	tau	numtrials	step_size	nn_bias	market	year
2	0.89442719	0.89442719	2000	1000	1000	87648	100000000	5000	4000	UK	2005
3	0.89442719	0.89442719	2000	1000	1000	87648	100000000	5000	4000	UK	2006
4	0.89442719	0.89442719	2000	1000	1000	87648	100000000	5000	4000	UK	2007
5	0.89442719	0.89442719	2000	1000	1000	87648	100000000	5000	4000	UK	2008
6	0.89442719	0.89442719	2000	1000	1000	87648	100000000	5000	4000	UK	2009
7	0.89442719	0.89442719	2000	1000	1000	87648	100000000	5000	4000	UK	2010
8	0.89442719	0.89442719	2000	1000	1000	87648	100000000	5000	4000	UK	2011
9											

A brief description of the column headings:

eta_in – is the fixed efficiency for the input stage of the storage device – the units are from 0 to 1, with 0 meaning a total loss or 0% efficient, and 1 meaning no loss or 100% efficient.

eta_out – is the fixed efficiency loss for the output stage of the storage device - the units are from 0 to 1, with 0 meaning a total loss or 0% efficient, and 1 meaning no loss or 100% efficient.

Cap_max – is the energy capacity of the storage device – Units are kWh

PLI – is the Power Limit In of the storage device – Units are kW PLO

– is the Power Limit Out of the storage device – Units are kW

tau – is the time constant of the storage device – Units are hours. This constant is used to determine the time-dependent loss of the storage device (self discharge) and can be described as follows: The time constant value in hours, is the number of hours taken for the energy in the storage device to decrease by $1 - \frac{1}{e} \approx 63.$8% when

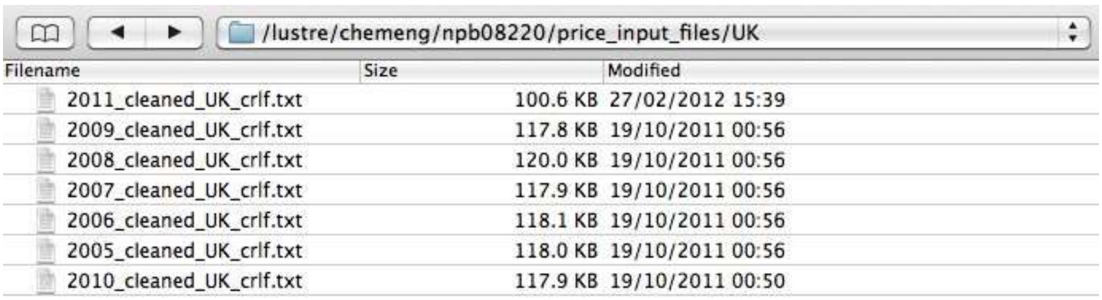
numtrials – is the number of iterations that the Fortran program should carry out.

step_size – is the maximum width of the window of periods that the program will seek a random period to compare the price. *i.e.* if the current period the algorithm is considering is the 1000th period of the year on the 20th day of the year (20th of January between 19:30 and 20:00), and the step size is has a value of 200, the algorithm will consider a window of price data from the 800th period of the year to the 1200th period of the year to find a random period to compare the prices. The algorithm therefore compares prices between the current period (the 1000th period) and the randomly picked period within the window determined by the step size.

nn_bias – is a constant involved in the random picking of a price point described in step_size above. This nn_bias constant provides a normal distribution curve approach to picking the random period for price comparison. In essence it gives a greater chance to picking a random period that is closer to the current price period than further away from the current price period (within the window set by the step_size constant).

`market` – is the market used for the price files, and must be two letters in length. This value is used to find the relevant sub-folder in the master price file folder – the UK data is found within a sub-folder named '`UK`' which is contained within the folder `price_input_files` contained typically in the user folder under the lustre file system on the HPC (`/lustre/chemeng/?????`). Note – this is different from the home folder for the user `?????`, which does not have the same hard-disk storage capacity as the lustre file system. The lustre file system was therefore chosen to store all program, development and result files.

year – is the year of the price files. The shell script `master_input_shell.sh` – uses this year value to copy price and program files into a sub-folder, which it creates. The syntax of the value should match with the name of the price file. The price files are contained within the relevant market folder (in the figure below – the folder is the `UK` sub-folder within the `price_input_files` folder, contained within the lustre home folder of user `npb08220`.)



The name of the price files is important and must stick to the format of `????_cleaned_UK_crlf.txt` where the value `????` is the year.

Appendix 5 – The master_input_shell.sh shell script

The `master_input_shell.sh` script

```
#!/bin/bash
```

```
# code to take master_input.txt file and create directories, copy programs and data
then run the files
#
#
#!!!! no additional linefeed or carriage return required if procedure followed: #!!!!
excel file should be saved as unicode-16 format, then opened in word as a unicode5.1
little endian and then saved as
#!!!! as a text file with western(ascii) format with line feed only and no insert
line breaks or character substitution
#!!!! this is then uploaded to the server using cyberduck, then the name changed to
master_input.txt



totallines=$(($(wc -l < master_input.txt)))



D_LIST=$(seq 2 $totallines)


for i in ${D_LIST}
do
eachrow=$(head -${i} master_input.txt | tail -1)
  DIR_NAME=RUNROW${i}                  # this section creates directories and moves
into the directory   if [ -e ${DIR_NAME} ] ; then
     rm -r ${DIR_NAME}                    # this line removes directories and
contents if already there   fi   mkdir ${DIR_NAME}                    # this
line creates directories   cd ${DIR_NAME}                        # this line
moves into the directory


#the next line creates a file called input.txt in each directory
#and transposes a line from the eachrow variable created from the master_input.txt
file, to this new file
  for var in $eachrow; do echo $var >> input.txt; done
 market=$(head -10 input.txt | tail -
1) year=$(head -11 input.txt | tail -
1)



# The next section checks the year - and copies the appropriate program file into the
directory
# it then compiles the appropriate program
# echo "../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt" >>
input.txt
# above line not used due to fortran prolems with character lengths - copy price file
to each directory instead if [ $((${year//$'\r'})) -eq 2005 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 2006 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe
 elif [ $((${year//$'\r'})) -eq 2007
] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 2008 ]
then
  cp ../full_grid_leap.f90 full_grid_leap.f90
```

```
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_leap.f90 -o sto.exe
 elif [ $((${year//$'\r'})) -eq 2009
] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe
 elif [ $((${year//$'\r'})) -eq 2010
] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 2011 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 1900 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 1901 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 1902 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 1903 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe


elif [ $((${year//$'\r'})) -eq 1904 ] then
  cp ../full_grid_normal.f90 full_grid_normal.f90
  cp ../../price_input_files/${market}/${year//$'\r'}_cleaned_UK_crlf.txt price.txt
ifort full_grid_normal.f90 -o sto.exe

fi  # this ends the if statement



# the next section copies the program launch file and runs this
 cp ../launch.sh
launch.sh


qsub -q serial.q launch.sh
  cd
..

done
```

Appendix 6 – Model Code – Fortran - full_grid_leap.f90

n.b. – line numbers were added in word – and so will not necessarily match with line numbers referred to in the code itself.

```
!I.A. Grant Wilson
!23/April/2012

!Maximising the revenue available to a storage system that can buy from the spot price market.
!Code adapted from paper: DOI 10.1039/C2EE02419E Edward Barbour, Grant Wilson et al.
!make sure power is in kW and prices are per MWh!

!! e_to_store is within the store****!!!
!! output_to_grid is outwith the store (requires efficiencies)***!! !!
grid_constraint has efficiencies - so must be outwith the store
!! ELI and ELO do not have efficiencies - so must be within the store


PROGRAM  Full_grid_1

IMPLICIT NONE

INTEGER, PARAMETER :: length = 17568
INTEGER, PARAMETER :: num_rev_output = 10000

CHARACTER::market*2
INTEGER :: i, n, numtrials, step_size, period_1, period_2
INTEGER ::temp, accept, ifill, window, year, scenario
INTEGER :: R, i_temp, i_temp2, accept_count, revenue_iterations(num_rev_output)
INTEGER :: flag1, flag2, flag3, flag4, flag5, flag6, flag7, flag8, flags_total
INTEGER :: flag1_tot, flag2_tot, flag3_tot, flag4_tot, flag5_tot, flag6_tot, flag7_tot, flag8_tot

REAL (kind = 8) :: prices(length)
REAL (kind = 8) :: time(length)
REAL (kind = 8) :: t(length)
REAL (kind = 8) :: Old_OTG(length), Old_ETS(length), Output_to_grid(length),
grid_constraint(length), Cumsum_Rev(length)
REAL (kind = 8) :: old_test_energy(length), test_energy(length), new_test_energy(length)
REAL (kind = 8) :: kwh_price(length), Revenue(length), revenue_iterations_value(num_rev_output)
REAL (kind = 8) :: E_stored(length), E_to_store(length)
REAL (kind = 8) :: Cap_max
REAL (kind = 8) :: HARVEST
REAL (kind = 8) :: prob_accept
REAL (kind = 8) :: dx, dx1, dx2, dx3, dx4, dx5
REAL (kind = 8) :: eta, eta_in, eta_out REAL
(kind = 8) :: tau
REAL (kind = 8) :: PLI, PLO, ELI, ELO
REAL (kind = 8) :: nn_bias
REAL (kind = 8) :: limit
REAL (kind = 8) :: time_loss, time_loss_2, time_loss_3, time_loss_4
REAL (kind = 8) :: old_Rev, new_Rev, New_quantity, Original_quantity
REAL (kind = 8) :: Rev1, Rev2, new_OtG_1, new_OtG_2
REAL (kind = 8) :: m, m2, time1, time2, total_cpu_time

call cpu_time ( time1 ) READ
(*,*) eta_in
```

```
READ (*,*) eta_out
READ (*,*) Cap_max
READ (*,*) PLI
READ (*,*) PLO
READ (*,*) tau
READ (*,*) numtrials
READ (*,*) step_size
READ (*,*) nn_bias
READ (*,*) market
READ (*,*) year


ELI = PLI/2
ELO = -PLO/2
!ELI = ELI*eta_in
!ELO = ELO*eta_out IF
(step_size>ELI) THEN
step_size = ELI
END IF

!****time file has to be in the correct place on the server***
OPEN(UNIT=22, FILE = '../../time_input_files/leap_year_time_crlf.txt')
OPEN(UNIT=25, FILE = 'price.txt')

!RECL increases width of output file before Linefeed
!OPEN(UNIT=73, FILE = 'scenario_moves.txt', RECL = 550)
!OPEN(UNIT=74, FILE = 'all_dx.txt', RECL = 750)
OPEN(UNIT=76, FILE = 'revenue_iterations.txt', RECL = 550)

READ(22,*) time
READ(25,*) prices

CLOSE(22)
CLOSE(25)


old_Rev = SUM(Revenue)
!change window to less than a year (17520) e.g. first month only is 48 * 31 = 1488
!first week is 336 and first 4 days are 192
window = 17568  accept_count
= 1
flag1_tot=0; flag2_tot=0; flag3_tot=0; flag4_tot=0; flag5_tot=0; flag6_tot=0; flag7_tot=0; flag8_tot=0
flags_total=0

!Initialise arrays
DO i = 1,length t(i)
= time(i)
Cumsum_Rev(i)=0
old_test_energy(i) = 0
!Remember to use the energy rather than power when calculating Revenue so divide by 2
kwh_price(i) = prices(i)/1000 !Prices are in £/MWh, convert the price to £ per kWh
```

```
grid_constraint(i) = ELI   !set as same limit as energy limit in
!Initialise other arrays E_stored(i)
= 0
E_to_store(i) = 0
Revenue(i) = 0
Output_to_grid(i) = 0
Old_OTG(i)=0   !for debugging purposes
Old_ETS(i)=0   !for debugging purposes
END DO

DO i = 1, num_rev_output revenue_iterations(i)=0
revenue_iterations_value(i)=0
END DO

!Start the Monte carlo trials...

!CALL RANDOM_SEED  !this sets the pseudo-random number seed to a different starting point DO
n = 1,numtrials

!Set up the variable that accepts or declines proposed changes accept
= 0 !Default is to decline

DO
!Choose a random amount to shift, either +ve or -ve.
CALL RANDOM_NUMBER(HARVEST)
dx = (step_size - ((HARVEST) * step_size * 2))
!Select a random period
CALL RANDOM_NUMBER(HARVEST)
period_1 = NINT(1 + ((HARVEST) * (window-1)))
!Biasing towards nearest neighbours and making sure period_1 /= period_2

CALL RANDOM_NUMBER(HARVEST)
period_2 = NINT(1 + ((HARVEST) * (window-1)))

!make sure period_1 is smaller
IF (period_2<period_1) THEN
temp = period_1 period_1 =
period_2 period_2 = temp
END IF

IF (period_2 < (period_1 + nn_bias)) THEN; accept = 1; END IF
IF (period_1 == period_2) THEN; accept=0; ENDIF !make sure periods are not equal
!Check for the exit command
IF (accept==1) EXIT

END DO

!set the default back to decline accept = 0 flag1=0; flag2=0; flag3=0;
flag4=0; flag5=0; flag6=0; flag7=0; flag8=0
```

```
time_loss = EXP((t(period_1)-t(period_2))/tau)

IF (dx>0) THEN

!scenario 1
        IF(E_to_store(period_1)>=0 .AND. E_to_store(period_2)>0) THEN
scenario=1              dx1 = (ELI-E_to_store(period_1))
!storage limit in            dx2 = E_to_store(period_2)/time_loss
!storage limit out    dx3 = (grid_constraint(period_1)+Output_to_grid(period_1))*eta_in
!grid limit in    dx4 = -Output_to_grid(period_2)/(eta_out*time_loss)                  !grid
limit out    dx = MIN (dx, dx1, dx2, dx3, dx4) END IF

!scenario 2
        IF(E_to_store(period_1)>=0 .AND. E_to_store(period_2)<=0) THEN
scenario=2
          dx1 = (ELI-E_to_store(period_1))                              !storage limit in
dx2 = (E_to_store(period_2)-ELO)/time_loss                        !storage limit out            dx3 =
(grid_constraint(period_1)+Output_to_grid(period_1))*eta_in          !grid limit in            dx4 =
(grid_constraint(period_2)-Output_to_grid(period_2))/(eta_out*time_loss) !grid limit out
          dx = MIN (dx, dx1, dx2, dx3, dx4)
        END IF

!scenario 3
        IF(E_to_store(period_1)<0 .AND. E_to_store(period_2)>0) THEN
scenario=3
          dx1 = -E_to_store(period_1)                                   !storage limit in
dx2 = E_to_store(period_2)/time_loss                              !storage limit out
dx3 = Output_to_grid(period_1)*eta_in                             !grid limit in            dx4 =
-Output_to_grid(period_2)/(eta_out*time_loss)                     !grid limit out            dx =
MIN (dx, dx1, dx2, dx3, dx4)
        END IF

!scenario 4
        IF(E_to_store(period_1)<0 .AND. E_to_store(period_2)<=0) THEN
scenario=4
          dx1 = -E_to_store(period_1)                                   !storage limit in
dx2 = (E_to_store(period_2)-ELO)/time_loss                        !storage limit out
          dx3 = Output_to_grid(period_1)*eta_in                         !grid limit in
dx4 = (grid_constraint(period_2)-Output_to_grid(period_2))/(eta_out*time_loss)  !grid limit out
          dx = MIN (dx, dx1, dx2, dx3, dx4)
        END IF

!This section checks the available space for moving energy between periods 1 and 2
i_temp = MAXLOC(E_stored(period_1:(period_2-1)), DIM=1)          i_temp2 =
period_1+i_temp-1
```

```
        time_loss_3 = EXP((time(period_1)-time(i_temp2))/tau)
m2 = Cap_max - MAXVAL(E_stored(period_1:(period_2 - 1)))
dx5 = (m2/time_loss_3)

        IF(dx5<0) THEN
        dx5 = 0
END IF

        dx = MIN(dx, dx5)
        IF (dx < 0) THEN; dx=0; ENDIF


!This section checks the revenue of the potential move - accept if revenue increases
!Works out the new values Output_to_grid would be if the move is accepted

accept = 0
        IF(scenario==1) THEN
          new_OtG_1=Output_to_grid(period_1)-dx/eta_in
          new_OtG_2=Output_to_grid(period_2)+(dx*time_loss)/eta_in
        END IF

        IF(scenario==2) THEN
          new_OtG_1=Output_to_grid(period_1)-dx/eta_in
          new_OtG_2=Output_to_grid(period_2)+(dx*time_loss*eta_out)
END IF

        IF(scenario==3) THEN
          new_OtG_1=Output_to_grid(period_1)-dx*eta_out
new_OtG_2=Output_to_grid(period_2)+(dx*time_loss)/eta_in          END
IF

        IF(scenario==4) THEN
          new_OtG_1=Output_to_grid(period_1)-dx*eta_out
          new_OtG_2=Output_to_grid(period_2)+(dx*time_loss*eta_out)
END IF

Rev1=Output_to_grid(period_1)*kwh_price(period_1) +
Output_to_grid(period_2)*kwh_price(period_2)
Rev2=new_OtG_1*kwh_price(period_1) + new_OtG_2*kwh_price(period_2)

IF(new_OtG_1<=grid_constraint(period_1) .AND. new_OtG_2>=-grid_constraint(period_2)) THEN
IF(Rev2 > Rev1) THEN; accept=1; END IF
END IF

ELSE

!dx<0
```

```
!scenario 5
        IF(E_to_store(period_1)>0 .AND. E_to_store(period_2)>=0) THEN
scenario=5
            dx1 = -E_to_store(period_1)                                        !storage limit in
dx2 = -(ELI-E_to_store(period_2))/time_loss                              !storage limit out
            dx3 = Output_to_grid(period_1)*eta_in                                    !grid limit in
dx4 = -((grid_constraint(period_2)+Output_to_grid(period_2))/(eta_out*time_loss))  !grid limit out
dx = MAX (dx, dx1, dx2, dx3, dx4)
        END IF

!scenario 6
        IF(E_to_store(period_1)>0 .AND. E_to_store(period_2)<0) THEN
scenario=6
            dx1 = -E_to_store(period_1)                                        !storage limit in
dx2 = E_to_store(period_2)/time_loss                              !storage limit out
dx3 = Output_to_grid(period_1)*eta_in                                  !grid limit in
dx4 = -(Output_to_grid(period_2))/(eta_out*time_loss)  !grid limit out            dx =
MAX (dx, dx1, dx2, dx3, dx4)
        END IF

!scenario 7
       IF(E_to_store(period_1)<=0 .AND. E_to_store(period_2)>=0) THEN
            scenario=7
            dx1 = (ELO-E_to_store(period_1))                                        !storage limit in
         dx2 = -(ELI-E_to_store(period_2))/time_loss                              !storage limit out
         dx3 = -(grid_constraint(period_1)-
Output_to_grid(period_1))*eta_in                                  !grid limit in              dx4 = -
((grid_constraint(period_2)+Output_to_grid(period_2))/(eta_out*time_loss))  !grid limit out
            dx = MAX (dx, dx1, dx2, dx3, dx4)
        END IF

!scenario 8
        IF(E_to_store(period_1)<=0 .AND. E_to_store(period_2)<0) THEN
scenario=8
            dx1 = (ELO-E_to_store(period_1))                                        !storage limit in
dx2 =  E_to_store(period_2)/time_loss                              !storage limit out              dx3
= -(grid_constraint(period_1)-
Output_to_grid(period_1))*eta_in                                  !grid limit in
            dx4 = -(Output_to_grid(period_2))/(eta_out*time_loss)  !grid limit out  !grid limit out
dx = MAX (dx, dx1, dx2, dx3, dx4)
        END IF

!This section checks the available space for moving energy between periods 1 and 2
i_temp = MINLOC(E_stored(period_1:(period_2-1)), DIM=1)
        i_temp2 = period_1+i_temp-1

        time_loss_4 = EXP((time(period_1)-time(i_temp2))/tau)
m = MINVAL(E_stored(period_1:(period_2 - 1)))
        dx5 = (-m/time_loss_4)!+(1e-8)

        IF(dx5>0) THEN
```

```
        dx5 = 0
END IF

        dx = MAX(dx, dx5)

        IF (dx > 0) THEN; dx=0; ENDIF


!This section checks the revenue of the potential move - accept if revenue increases
!Works out the new values Output_to_grid would be if the move is accepted

accept = 0
        IF(scenario==5) THEN
          new_OtG_1=Output_to_grid(period_1)-dx/eta_in
          new_OtG_2=Output_to_grid(period_2)+(dx*time_loss)/eta_in
        END IF

        IF(scenario==6) THEN
          new_OtG_1=Output_to_grid(period_1)-dx/eta_in
          new_OtG_2=Output_to_grid(period_2)+(dx*time_loss*eta_out)
END IF

        IF(scenario==7) THEN
          new_OtG_1=Output_to_grid(period_1)-dx*eta_out
new_OtG_2=Output_to_grid(period_2)+(dx*time_loss)/eta_in          END
IF

        IF(scenario==8) THEN
          new_OtG_1=Output_to_grid(period_1)-dx*eta_out
          new_OtG_2=Output_to_grid(period_2)+(dx*time_loss*eta_out)
        END IF

Rev1=Output_to_grid(period_1)*kwh_price(period_1) +
Output_to_grid(period_2)*kwh_price(period_2)
Rev2=new_OtG_1*kwh_price(period_1) + new_OtG_2*kwh_price(period_2)
IF(new_OtG_1<=grid_constraint(period_1) .AND. new_OtG_2>=-grid_constraint(period_2)) THEN
IF(Rev2 > Rev1) THEN; accept=1; END IF
END IF


END IF

IF(dx==0) THEN; accept = 0; END IF


!now if the move is accepted then all the variables can be updated..
IF(accept == 1) THEN

      time_loss_2 = EXP((time(period_1)-time(period_2))/tau)

```

```
!update energy in store at periods 1 and 2
       E_to_store(period_1) = E_to_store(period_1) + dx
       E_to_store(period_2) = E_to_store(period_2) - dx*time_loss_2
!update output to grid at periods 1 and 2
       Output_to_grid(period_1)=new_OtG_1
       Output_to_grid(period_2)=new_OtG_2

!update state of charge between periods 1 and 2
DO ifill = period_1,(period_2 - 1)
E_stored(ifill)=E_stored(ifill)+(dx*EXP((time(period_1)-time(ifill))/tau))
END DO


!Check for flags in debugging
IF(scenario==1) THEN; IF (dx < 0) THEN; flag1=1; flag1_tot=flag1_tot+1; ENDIF; END IF
IF(scenario==2) THEN; IF (dx < 0) THEN; flag2=1; flag2_tot=flag2_tot+1; ENDIF; END IF
IF(scenario==3) THEN; IF (dx < 0) THEN; flag3=1; flag3_tot=flag3_tot+1; ENDIF; END IF
IF(scenario==4) THEN; IF (dx < 0) THEN; flag4=1; flag4_tot=flag4_tot+1; ENDIF; END IF
IF(scenario==5) THEN; IF (dx > 0) THEN; flag5=1; flag5_tot=flag5_tot+1; ENDIF; END IF
IF(scenario==6) THEN; IF (dx > 0) THEN; flag6=1; flag6_tot=flag6_tot+1; ENDIF; END IF
IF(scenario==7) THEN; IF (dx > 0) THEN; flag7=1; flag7_tot=flag7_tot+1; ENDIF; END IF
IF(scenario==8) THEN; IF (dx > 0) THEN; flag8=1; flag8_tot=flag8_tot+1; ENDIF; END IF


END IF

flags_total=(flag1_tot+flag2_tot+flag3_tot+flag4_tot+flag5_tot+flag6_tot+flag7_tot+flag8_tot)


!The following sections allow output of data for debugging etc.
IF (accept==1) THEN
!write to files the first accepted 2000 values for total revenue, then every 100th - used for figures to
show trending to final value
IF (accept_count<2000) THEN; revenue_iterations(accept_count)
= n; revenue_iterations_value(accept_count) = SUM(Output_to_grid*kwh_price); ENDIF
IF ((MOD((accept_count-2000),100)==1) .AND. (accept_count<num_rev_output)) THEN;
revenue_iterations(accept_count) = n; revenue_iterations_value(accept_count) =
SUM(Output_to_grid*kwh_price); ENDIF

!next section outputs to all_dx.txt file for debugging
!IF (accept_count==1) THEN;
!WRITE(74,*) ' n ', 'accept', ' period_1 ', ' period_2 ', ' scenario ', ' dx ', ' dx1 ', ' dx2 ', ' dx3 ', ' dx4 ', '
dx5 ', ' TL1 ', ' TL2 ', ' TL4 ', ' Old_OTG1 ', ' Old_OTG2 ', ' OTGP1 ', ' OTGP2 ', ' new_OtG_1 ', '
new_OtG_2 ', ' Old_ETS1 ', ' Old_ETS2 ', ' ETS1 ', ' ETS2 ', ' Rev2-Rev1 ', ' gc1 ', ' gc2 ', ' flag1 ', '
flag2 ', ' flag3 ', ' flag4 ', ' flag5 ', ' flag6 ', ' flag7 ', ' flag8 ', ' flags_total ' !all_dx.txt file see line ~68
!ENDIF
!WRITE(74,*), n, accept, period_1, period_2, scenario, dx, dx1, dx2, dx3, dx4, dx5, time_loss,
time_loss_2, time_loss_4, Old_OTG(period_1), Old_OTG(period_2), Output_to_grid(period_1),
Output_to_grid(period_2), new_OtG_1, new_OtG_2, Old_ETS(period_1), Old_ETS(period_2),
E_to_store(period_1), E_to_store(period_2), Rev2-Rev1, grid_constraint(period_1),
grid_constraint(period_2), flag1, flag2, flag3, flag4, flag5, flag6, flag7, flag8, flags_total
!all_dx.txt file see line ~68
```

```
!140 format (5a10, 9a5, 22a11)
!150 format (5i15,22f15.3,9i6)
!DO i = 1,window
!use line below to make output data used to prepare video
!WRITE (73,*), n, accept_count, scenario, E_stored(i), Rev2-Rev1
!END DO


accept_count = accept_count+1
ENDIF

Old_OTG(period_1)=Output_to_grid(period_1)
Old_OTG(period_2)=Output_to_grid(period_2)
Old_ETS(period_1)=E_to_store(period_1)
Old_ETS(period_2)=E_to_store(period_2)


END DO ! end of main program loop





!The following sections output data for graphing and debugging

OPEN(UNIT=60, FILE = 'Run_deets.txt')
OPEN(UNIT=72, FILE = 'output_for_figures.txt', RECL = 550)

DO i = 1,window
Revenue(i) = Output_to_grid(i)*kwh_price(i)
IF (i==1) THEN; Cumsum_Rev(i)=Revenue(i); ENDIF
IF (i>1) THEN; Cumsum_Rev(i)=Cumsum_Rev(i-1)+Revenue(i); ENDIF
IF (i==1) THEN; WRITE(72,FMT='(a7,6a14)'),'period', 'kwh_price(i)', 'E_to_store(i)', 'E_stored(i)',
'OTG(i)', 'Revenue(i)', 'Cumsum_Rev(i)'; ENDIF
WRITE(72, FMT='(i, f8.5, 5f14.5)'), i, kwh_price(i), E_to_store(i), E_stored(i), Output_to_grid(i),
Revenue(i), Cumsum_Rev(i)
END DO
CLOSE(72);CLOSE(73)


new_Rev = SUM(Revenue)
Original_quantity = SUM(new_test_energy)
New_quantity = SUM(Output_to_grid)


OPEN(UNIT=61, FILE = 'upper_boundary.txt')
WRITE(61, *), new_Rev
CLOSE(61)

OPEN(UNIT=81, FILE = 'flag_scenarios.txt', RECL = 550)
```

```
WRITE(81, FMT='(9a12)'), 'flag1', 'flag2', 'flag3', 'flag4', 'flag5', 'flag6', 'flag7', 'flag8', 'flags_total'
WRITE(81, FMT='(9i12)'), flag1_tot, flag2_tot, flag3_tot, flag4_tot, flag5_tot, flag6_tot, flag7_tot,
flag8_tot, flags_total
CLOSE(81)

OPEN(UNIT=82, FILE = 'flags_total.txt')
WRITE(82, *), flags_total
CLOSE(82)

DO i = 1,num_rev_output
IF (revenue_iterations(i) > 0) THEN
WRITE (76, FMT='(i,f12.2)') revenue_iterations(i),  revenue_iterations_value(i)
END IF
END DO
CLOSE(76)

call cpu_time ( time2 )


WRITE (60,110) '(time independent) round trip efficiency = ', eta_in*eta_out
WRITE (60,110) '(time independent) efficiency in (1=100%) = ', eta_in
WRITE (60,110) '(time independent) efficiency out (1=100%) = ', eta_out
WRITE (60,110) 'max capacity (kWh) = ', Cap_max
WRITE (60,110) 'Power Limit In (kW) = ', PLI
WRITE (60,110) 'Power Limit Out (kW) = ', PLO
IF (tau < 10000) THEN; WRITE (60,110) 'storage time constant (hours)  = ', tau; END IF
IF (tau >= 10000) THEN; WRITE (60,FMT='(a45,es15.3e2)') 'storage time constant (hours)  = ', tau;
END IF
WRITE (60,120) 'number of trials = ', numtrials
WRITE (60,120) 'step_size = ', step_size
WRITE (60,110) 'nearest neighbour Bias = ', nn_bias
WRITE (60,130) 'market = ', market
WRITE (60,120) 'year = ', year
110 format (a45,f15.4)
120 format (a45,i15)
130 format (a45,a15)
!140 and 150 used previously
WRITE (60,110) 'Old Revenue = ', old_Rev
WRITE (60,110) 'new Revenue = ', new_Rev
WRITE (60,110) 'Original energy output = ', Original_quantity
WRITE (60,110) 'New energy output = ', New_quantity
WRITE (60,120) 'Flags total = ', flags_total
WRITE (60,110) 'total cpu time = ', time2-time1

CLOSE (60)
```

```
!STOP

END PROGRAM Full_grid_
```

Appendix 7 – The UK's natural gas infrastructure

Figure 123 - The UK's natural gas infrastructure, source: (DUKES 2.1.1, 2011)