The Role of Interconnectors in Challenging the UK‘s Carbon Footprint

Contribution of Interconnectors to Decarbonisation of Future Energy Scenarios

Sandra Rán Ásgrímsdóttir

Darwin College

Supervisor: Richard McMahon

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Centre for Sustainable Development
Department of Engineering
University of Cambridge
Trumptington Street
Cambridge
CB2 IPZ
United Kingdom

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Declaration

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification.

In accordance with the Department of Engineering guidelines, this thesis does not exceed 15,000 words.

Sandra Rán Ásgrímsdóttir Date
Cambridge

Abstract

Climate change and depletion of resources are commonly discussed in today's societies. Calls have been made for action so dangerous effects such as sea level rises, increase in frequency of extreme weather events and melting of glaciers can be avoided. The United Kingdom (UK) has set a legally binding target for reduction in emissions by 2050 and it is obvious that many sectors will need to be addressed so the target can be achieved. The electricity sector being a prime target as it is responsible for one third of overall emissions in the UK.

Precisely how the goal will be reached is still unknown. Several plausible pathways have been published by various institutions and organisations, providing potential scenarios. All currently proposed pathways, however, involve a relatively small capacity of interconnectors, even though the technology has become a feasible option for bulk import of competitively priced low carbon electricity.

This thesis proposes new pathways for the UK electricity system, where interconnectors play a significant role, which are compared with existing pathways in terms of cost and reduction in emissions. Results from the comparison of scenarios where interconnectors play a significant role with scenarios where the latter have a modest contribution show that interconnectors could play a more significant role in reducing emissions in the electricity sector as pathways with high capacity of interconnectors and renewables are shown to be the most cost effective in reducing emissions, achieving the most reduction for per pound spent.

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List of Abbreviations and Acronyms

CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CM	Capacity Market
DECC	Department of Energy and Climate Change
EDR	Electricity Demand Reduction
EEA	European Economic Area
EMR	Electricity Market Reform
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GHG	Greenhouse Gas
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
O&M	Operation and Maintenance
Ofgem	Office of Gas and Electricity Markets
UK	United Kingdom
VSC	Voltage Source Converter
XLPE	Cross-Linked Polyethylene Insulation

1 Introduction

According to climate change scientists, Greenhouse Gas (GHG) emissions need to peak by 2020, then at least be halved by 2050, and fall to zero later this century to avoid dangerous climate change which could lead to melting of glaciers, sea level rises and increase in extreme weather events (Committee on Climate Change, n.d.). Out of all GHG emissions, carbon dioxide (CO_2) emissions contribute the largest share and are thus the target of many GHG emissions reduction policies. Effects of climate change are regularly discussed in the international community and in the past few decades calls for action have been made. The European Union aims to cut emissions by 85-95% by 2050 (European Commission, 2015) compared to 1990 levels and the United Kingdom (UK) has similarly set a legally binding target for 80% reduction in emissions by 2050, compared to the 1990 baseline (HM Government, 2011). Many sectors will need to be addressed so the target can be achieved, the electricity sector being a prime target as it is responsible for one third of overall emissions in the UK (Committee on Climate Change, 2012; HM Government, 2011).

Precisely how the goal will be reached is still uncertain, however plausible pathways have been published by various institutions and organisations, providing potential scenarios for the future development of the UK energy system. All currently proposed pathways, however, involve a relatively small role for interconnectors, even though the technology has become a feasible option for bulk import of competitively priced low carbon electricity (Department of Energy and Climate Change, 2013a) .

This study proposes new pathways for the UK electricity generation system, in which interconnectors play a more important role than they have in the existing ones. The new pathways are compared with official pathways with respect to emissions and cost. The comparison aims to determine which pathway, and thus what energy infrastructure mix, would be the most beneficial in terms of both cost and decarbonisation of the UK electricity system.

The thesis is structured in the following way. First the background of the current situation and the UK electricity sector is given followed by a review of current and developing electricity generation technologies. Thereafter the methodology of the research is explained to the reader and afterwards results are shown and analysed. Finally results are discussed with respect to limitations and further work needed.

1.1 Background

1.1.1 Carbon Footprint

Environmental footprints represent resource consumption and waste generation and are often a good indicator of the sustainability of an activity (Alderson et al., 2012; Cranston and Hammond, 2010). The carbon footprint is a similar method but is limited to carbon emissions related to the activity. Footprints are most often calculated using a life cycle analysis method and expressed in spatial units, or mass (weight) in the case of carbon footprints (Alderson et al., 2012). The life cycle assessment takes into account energy inputs and emission outputs from all life stages of the product, from cradle to grave. As carbon footprint is a widely known measure, both by the public and professionals, it was chosen as an indicator for carbon emissions from electricity generation.

All electricity generation technologies emit at some stage of their life, be it during operation or other non-operational phases of the life cycle. A carbon footprint is thus a good way to compare technologies on their emissions throughout their system life (Parliamentary Office of Science and Technology, 2006) .

While fossil fuelled technologies have the highest footprint, low carbon technologies also have a footprint. The range of footprint between for some electricity generation technologies can be seen in Table 1. The units are grams of carbon dioxide equivalent per kilowatt hour of electricity generated, or gCO_2eq/kWh. Each technology has a range of assumed carbon footprints that vary between studies. Due to the difference in maturity of technologies, footprints for some technologies are better known than for others. Carbon Capture and Storage (CCS) has a wider range in carbon footprint than hydro due to low maturity of the technology. Table 1 shows the median footprint of the technologies.

Table 1. Carbon Footprint of Electricity Generation Technologies

Generation Technology	Median Carbon Footprint
Coal	850 gCO_2eq/kWh
Gas	400 gCO_2eq/kWh
Carbon Capture and Storage (CCS)	200 gCO_2eq/kWh**
Nuclear	5.5 gCO_2eq/kWh
Hydro	10 gCO_2eq/kWh
Wind	4.64 gCO_2eq/kWh*
Solar	75 gCO_2eq/kWh
Biomass	285 gCO_2eq/kWh

(Parliamentary Office of Scienece & Technology, 2011), * (Perry et al., 2008),**Median for both coal and gas CCS generation.

While the carbon footprint for electricity generation in the UK fell from 718 gCO_2eq/kWh in 1990 to 500 gCO_2eq/kWh in 2008 the sector is still responsible for about one third of overall emissions and must become as close to carbon free as possible by 2050 (HM Government, 2011; Parliamentary Office of Scienece & Technology, 2011). The choice of electricity generation technologies will thus play a role in the path of reaching future targets for emissions.

1.1.2 UK electricity generation

The UK electricity sector is highly dependent on electricity generated from fossil fuels. While low carbon generation - that is generation from nuclear or renewables - has increased in recent years, it only accounted for 33% of total generation in 2014. The rest was generated from fossil fuels, with 33% from coal and 28% from gas (European Network of Transmission System Operators for Electricity, 2014).

Low carbon generation accounted for 31% of total generation in 2013, out of which 16% was generated from nuclear sources (MacLeay et al., 2014). These numbers demonstrate how dependent low carbon generation in the UK is on nuclear generation, as it is responsible for more than half of the total low carbon generation. The UK has 16 nuclear reactors operating, and of these all but one are expected to shut down before 2023 (World Nuclear Association, 2015). With most of the nuclear reactors shutting down the electricity sector needs a short term alternative to at least maintain current levels of low carbon generation.

Within the renewables sector, bioenergy had the biggest share in 2013, accounting for 34% of total renewable generation, followed by offshore wind with 21% and hydro with 8,8% (MacLeay et al., 2014). Bioenergy is the most carbon intensive renewable source with an estimated carbon footprint ranging between 60-550 gCO_2eq/kWh depending on technology and feedstock used. Combustion of wood chips is estimated to range between 60-270 gCO_2eq/kWh while straw has a higher range from 200 gCO_2eq/kWh up to 550 gCO_2eq/kWh (Parliamentary Office of Science & Technology, 2011). While bioenergy is often considered carbon neutral due to the carbon dioxide (CO_2) captured during growth of the plants the footprint states otherwise and should thus be taken into account when choosing technologies for the future.

1.1.3 Proposed Pathways

Due to the government's legally binding commitment to reduce carbon emissions by 80% by 2050, compared to 1990 levels, many different institutions and organisations have proposed low carbon pathways for the future UK electricity system.

The Department of Energy and Climate Change (DECC) stated in the *Carbon Plan* (2011) that decarbonisation of the electricity grid can be achieved with increased renewables, new generation nuclear and by fitting gas and coal power stations with carbon capture and storage (CCS) technologies. The *Carbon Plan* assumes renewable electricity will mainly be produced from onshore and offshore wind and that unabated fossil fuel stations will only be used at times of peak demand. With the addition of marine and bioenergy this plan is proposed as the most feasible and low cost pathway to reach decarbonisation of the UK electricity system. (HM Government, 2011; UK Energy Research Centre, 2011)

While the *Carbon Plan* proposes three pathways to reach the target for decarbonisation many others have been proposed. The following subset of these pathways was used as the starting point for the analysis in this study:

- Pathway developed using the MARKAL optimisation model
- Pathways by DECC published in the *Carbon Plan*
- Pathways by the National Grid

1.1.3.1 MARKAL

The MARKAL (market allocation) model is a widely applied model supported by the International Energy Agency (IEA) and used in over 30 countries. The model is a bottom up, dynamic, linear programming optimisation model. The UK MARKAL has been thoroughly applied to investigate trade-offs between economic, social and technological factors in various future UK energy scenarios. Starting from a range of inputs and assumptions the model delivers a cost optimum solution for an energy system development (Kannan et al., 2007). As the MARKAL model is an optimisation model it is heavily dependent on cost of technologies.

In this project the core UK MARKAL run, produced for DECC as an analysis support to the setting of the forth carbon budget, is used. The core UK MARKAL run results in a power mix of 33 GW capacity from nuclear, 45 GW from renewables and 28 GW from fossil fuels with CCS power in 2050 (HM Government, 2011).

1.1.3.2 DECC

From the core UK MARKAL run DECC developed three new plausible pathways that were published in the *Carbon Plan* (2011). The pathways are the following:

DECC scenario 1: Higher renewables, more energy efficiency

> This pathway assumes expansion in renewable technologies resulting from reduction in cost and innovation that also allows electricity storage capacity to grow. Increase in awareness and smart technologies reduce overall demand. The power mix consists of 55% wind along with other renewables such as solar, marine and hydro. The baseload is covered by nuclear and CCS along with 20GW of pumped storage.

DECC scenario 2: Higher CCS, more bioenergy

> Successful CCS deployment is the foundation for this pathway, alongside a significant amount of sustainable bioenergy and imports of natural gas. The power mix consists of 36GW capacity of renewables, 40GW CCS and 20GW nuclear in 2050.

DECC scenario 3: Higher nuclear, less energy efficiency

> In this pathway, CCS is not deployed at a large scale and wind and solar innovation does not result in cost reduction. Nuclear is thus the main electricity source with natural gas as backup for peak demand and to add flexibility to the system. The power mix consists of 75GW installed nuclear capacity, 20GW wind with the rest covered by other renewables, bioenergy and minor contributions from CCS.

1.1.3.3 National Grid

Duncan Rimmer, from the National Grid, developed a pathway for DECC which was used as an expert pathway in their 2050 web tool. This pathway assumes a future power mix of 35% CCS, 40% nuclear and 25% wind (Rimmer, 2011).

In addition to Rimmer’s pathway the National Grid published four new energy scenarios in 2014. The document, UK Future Energy Scenarios (2014a), shows four plausible future scenarios for the electricity system up to 2030. These range from high affordability and sustainability to no progression. However, since these scenarios are limited to 2030 they are not considered in this study.

1.1.4 Interconnections

An interconnection is a physical link of electricity transmission between separate systems. Interconnectors are normally operated with High Voltage Direct Current (HVDC) and used in long distance bulk power transmissions, long haul submarine cable crossings or when connecting grids with different frequencies. While High Voltage Alternating Current (HVAC) is used on normal transmission systems HVDC is preferred in interconnection as it allows for asynchronous interconnections and significant power losses can be avoided when transferring bulk power longer distances (Bahrman and Johnson, 2007). The interconnector system consists of a converter station that converts high voltage alternating current (HVAC) to HVDC, a HVDC cable and another converter station that converts the power back to HVAC so it can be transferred to the end user (Meah and Ula, 2007). The revenue stream of interconnectors comes from the difference in electricity prices between countries. Generators create revenue by selling electricity to countries with higher prices while consumers on the other side benefit from lower wholesale prices of electricity. However, not all interconnectors have to make revenues as their purpose could also be to increase security of supply (Newbery, 2015; Ofgem, 2014a).

The UK has 4GW interconnection capacity via four interconnectors. The oldest is a link to France with 2GW capacity that went into service in 1986 (ELEXON, n.d.). In 2011 a link to the Netherlands with 1GW capacity was added and two links, 500MW each, connecting to Northern Ireland and the Republic of Ireland went into service in 2002 and 2012 respectively (ELEXON, n.d.). In addition to current interconnectors, agreements have been made for a 1400MW interconnector to Norway and a 1000MW interconnector to Belgium (National Grid, n.d., n.d.).

For those countries the UK is currently connected to, the share of electricity generation from low carbon sources is around 15% - 25%, except for France where 96% is generated from low carbon sources, of which 76% is from nuclear. As the highest capacity link is to France this results in approximately 50% of the imported electricity being low carbon. Furthermore, with the link to Norway the shares of low carbon electricity are likely to increase as Norway generates most of its electricity from hydropower. Not only will this link allow for further bulk transfer of low carbon electricity to the UK, but it will also offer a certain balancing mechanism, as the Norwegian hydropower stations could provide energy storage for the UK, in the form of pumped storage.

As further interconnections have been considered to be beneficial both for the UK and European partners, additional interconnection projects have been under consideration including connections to Denmark and Iceland (European Network of Transmission System Operators for Electricity, 2014). Furthermore, indirect imports of solar energy from North Africa via Spain or France have also been considered (Green Match, 2015; Nur Energie Ltd, 2015; Redpoint, 2013a).

The European Union (EU) agreed a non-binding target for electricity interconnection between member states equivalent to at least 10% (European Council, 2002) of installed production capacity by 2020 as well as an aspiration of 15% interconnection capacity between member states by 2030 (European Commision, 2015). The UK currently has 5% interconnectivity and despite new interconnectors to Norway and Belgium it seems unlikely to reach the 10% target by 2020 (MacLeay et al., 2014; National Grid, 2014b). Being an island the UK faces greater challenges when compared to other EU member states since all interconnections would have to be established via submarine cables. Despite that, the target is clear and more connections will be needed if it is to be achieved.

Interconnections are believed to deliver many benefits to the UK, both in the form of increased security of supply and lower prices for consumers, and also because of the low carbon energy that could be provided via those connections, thus lowering emissions and the carbon footprint of electricity in the country. Many reports, such as *Getting more connected* by National Grid (National Grid, 2014b), *Getting Interconnected* by Policy Exchange (2014), and *Impacts of further electricity interconnection on Great Britain* by Redpoint (2013a), along with other reports state that interconnections would be beneficial for the UK with respect to social, environmental and economic aspects.

1.1.4.1 Interconnection Policy

The UK Government has been supportive of more interconnections as was shown in the Energy Act (2004) where a licensing regime for Electricity Interconnectors was set out. The 2013 Energy Act introduced new incentives for low carbon electricity generation in the form of the Electricity Market Reform (EMR) which could incentivise low carbon interconnectors (HM Government, 2013a). The EMR introduced several new mechanisms, in particular the Capacity Market (CM) and the Contract for Difference (CfD) reforms. The goal of the CM consists in ensuring security of supply to the consumer. Capacity is auctioned out to investors who then receive a set revenue in exchange for providing reliable capacity, while facing financial penalties should they fail to supply the agreed capacity when needed (DECC, 2012a). The CfD aims to support investment in all low carbon electricity generation by providing long term stabilisation in revenues and is a transition from the Renewables Obligation which was a support mechanism for large scale renewable electricity generation (DECC, 2014). Under the CfD the generator sells its power at a fixed price over the duration of the contract and thus limits exposure to electricity price volatility and reduces commercial risk (DECC, 2012a).

The latest addition to these regimes is the Cap and Floor regime (Ofgem, 2014a). This new framework is a regulated merchant model which is meant to encourage new interconnectors by limiting downside to investors. It does so by providing regulated revenue at the floor and protecting consumers with the cap, ensuring that high returns are passed back to the consumers. This regime will be applied on the proposed interconnector linking UK to Belgium (Ofgem, 2014b).

European Policy

As mentioned in chapter 1.1.4 the EU has promoted interconnectivity between member states in recent years and believes in an internal European Electricity Market (*Regulation (EC) No 714/2009*, 2009). The EU requires countries to offer both regulated and merchant models for interconnections but the rules as enforced by the European Commission lean towards a regulated approach (Moore and Newey, 2014). To receive exemptions from certain elements of the regulations merchant interconnector investors need to apply for permission and fulfil certain conditions from article 17 of Regulation (EC) NO 714/2009.

While most countries the UK has connected to, or is considering connecting to, are member states of the EU, Norway and Iceland are not. Norway is connected to Sweden, Denmark, Russia and the Netherlands and a licence has been granted for connection to Germany and the UK (Global Transmission, 2009; Ministry of Petroleum and Energy, 2014). Export and import of electricity is thus regulated and a framework is in place for interconnectors. In Iceland however, there is no provision with regards to export of electricity in the Icelandic

Electricity Act 65/2003. While not touching on exports the act outlines that transmission of electricity is licensed by the government and operated by a single partner (Alþingi, 2003). A change in the Icelandic Electricity Act is thus needed before an interconnector can start operation. Both Iceland and Norway are part of the European Economic Area (EEA) and thus subject to EU rules within the energy sector, however, due to delays not all regulations and directives have been adopted (European Free Trade Association, 2015).

2 Low Carbon Technologies

To achieve a reduction in emissions from the electricity sector the future pathway chosen must consist of a mix of low carbon generation technologies. While the UK has a significant generation capacity of wind, solar, and marine energy, all of those can be considered intermittent sources that will need an additional balancing mechanism to ensure that supply meets demand.

With the aim of decarbonisation the UK will have to reform its generation mix. This chapter reviews the characteristics of existing and developing low carbon technologies the UK could use for future electricity generation. Future possibilities and limitations of those same technologies have also been reviewed with reference to existing literature.

Since hydro power has already been exploited close to its limits and geothermal power is not considered to have significant possibilities for electricity generation in the UK those two technologies are excluded in this review.

2.1 Wind

The UK has great wind resources, both onshore and offshore, and along with technical progress the possibilities for increased power generation from wind are rising. However, wind is an intermittent resource and back up generation is usually necessary to assure balance between demand and supply at all times. Despite the intermittency, cost benefit assessments have shown that the UK electricity system can accommodate significant increase in generation without a large increase in overall costs of supply (Strbac et al., 2007).

2.1.1 Onshore Wind

Onshore wind is one of the most mature renewable technology, and currently the cheapest electricity resource in the UK (Bassi et al., 2012; MacLeay et al., 2014). Onshore wind capacity, at 7,513 MW in 2013, was the biggest contributor to renewable electricity in the UK, accounting for 38% of overall renewable generation capacity (MacLeay et al., 2014). New turbine technology has unlocked new sites with low and medium wind resources thus increasing the number of possible projects (International Energy Agency, 2015a).

Due to reduction in cost of onshore installations in recent years the UK has been able to reduce subsidies for the technology and a further 10% reduction is planned between 2013 and 2017 (DECC, 2015). In some countries onshore wind has matured to the stage where it is competitive with other technologies without subsidies (IEA, 2014a). Moreover the IEA (2015b) assumes in its roadmap for wind that cost for onshore energy will drop further, by as much as 25% by 2050.

2.1.2 Offshore Wind

With shallow waters and strong winds the UK has some of the best offshore wind resources in the world. With stronger and more stable winds offshore it is possible to produce more energy per turbine than onshore, and offshore turbines are thus often larger than those onshore. In 2013 offshore wind capacity in UK was 3,696 MW accounting for 19% of total renewable capacity (MacLeay et al., 2014).

As offshore turbines are larger they also have a more complex structural design for the tower and the foundation which makes these more expensive than the onshore turbines (Ackermann and Söder, 2000). The IEA (2015b) assumes that with continued research and development, energy costs for offshore technologies could drop by up to 45% by 2050. The UK government established a task force in 2011 to investigate if levelised costs of offshore wind could be reduced to £100/MWh by 2020. In June 2012, the task force concluded that while it would be possible to reduce the cost, it would be difficult and strict recommendations would have to be followed (DECC, 2013b).

While onshore wind generation has become competitive with conventional energy in most places, offshore wind has not. Van der Zwaan et al. (2012) argue that the predicted cost reduction hasn't been achieved due to the surge in prices of commodities and greater distance from shore, resulting in greater depth causing the structure of the turbine having to be under constant development. Bilgili et al. (2011) and Breton and Moe (2009) similarly state that offshore wind is promising but requires further research and development on several aspects, such as foundation design and installation procedures, to become competitive. Similar conclusions have been reached in a recent analysis carried out by the IEA (2015b). Levi and Pollitt (2015) argue that further development is needed in the field and money could be saved by waiting three to four years before implementing further offshore capacity. However, the latter also mention that due to being a world leader in offshore capacity it would be most sensible if the UK would lead the development of offshore wind. If environmental costs are considered, waiting could do more harm to the environment.

2.2 Solar PV

Photovoltaic (PV) cells capture sun radiation and the interaction between the radiation and electrons in the cells produces an electrical current (Green, 2000). Solar PV installations have grown quickly in the past four years, resulting in a steep decline in price (IEA, 2014a).

The potential of solar in the UK has been estimated at 700-800 kWh for each installed kW of PV capacity (Šúri et al., 2007). Analysis by Muneer et al (2003) showed that a stable supply of PV power could be generated in the UK with the lowest availability from October to February, when the demand is the highest. Solar is an intermittent resource in the UK and thus requires reserve technologies to balance demand and supply and guarantee reliable supply (Sims et al., 2003). The IEA (2014b) predicts in its technology roadmap for solar PV that the UK would reach about 10GW capacity of PV by 2020. According to the latest Digest of UK Energy Statistics (2014), installed capacity of solar PV reached 2,780 MW in 2013, with most installed through feed in tariffs provided by the government.

The reduction in solar PV price results mainly from a reduction in unit cost, driven by technical advancement and research for efficiency in the field (Tyagi et al., 2013). In some markets utility scale solar PV has already become competitive and with continued research prices are projected to drop further thus becoming competitive with conventional technologies worldwide (IEA, 2015a). In most markets however, a policy support mechanism will be necessary for the technology to reach competitive levels as long as fuel prices don’t reflect environmental factors (IEA, 2014b).

2.3 Marine

Marine technology uses energy from waves and tidal currents to generate electricity. The kinetic energy present is converted to electricity using turbine technology in the case of tidal currents, in a similar manner to conventional turbines, and various other concepts have been proposed for waves (Ben Elghali et al., 2007). The UK is considered a world leader in marine technology and while the technology is still in its early stages it was used to generate 6 GWh of electricity in 2013 (MacLeay et al., 2014).

Marine technology is an immature technology when compared to solar PV and wind (Drew et al., 2009; Sims et al., 2003). DECC (2015) assumes that up to 300 MW capacity could be deployed by 2020. However, with only 7 MW installed in 2013 that seems unlikely to happen (MacLeay et al., 2014).

Before marine technology can become commercially viable, further technological development and cost reduction is needed. Currently, development has high investment costs and few different devices are in development, but these are usually carried out by small developers. Thus further investment is needed both in the public and private sector so development can continue and become competitive commercially (HM Government, 2010).

2.4 Bioenergy

Bioenergy is a renewable technology that is usually sourced from biomass, such as forestry, agricultural and municipal residues and wastes. Several different methods can be used to generate electricity from biomass, depending on the physical nature and chemical composition of the material, such as combustion, gasification, co-firing and anaerobic digestion (Bauen et al., 2009).

While biomass is considered renewable if produced unsustainably this can have high impacts in the form of carbon emissions, land use changes, water depletion and loss of biodiversity (IEA, 2011; Rowe et al., 2009; Thornley et al., 2009). Due to these issues bioenergy has been facing sustainability challenges and policy uncertainty in OECD countries in recent years which has decreased the bankability of large projects (IEA, 2015a). To improve reliability, efficiency and sustainability of bioenergy technologies further development is needed (Bauen et al., 2009).

Bioenergy in the UK had a 4,002 MW capacity in 2013 and accounted for 34% of total generation from renewables (MacLeay et al., 2014). DECC supports large scale generation of biomass electricity as well as small scale generation from anaerobic digestion (DECC, 2015). The cost of bioenergy generally lies between the costs of onshore and offshore wind technologies, with levelised cost ranging from 50 – 200 £/MWh (DECC, 2012b).

The main constraints on future development of bioenergy arise from uncertainty in supply chains and markets as well as effectiveness of emission reduction of the technology compared to fossil fuels (HM Government, 2010).

2.5 Carbon Capture and Storage (CCS)

Carbon capture and storage is a technology that consists in capturing CO_2 emissions from power plants, followed by transport and storage of the captured CO_2 underground in geological formations (Gibbins and Chalmers, 2008; Haszeldine, 2009; IEA, 2009; Szulczewski et al., 2012).

Large scale CCS projects have not yet become commercial but all three components of the technology - capture, transport and storage of CO_2 - are being undertaken separately at a commercial scale. Additional research and development along with reduced costs remains to be demonstrated on a commercial scale for large scale CCS projects (IEA, 2009).

The first complete commercial electricity generation unit with full capture of emissions went into service in Canada in October 2014 (IEA, 2015a). A small demonstration plant (30MW) with CO_2 capture is operating near Berlin in Germany and the UK Government has ambitions to start similar projects within the UK (Coninck et al., 2009). Two projects, White Rose and Peterhead, have been awarded funding and are projected to become UK's first commercial scale CCS projects. However future costs are uncertain, with DECC (2013c) projecting levelised costs for commercial plants in 2025 in the range of £88/MWh - £105/MWh when used with gas and £89/MWh - £173/MWh with coal.

Large deployment of CCS faces challenges both in regard to public acceptance as well as in technical development (Acke et al., 2011). Viebahn et al (2012) conluded that there might not be need for CCS to achieve decarbonisation goals in Germany, and possibly Europe as well, and that by 2020 several renewable technologies could generate electricity at lower cost than CCS power plants. While progress is being made IEA (2015a) still considers the technology underdeveloped if considered with regard to limiting climate change to a global temperature rise of 2°C.

2.5.1 Negative Emissions

Using CCS technology with bioenergy generation is considered to have negative emissions (IEA, 2011). Similarly bioenergy is considered to have negative emissions when it is utilised in conjunction with reforestation (Vuuren et al., 2013). Negative emissions are achieved through a net reduction of CO_2 from the atmosphere, which results when biomass absorbs carbon during its lifetime and the emissions produced during combustion are captured and stored (IEA, 2011).

2.6 Nuclear

Nuclear electricity generation accounted for about 20% of total electricity generation in the UK in 2013 with capacity of 9,906 MW (MacLeay et al., 2014). The UK government expects this technology to play a significant role in its future energy mix, considering nuclear as an essential technology in delivering a sustainable and secure low carbon future for the energy system (HM Government, 2013b). While all but one out of current 16 generating nuclear reactors in the UK should close down by 2023 (World Nuclear Association, 2015) the industry has set out plans to deliver around 16GW of new nuclear capacity by 2030 (HM Government, 2013b).

Nuclear power is a mature technology and the largest source of low carbon electricity in OECD countries (IEA, 2015c). Main concerns about the technology are related to reactor safety and transport and disposal of radioactive waste (Sims et al., 2003). Third generation reactors which are under construction are expected to deliver increased safety. However this will come at an increased cost compared to previous reactors (IEA, 2015c) due to higher capital costs and increased construction time (Harris et al., 2013).

Du and Parsons (2009) showed that between 2003 and 2007 the overnight capital cost of building a nuclear power plant had approximately doubled from $2,000/kW to $4,000/kW. Harris et al (2013) similarly found that if considered with respect to historical trends and recent overnight estimates, levelised cost of nuclear would be well above previous market estimates in the range from £164/MWh to £175/MWh, while older estimates ranged between £40/MWh to £95/MWh. In comparison DECC (2013c) assumed that the cost of nuclear in 2020 would range between £83/MWh to £108/MWh.

In 2013 the government granted a licence for the first new nuclear power station, Hinckley Point C, since 1995, expected to be first of five new sites to be developed by 2030 (HM Government, 2013b). However, due to delays and budget overruns in similar projects in Finland and France the future of the new projects is unclear (Bradford, 2012; Macalister, 2014). While other developments of nuclear reactors, such as the Westinghouse AP1000 reactor, might prove to be more successful in the future, there are no guarantees yet.

2.7 Interconnectors

As mentioned in chapter 1.1.4 interconnectors are a physical link to transfer electricity between countries. For distances longer than 60-70 km and capacities higher than 1 GW it is a general rule of thumb to use HVDC which can be both in the form of overhead lines and cables (Hook and Jones, 2013). The reliability of long HVDC cables has increased considerably over the last few decades decreasing from 0.264 failures/year/100 km in 1986 to 0.100 failures/year/100 km in 2009 (Karlsdóttir, 2013). The availability of a cable thus depends in large part on its length, however weather conditions also play a role. A report by Sinclair Knight Merz (2012) for OFGEM they showed that changing the length of a subsea cable from 700 km to 350 km would only increase the availability from 94.67% to 95.92%. Transmission losses also have to be considered when planning an interconnector. In a report from Redpoint (2013a) interconnector losses are derived assuming 1.5% loss due to conversion between AC and DC and further 0.75% transmission loss per 100 km. Sinclair Knight Merz (2013) however state that transmission losses have been falling and are approaching 1%. With more investment in the cable itself costs and losses can be reduced even further.

Redpoint (2013a) assembled prices from 12 proposed interconnector projects with published information on cost and used linear regression of cable length to estimated cost in £/MW. The results can be seen in Table 2.

Table 2. Interconnection costs and losses (Redpoint, 2013)

Interconnector	Distance (km)	Cost (£m/MW)	Losses (%)
Belgium	140	0.52	2.55%
Denmark	600	1.00	6.00%
France (long)	195	0.58	2.96%
France (short)	70	0.45	2.03%
Germany	480	0.87	5.10%
Iceland	1200	1.62	10.50%
Ireland	170	0.55	2.78%
Ireland (North)	170	0.55	2.78%
Netherlands	260	0.64	3.45%
Norway (England)	711	1.11	6.83%
Norway (Scotland)	570	0.96	5.78%
Spain	850	1.25	7.88%
Sweden	900	1.31	8.25%

The costs of interconnection projects are highly dependent on distance as can be seen in Table 2. However, reduction in losses along with development in cross-linked polyethylene insulation (XLPE) technology could enable a significant reduction in overall costs of HVDC projects in the near future (Hook and Jones, 2013; Redpoint, 2013a). Ongoing developments, such as with Voltage Source Converter (VSC) technology, are also likely to contribute further to reduction in cost of overall HVDC systems (Hook and Jones, 2013).

Interconnectors are often seen as a feasible investment as they allow for connection to countries where electricity prices are lower and thus lower wholesale electricity prices in the UK (National Grid, 2014b). However, while interconnections are often seen as good investment between markets with low and high electricity prices, Parail (2010) found that interconnectors between markets without consistent price difference could also generate considerable revenues. Additionally, reports have demonstrated that an increased capacity of interconnectors could lead to an overall lower systems cost compared to alternatives (National Grid, 2014b; Redpoint, 2014).

Further support of interconnection is associated with the increased security of supply linked with interconnectivity. Analyses have shown that interconnections can increase security of energy supply, especially when connecting to variable sources, and can help solve some challenges related to intermittent renewables. For example wind power generation in the UK could be balanced with hydro power from Norway and Iceland or solar energy from Spain and

Africa. (DECC, 2013a; Hunt et al., 2014; National Grid, 2014b; Redpoint, 2013a). It should be acknowledged that Norway can’t provide storage services for every country in Europe and thus other countries, such as Iceland and Spain, should be considered as well.

Iceland and Norway have excellent hydro resources that could be used for both bulk power transfer and balancing (Boston and Thomas, 2015). In the Icelandic Energy Policy (2011) projections estimated that about 13 TWh/year of available, and acceptable, hydropower resources in the country were still not being harnessed and in Norway the number was estimated to be around 30 TWh/year in 2012 (Norwegian Water Resources and Energy Directorate, 2013). In addition to those numbers are the geothermal resources in Iceland, which covered approximately 30% of electricity generation in 2012 and onshore wind possibilities that are estimated to generate similar energy as offshore generation elsewhere but are still under development (Askja Energy, 2015; OECD, 2014). Solar power potential in both Spain and Africa has proven to be much higher than estimated demand in 2050 and there are thus great opportunities for bulk transport of clean solar energy from those areas (Domínguez Bravo et al., 2007; Trieb et al., 2009).

2.7.1 Future Bottlenecks of Current Transmission Infrastructure

With development and changes in the electricity mix future bottlenecks need to be identified. The main constraints on the current electricity transmission system are mainly in the network between Scotland and England. Generation in Scotland exceeds network capacity available for transmitting the power to the major load centres in the south. Similarly there are bottlenecks in entry to the grid on the east and west coast of England and Wales (Clarke et al., 2008). In 2013 work was started on a 2,200MW HVDC cable connecting Scotland and Wales, planned to start operation 2016 and could help with transmission of electricity from Scotland to England and Wales (Western HVDC, n.d.). With further investment in renewable energy and interconnectors it is highly likely that further reinforcement of the transmission grid will be needed.

3 Methodology

The aim of the study was to develop new future electricity pathways and compare these with existing proposed pathways in relation to cost and emissions.

All pathways were first modelled using a user friendly calculator developed by DECC (2012c) and available online that allowed a first level analysis of the scenarios and generation capacities. Since the DECC calculator does not include a load curve, pathways were later modelled in more detail with the Long-range Energy Alternatives Planning (LEAP) software, developed by the Stockholm Environment Institute (2012).

All pathways were compared and evaluated on the basis of emissions costs. A cost sensitivity analysis of each pathway was also performed.

3.1 Rationale for Choice of Model

While there are several alternatives for energy scenario modelling the decision was made to use LEAP. LEAP is a widely-used program for energy policy analysis and climate change mitigation assessment. The program is user friendly and thus a limited knowledge of programming is needed for its use (Heaps, 2012).

While it is not an optimisation model like MARKAL it allows for both accounting and simulation methodologies which MARKAL does not (Bhattacharyya and Timilsina, 2010; Connolly et al., 2010). LEAP simulates all sectors of the system and accounts for total system impacts using the integrated Technology and Environmental Database (TED). The TED has information on environmental impact, characteristics and cost of a wide range of existing and developing technologies (Shin et al., 2005). In this simulations the TED costs were however not used but instead costs from DECC. LEAP takes in the cost, capacity and merit order of technologies specified. Information has to be specified for the base year and the changes until the final year of the horizon. LEAP then dispatches costs and emissions for the whole system along with the generation mix for each year in the time period.

3.2 Supply and Demand

As the focus is on the supply of electricity, only one demand scenario is used for all pathways, adopted from the core UK MARKAL run as it was generated by an optimization model. Furthermore this demand levels are similar to the Future Energy Scenarios published by the

National Grid (2014a). The supply mix for each pathway was collated from the DECC calculator. To estimate the supply capacities of new pathways these were first entered into the DECC calculator and then figures derived from those results.

3.3 New Pathway Criteria

Three pathways were developed with the criterion of having a higher capacity of interconnectors previously proposed pathways by DEECC and the National Grid, while still achieving the decarbonisation of the electricity sector. The supply mix for these new pathways mainly relies on increased capacity from interconnectors and renewables, with two also including nuclear and CCS for backup. The majority of the renewable generation comes from wind and solar PV. Biomass is not considered as a feasible option due to uncertainty carbon neutrality and impacts on land use. While nuclear and CCS are uncertain in regard to deployment and cost they are used for comparison as baseline and balancing has to be covered by technologies that are not as intermittent as solar and wind. The new pathways developed are as follows:

Scenario I This pathway assumes development of 16GW of capacity from new nuclear generators, as proposed by the government. Solar PV and wind are used to cover a large part of the generation along with interconnectors providing back up.

Scenario II The second new pathway assumes that a 35 GW capacity of interconnectors is implemented providing also balancing services while renewable generation covers the rest. Due to uncertainties in nuclear and CCS there is no installation of those technologies with interconnectors covering 50% of demand. It is not specified where the interconnector capacity will come from, but assumed that it originates from the countries discussed in chapter 2.7.

Scenario III The third pathway assumes that all interconnectors proposed in the ENTSO-E (2014) *Ten-Year Network Development Plan* portfolio are implemented, along with moderate capacity of renewables, mainly wind and solar PV. CCS technologies are used for back up.

3.4 Time Horizon

The time horizon of the model ranges from 2010 to 2050. This time horizon was chosen based on EU and UK targets for decarbonisation by 2050. The base year was selected as 2010 due to the availability of data and the integrated horizon of the DECC calculator. Due to a wide horizon some assumptions had to be made for technologies and costs which are explained in the next section.

3.5 Model Assumptions

Due to a wide time horizon and the inclusion of technologies with low maturity, some assumptions had to be made during the process of modelling the pathways. To make all pathways comparable data for efficiency, capacity/load factors, capacity credit and fuel costs from the DECC calculator were used in the LEAP model. It was further assumed that CCS technologies have the same emission mix of conventional coal and gas generation technologies and that 80% of the CO_2 emissions are captured.

A capacity margin of 5% is used in the model and was estimated as an average from the 2014 *Electricity Capacity Assessment* carried out by Ofgem (2014c). Furthermore a load curve for the UK from 2010, available online in the National Grid's historic demand data set, was used and adapted to the model (National Grid, 2015).

3.5.1 Interconnection Assumptions

As mentioned in Chapter 1.1.4 the UK currently has 4GW capacity from interconnections with 2,4GW more planned in the next three to four years. Further interconnections are proposed and listed in the Ten-Year Network Development Plan published by ENTSO-E (2014) totalling approximately 15GW of interconnection capacity. From the information covered in the technology review and suggested capacities from other reports a maximum capacity of 35GW was considered for 2050, which aligns with the capacity proposed as feasible by E3G (Moore and Newey, 2014). Where the interconnection capacity origin is not specified in the model, it is assumed that it will be from the same countries as existing interconnections with additions from Spain, Africa, Iceland and possibly Denmark.

In accordance with UK decarbonisation targets and the purpose of the comparison it is further assumed that the generation mix of supply via interconnectors consists of 10% conventional energy by 2030 and is completely decarbonised by 2050. Furthermore, it is assumed that the interconnectors are always available for dispatch.

3.6 Model Exclusion

The model only includes interconnector investment on the UK side and thus excludes all investments required within the country linking to the UK. Investments in additional capacity and grid connections in other countries are thus excluded. Lastly development in energy storage is excluded from the model.

3.7 Cost Sensitivity Analysis

Cost sensitivity analysis in LEAP is performed using the most recent data published in DECC’s 2013 Electricity Generation Cost report. The data includes capital costs, fixed operation and maintenance cost (O&M) and variable O&M costs. Costs were implemented for all technologies representing high, median and low cost scenarios. The costs were collected from reports by Redpoint (2013b) and Parsons Brinckerhoff (2013), commissioned by DECC. As a cost for conventional coal was not found in the cited documents, these were adapted from the U.S. National Renewable Energy Laboratory’s workbook (2015). Costs used for all technologies are presented in Appendix 8.1.

The capital costs of interconnectors were taken from Redpoint’s (2013a) report on interconnectors for DECC, which includes cost estimates for various interconnectors based on distance as shown in Table 2. An average of the costs of interconnectors listed in the table was used in the model to represent the wide range of interconnection possibilities. The price for fixed O&M was adapted from the most recent plans for the connection with Belgium, the NEMO link (Stokes and Chapman, 2013). It is assumed that the trading cost is included in the capital and the fixed O&M cost of the interconnectors, similarly to the method used in the DECC calculator.

To evaluate the impact the average interconnector cost could have on the results an additional scenario is simulated with the highest proposed cost from Table 2. Table 3 lists the costs used for interconnectors.

Table 3. Cost of interconnectors

	Average Capital Cost (£m/MW)	Fixed O&M (£m/MW)
Average Cost	0.88	0.00659
Highest Cost	1.62	0.00659

Additionally all scenarios are modelled with the fixed cost of interconnectors as well as an assumed reduction in cost of 20% over the time period.

4 Results

This section shows results from the simulation of each pathway, as well as a comparison between pathways and cost scenarios. As all pathways were simulated first using the DECC calculator and later using LEAP, only results from the latter will be demonstrated.

This section shows in detail the generation capacity of each pathway, both with figures and tables, and the estimated generation according to merit order, which is the preference of technologies chosen by the modeller. Further results for emissions and cost of each pathway are compared and discussed, with the aim of determining which pathway would be the most feasible to achieve the UK target for decarbonisation. Finally, the cost sensitivity analysis is carried out to investigate the effect changes in cost could have on the results.

Table 4 shows the pathways that were modelled and the abbreviations used for referencing in figures and tables.

Table 4. Modelled pathways

Model	Abbreviation
MARKAL UK	MARKAL
National Grid	NG
DECC scenario 1	DECCsc1
DECC scenario 2	DECCsc2
DECC scenario 3	DECCsc3
Scenario I	ScI
Scenario II	ScII
Scenario III	ScIII

4.1 Generation Capacity

With different options for the supply mix the pathways vary in the shares of different technologies and feedstock fuels. Figure 1 and Figure 2 give an example of different generation capacities between pathways in the years 2030 and 2050.

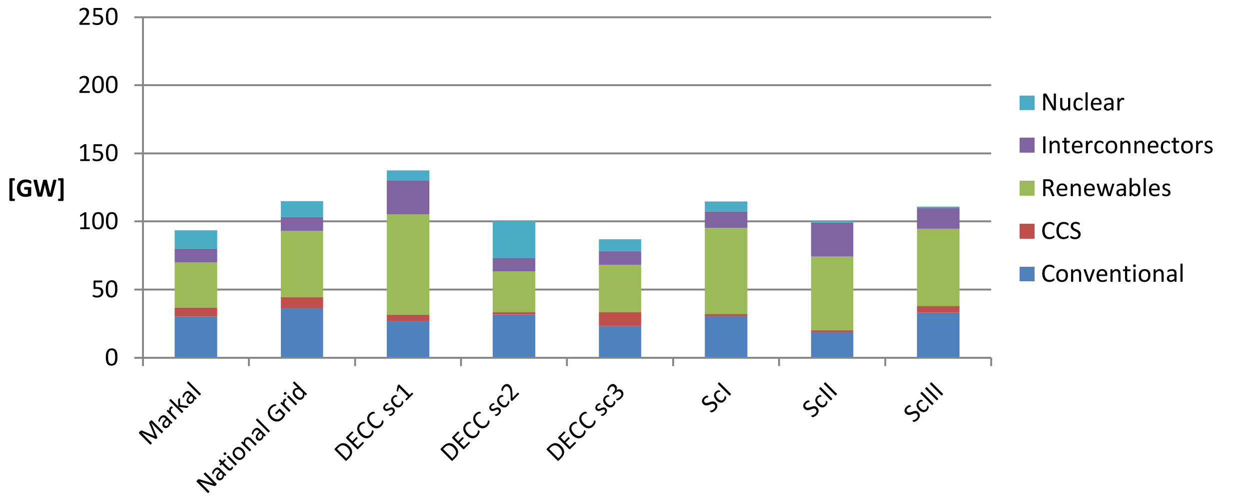

Figure 1. Generation capacity by scenario in 2030

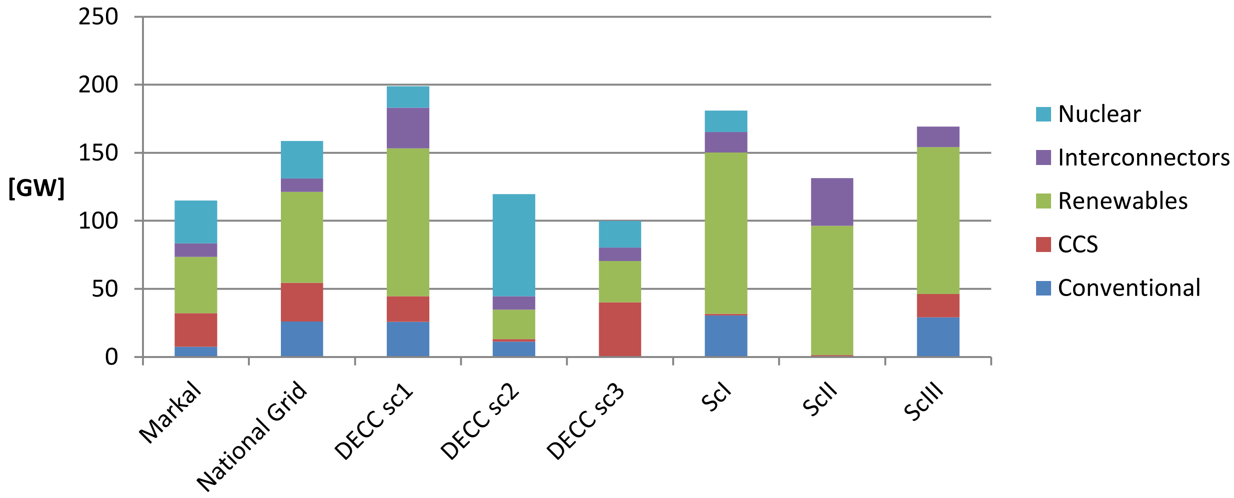

Figure 2. Generation capacity by scenario in 2050

The change in generation capacity between scenarios is related to the capacities of intermittent renewables and difference in installed capacity of backup gas.

The following chapters show details of future capacity and generation of each pathway considered in this study.

4.1.1 Generation Capacity and Output of Each Scenario

4.1.1.1 MARKAL

The MARKAL pathway was modelled based on data collated from the DECC calculator. Figure 3 shows the generation capacity of the pathway throughout the time horizon of the model.

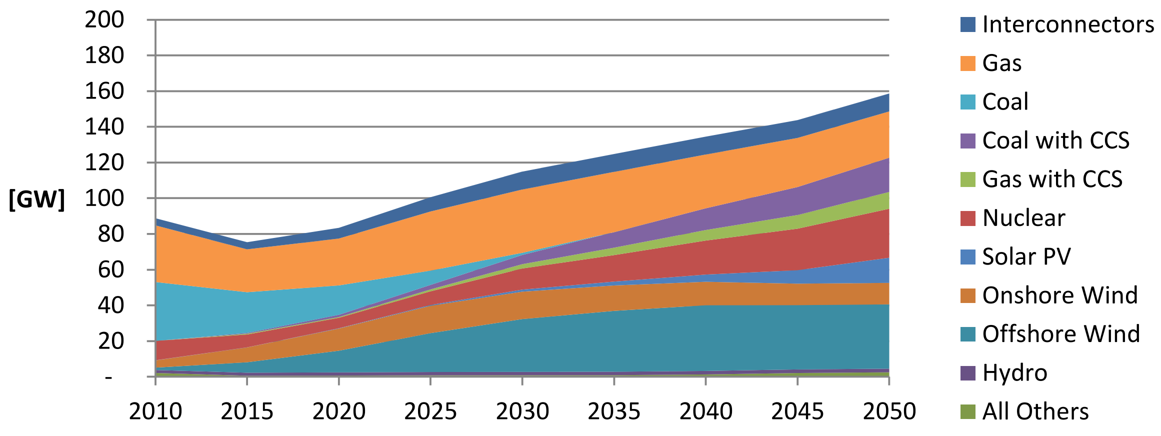

Figure 3. MARKAL generation capacity by technology

The MARKAL pathway has the electricity supply shared somewhat evenly by a number of different technologies. Figure 4 shows the change in electricity generation by source throughout the time horizon. This pathway relies on electricity generated by nuclear power, with contributions from wind and CCS also playing a significant role.

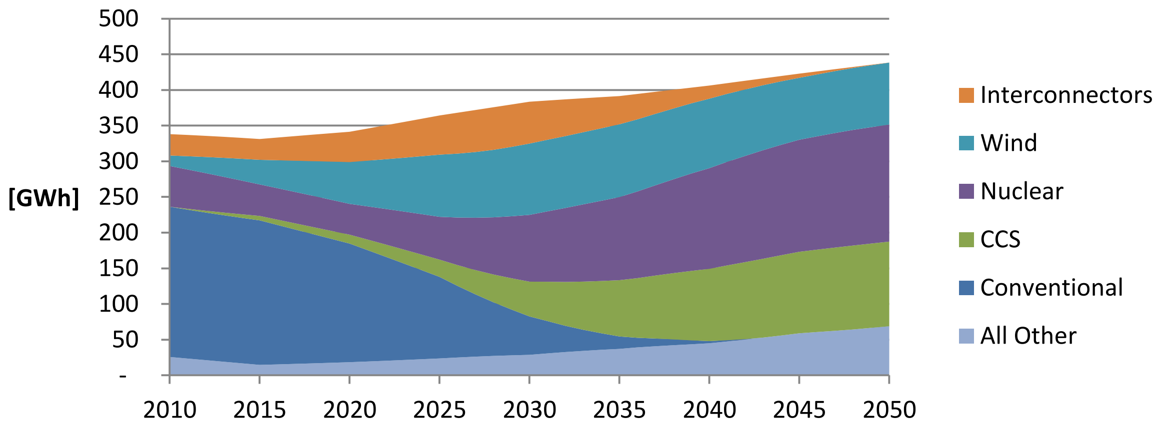

Figure 4. MARKAL generation output by feedstock fuel

4.1.2 National Grid

The data for the NG pathway was derived from the DECC calculator and implemented in LEAP. Figure 5 shows the pathway's change in capacity of from 2010 until 2050.

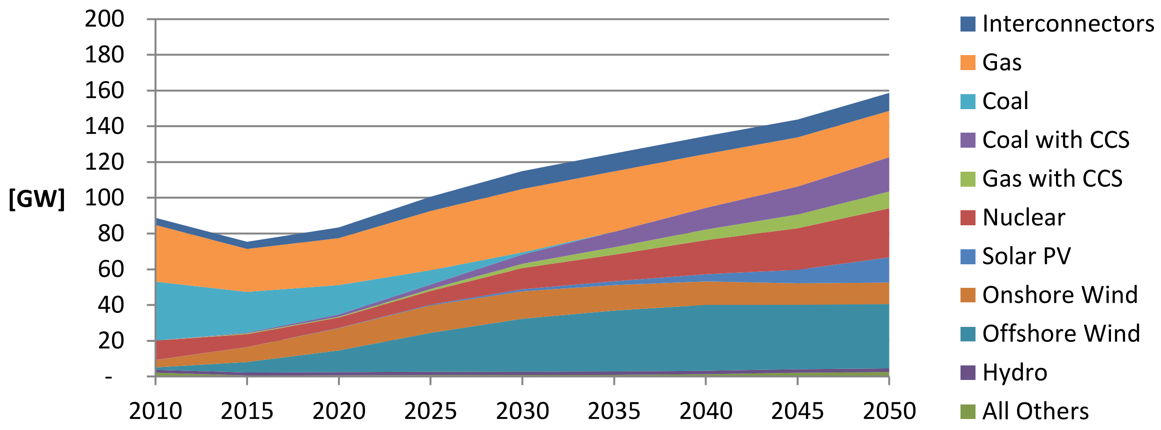

Figure 5. National Grid generation capacity by technology

Figure 6 shows generation for this scenario based on merit order. The figure demonstrates clearly Rimmer's assumption from chapter 1.1.3.3 where it was discussed how the fuel mix would be an equal split between nuclear, CCS and wind generation in 2050.

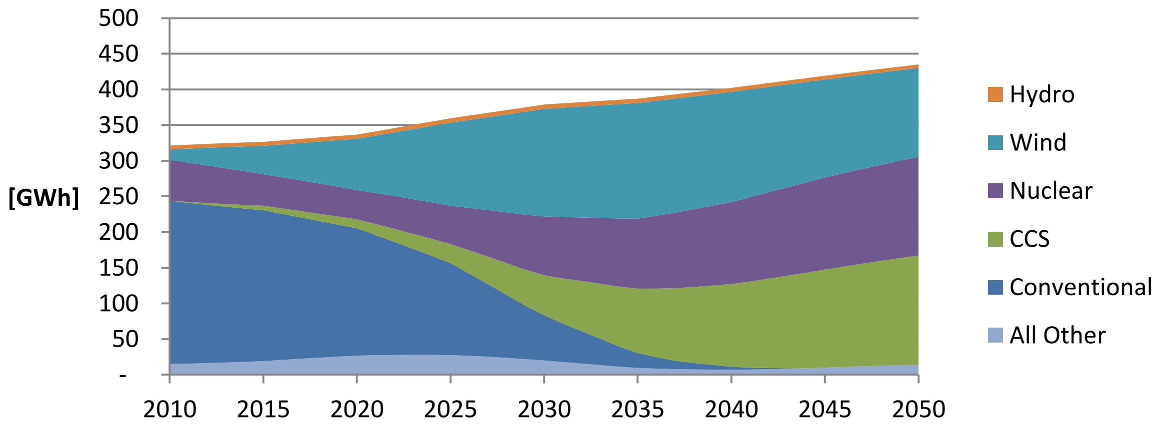

Figure 6. National Grid generation output by feedstock fuel

4.1.3 DECC scenario 1

DECCsc1 is the first DECC pathway and relies largely on renewables as described in chapter 1.1.3.2. Figure 7 shows how the capacity is a mix of various technologies with wind having the highest capacity in 2050. The large share of gas is related to development of backup gas generators that could balance between supply and demand as the pathway has a significant reliance on intermittent renewables.

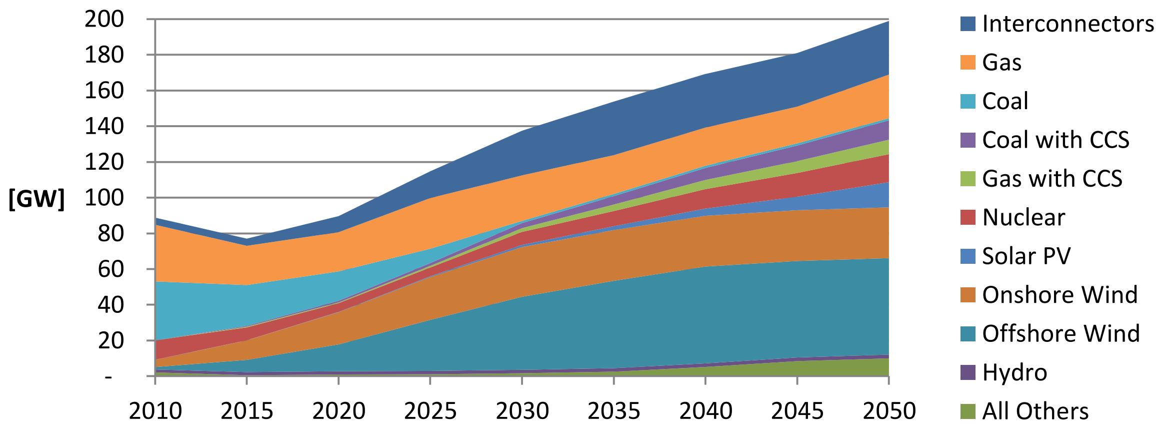

Figure 7. DECCsc1 generation capacity by technology

While wind is below 50% of total capacity, Figure 8 demonstrates that the source could cover about 60% of the demand in 2050. Gas is scarcely used for generation in spite of the significant installed capacity but is available for back up when needed.

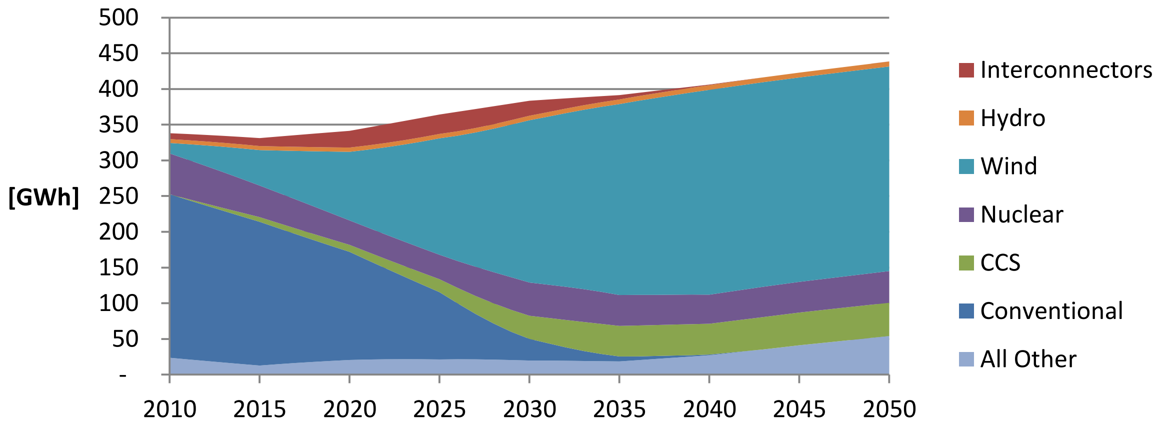

Figure 8. DECCsc1 generation output by feedstock fuel

4.1.4 DECC scenario 2

The second DECC pathway, DECCsc2, assumes limited development of renewables and new technologies with large scale deployment of new nuclear generation. Figure 9 shows that nuclear capacity is expected to cover more than half of total installed capacity by 2050.

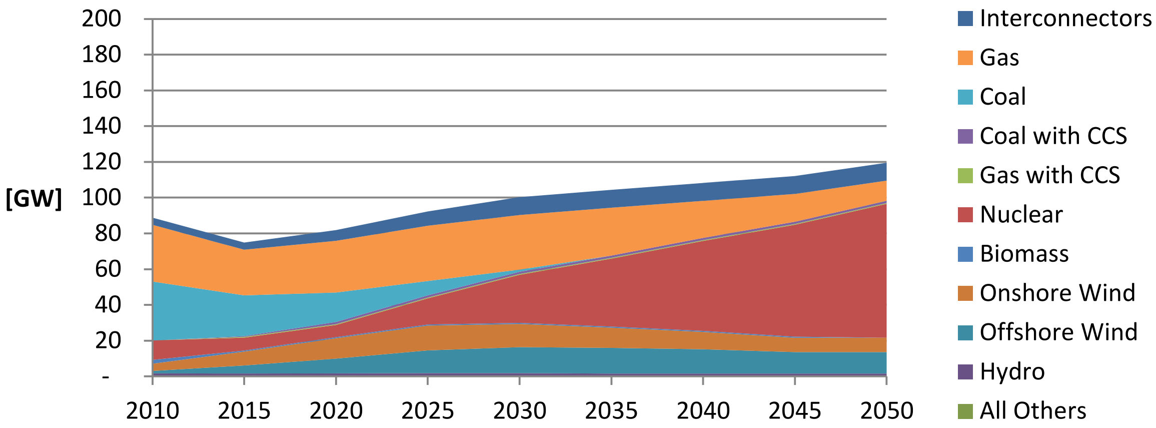

Figure 9. DECCsc2 generation capacity by technology

In terms of electricity generated by source, nuclear covers about 80% of generation, as installed capacity of gas and interconnectors are only used for back up (Figure 9). Figure 10 shows the substantial increase in nuclear generation from 2020 along with a steady contribution from wind.

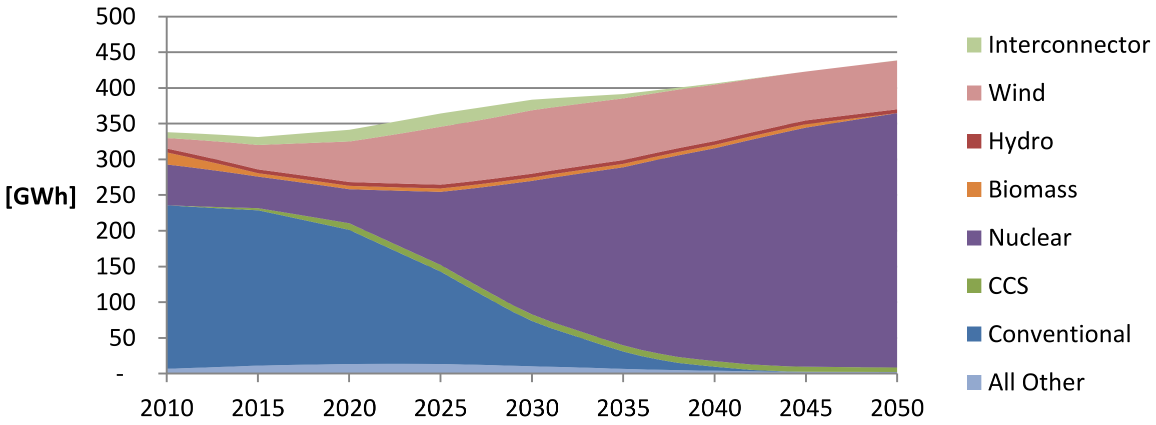

Figure 10. DECCsc2 generation output by feedstock fuel

4.1.5 DECC scenario 3

The third DECC pathway assumes successful deployment of CCS. Figure 11 shows the total installed capacity by source. For this scenario, the total capacity in 2050 comprises of a mix of interconnections, CCS, nuclear and wind. With CCS having the highest capacity.

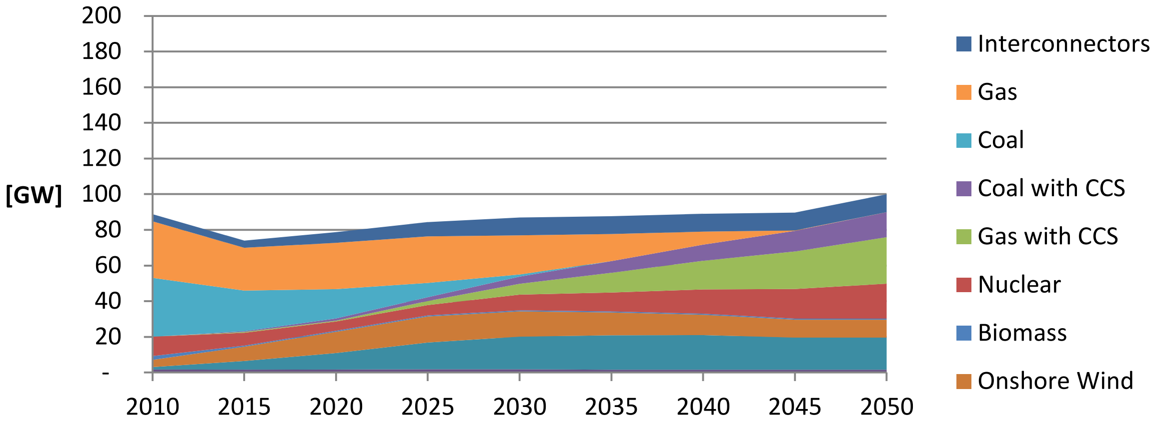

Figure 11. DECCsc3 generation capacity by technology

As the focus is on CCS technology, relating to a high merit order of the technology, CCS covers most of the generation as is shown in Figure 12. CCS covers about 50% of total electricity generation in 2050 while nuclear and wind cover around 25% each.

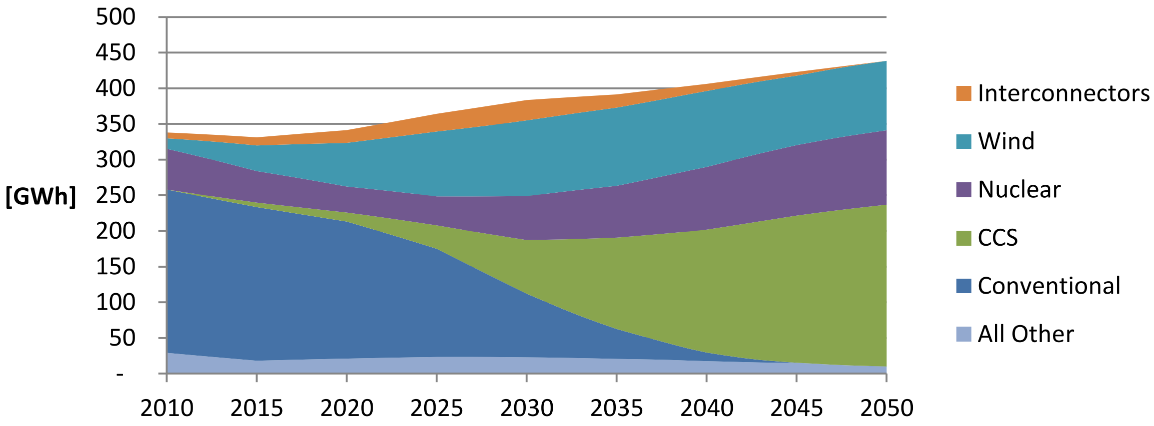

Figure 12. DECCsc3 generation output by feedstock fuel

4.1.6 Scenario I

ScI is the first new pathway developed for the purpose of the comparison. The scenario has a 16GW capacity of nuclear by 2050. The remaining installed capacity is covered by renewable generation and interconnectors with backup generation from unabated gas, which explains the large capacity of gas seen in Figure 13.

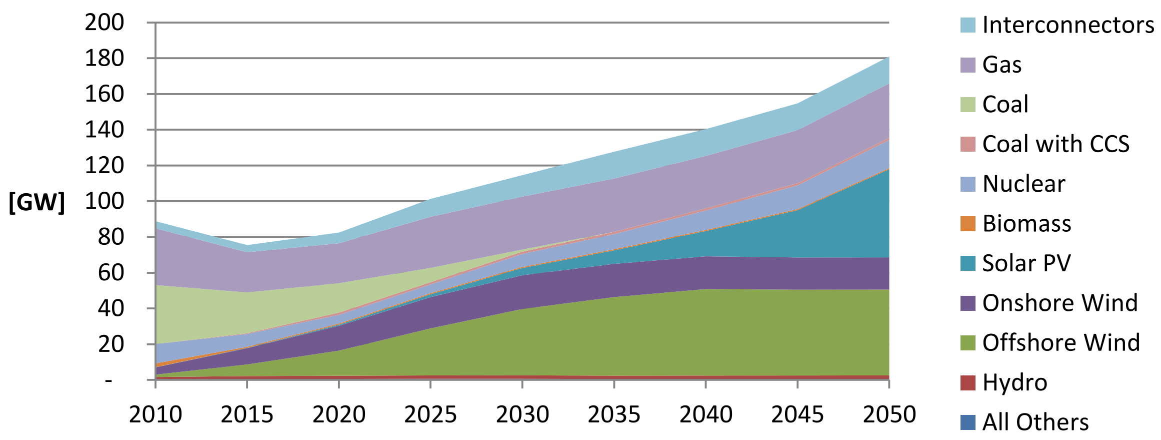

Figure 13. ScI generation capacity by technology

Figure 14 shows the total electricity generated, disaggregated by source, with supply mainly using available capacity of nuclear, renewables and significant bulk transport via the interconnectors.

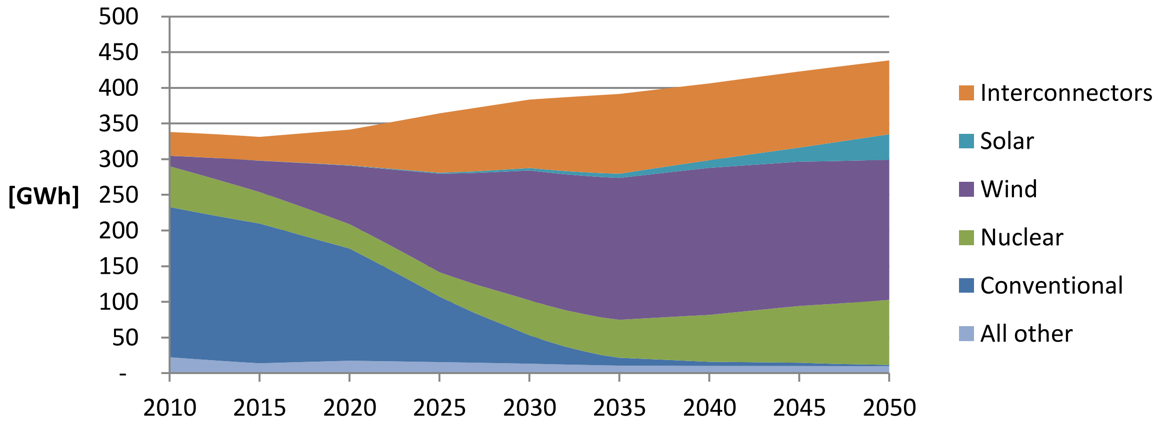

Figure 14. ScI generation output by feedstock fuel

4.1.7 Scenario II

The second new pathway has the largest capacity of interconnectors of all pathways, 35 GW in 2050. This pathway meets the remaining demand with additional renewable capacity as can be seen in Figure 15. Offshore wind covers the largest capacity, around 40GW, while solar and interconnectors are not far behind and onshore wind with slightly less than 20 GW.

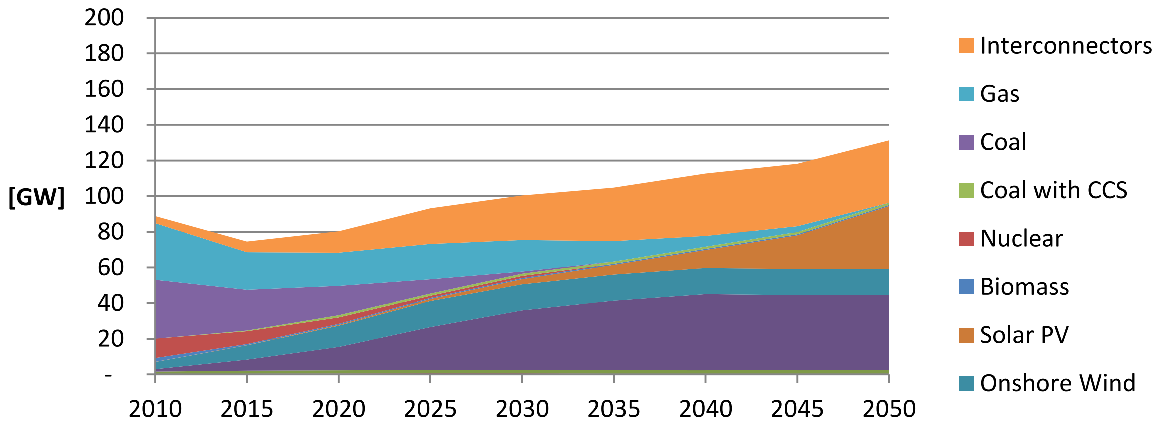

Figure 15. ScII generation capacity by technology

As solar PV has limited availability in the UK in winter, Figure 16 shows that generation mainly relies on imports via interconnectors and wind generation, with the former covering slightly more than 50% of demand.

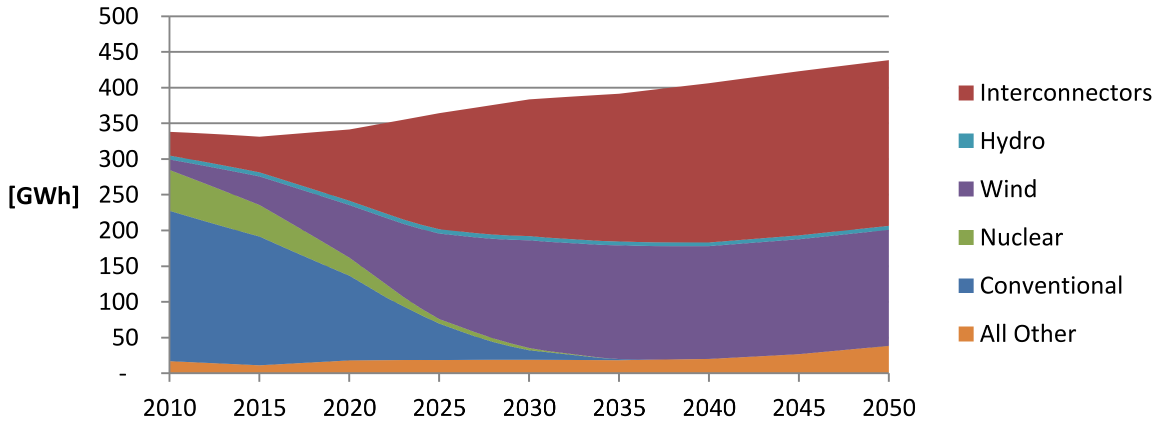

Figure 16. ScII generation output by feedstock fuel

4.1.8 Scenario III

The third and last pathway implements 15GW capacity of interconnectors by 2030, a moderate capacity of wind and with significant solar PV capacity is installed by 2050. Backup capacity is covered by CCS and gas. Figure 17 shows the capacity for the different technologies throughout the time horizon of the model.

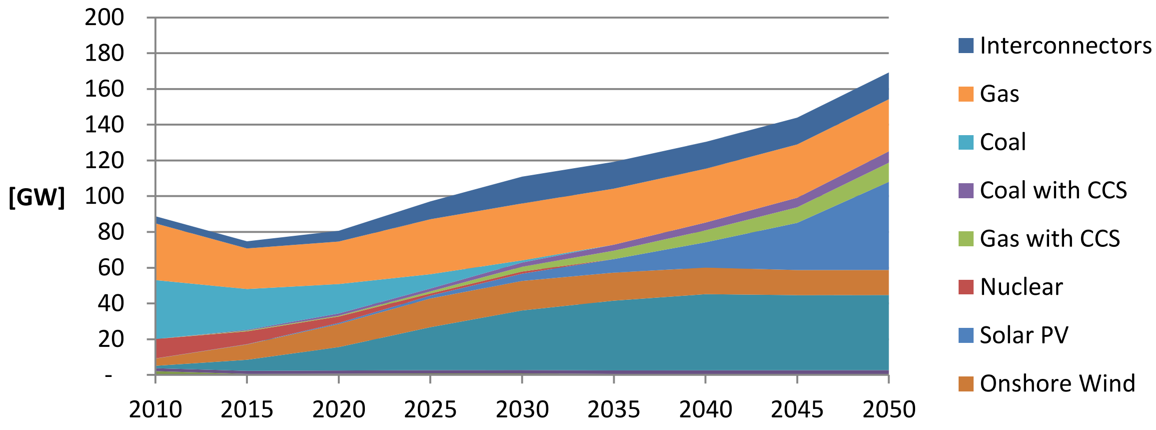

Figure 17. ScIII generation capacity by technology

Figure 18 shows that wind covers most of the electricity generation for this pathway in 2050. Interconnections also contribute significantly, and CCS and gas cover most of the remaining electricity that can't be generated by interconnectors or renewables.

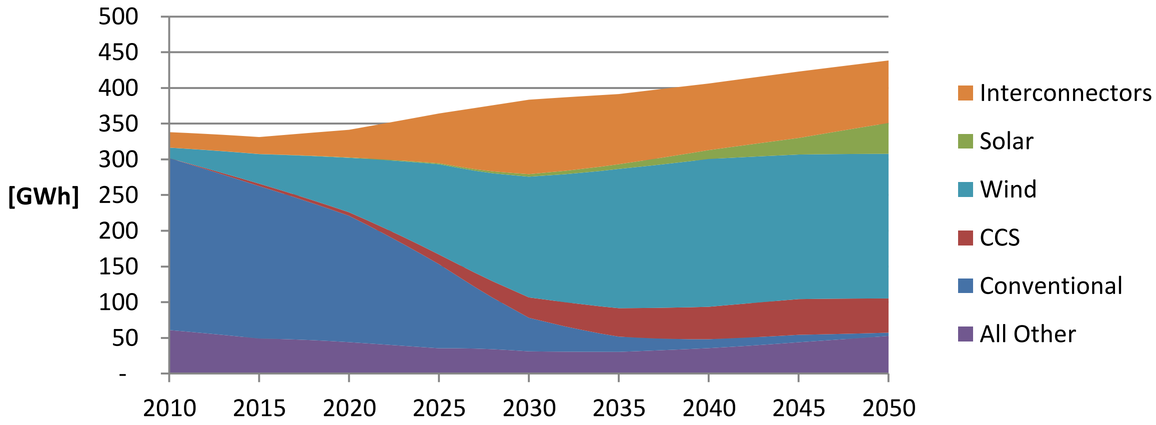

Figure 18. ScIII generation output by feedstock fuel

4.2 Emissions

After presenting the different technologies in each pathway the next step is to compare these in regard to emissions and costs.

CO_2 emissions were calculated by LEAP for each electricity system. Figure 19 shows emissions by pathway for the time horizon of the model. LEAP dispatches according to merit order and due to a different order of technologies between pathways, emissions are different for the pathways for the base year. The figure however shows that all pathways would result in CO_2 emissions reduction throughout the time period. ScII achieves reduction earliest in the period while DECCsc3 CO_2 emission reduction occurs at a slower rate throughout the time horizon.

The relatively faster decrease in CO_2 emissions achieved in ScII can be attributed to the high capacity of interconnectors installed that would lead to a high capacity of renewable and low carbon sources, replacing retiring conventional generation plants early on in time.

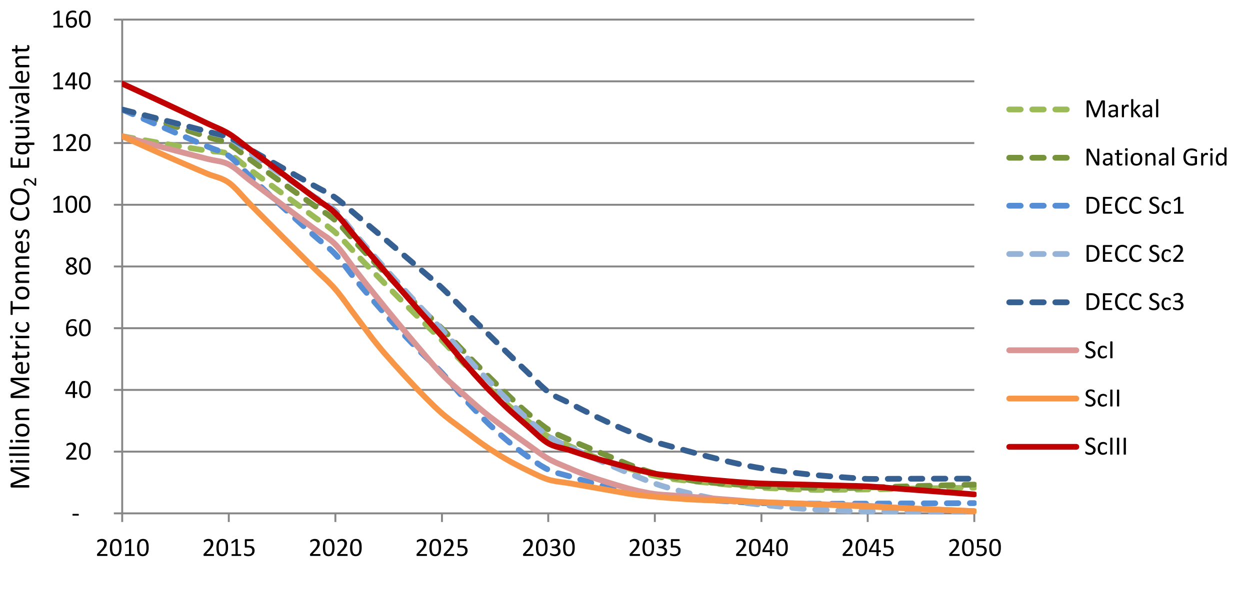

Figure 19. Emissions per year by pathway

To highlight the different rates of emission reduction between pathways, cumulative emissions reductions for each pathway are shown in Table 5. The values show that pathway ScII achieves the highest reduction by 2030, with slower rates of reduction for the remaining period up to 2050. DECCsc1 also achieves a high decrease in CO_2 emissions for the electricity sector before 2030 while DECCsc2 and DECCsc3 have slower rates of emissions reduction through the horizon.

Table 5. Cumulative reduction in emissions for each pathway.

Pathway	2030	2050
Markal	80%	93%
National Grid	79%	93%
DECC Sc1	89%	97%
DECC Sc2	81%	100%
DECC Sc3	70%	91%
ScI	86%	99%
ScII	91%	99%
ScIII	84%	96%

4.3 Cost

The costs of each pathway are also compared and these vary in accordance to installed technologies and generation. Pathways with high capacity from generation technologies that use fossil fuels have higher overall costs than those with higher share of renewable generation. Pathways with higher share of currently non-commercial technologies, such as CCS and new nuclear generators, also demonstrate higher production costs compared to pathways with smaller share of capacity from those sources.

Figure 20 and Figure 21 show the cumulative cost of electricity generation in 2030 and 2050. All pathways have fairly similar costs in 2030 while in 2050 the difference is more pronounced. Scenario II, which has the lowest cumulative cost in 2050, is the pathway that has high shares of interconnectors in combination with renewable generation. However, the highest cost pathway, DECCsc1, has a large capacity of interconnectors and gas for backup along with fairly large capacity of renewables and CCS. Detailed cost information for all pathways can be found in appendix 8.2.

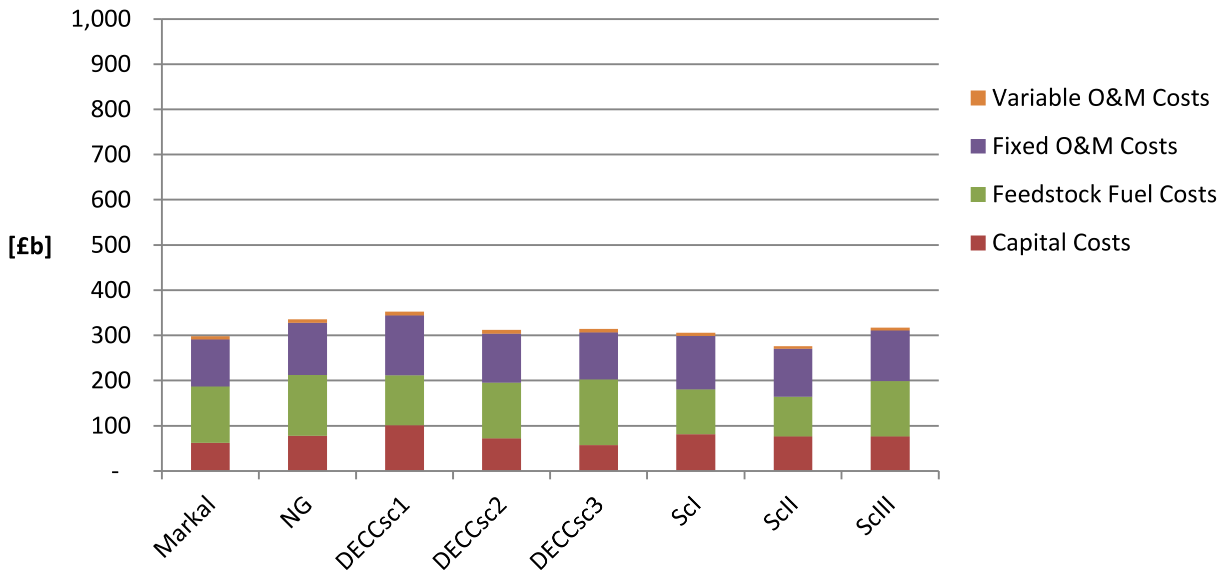

Figure 20. Cumulative cost of production by pathway in 2030

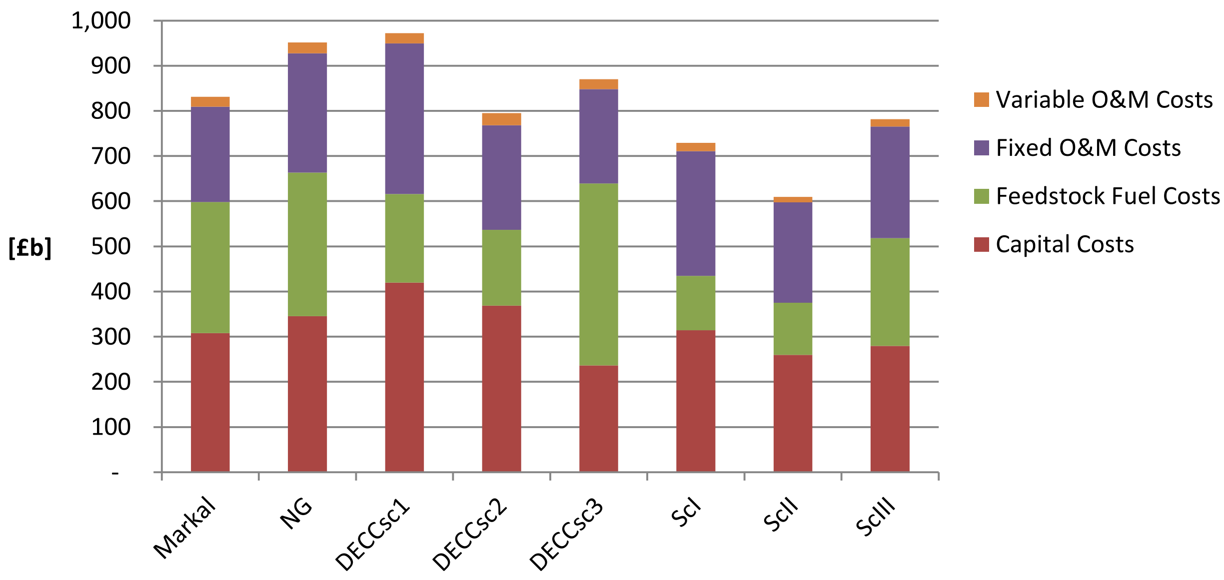

Figure 21. Cumulative cost of production by pathway in 2050

As the main purpose is to compare cost and reduction in emissions between future electricity system pathways, emissions reduction achieved per unit cost is shown in Figure 22.

Figure 22 shows that in addition to having the lowest cumulative cost of production, pathway ScII also achieves the highest reduction for per pound invested in new capacity before 2030. Towards the end of the time horizon, the reduction achieved tends to zero for all pathways with some showing a slight increase in costs per each unit of emissions' decrease while other pathways continue to reduce this ratio.

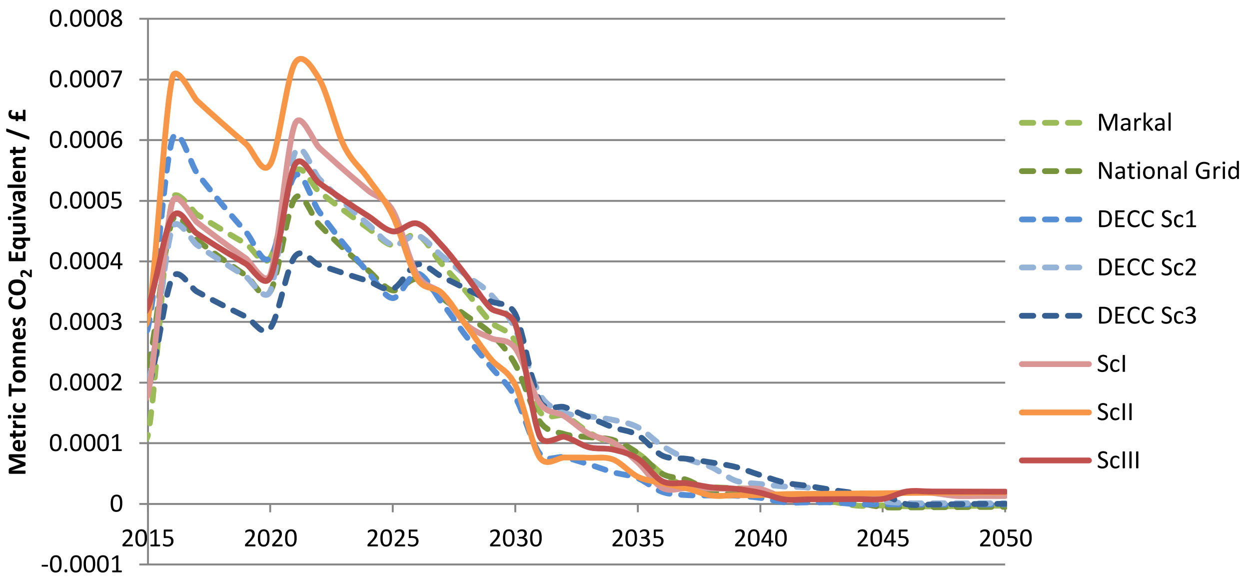

Figure 22. Reduction in Emissions Achieved for Per Pound Spent

4.4 Cost Sensitivity

All results presented so far were obtained by a dynamic dispatch using the median cost alternative for different generation technologies. A cost sensitivity analysis was carried out to investigate the impact that a) lower or higher cost of production could have on the results and b) the change in cost of interconnectors could have on the overall results.

The sensitivity analysis with high, low and median cost alternatives considered for each electricity system pathway showed that those with higher capacity of non-commercial technologies and fossil fuel sources had greater variation in cost than those based on well-established technologies and renewable sources. Figure 23 shows the deviation of three pathways, MARKAL, ScI and ScII, from their median cost scenario. The deviation in cost is shown as a percentage value of the median cost scenario. The MARKAL scenario has the highest percentage difference while ScII has the lowest percentage difference. The low sensitivity of the ScII pathway is in part explained by the relatively higher share of interconnectors in this pathway and the general assumption of constant cost of interconnectors throughout the time period. However, despite the difference in costs between pathways the different cost alternatives – low, median and high - have no impact on the relative order of overall costs of electricity production for the different system pathways. Further variations in costs between pathways can be seen in appendix 8.2.

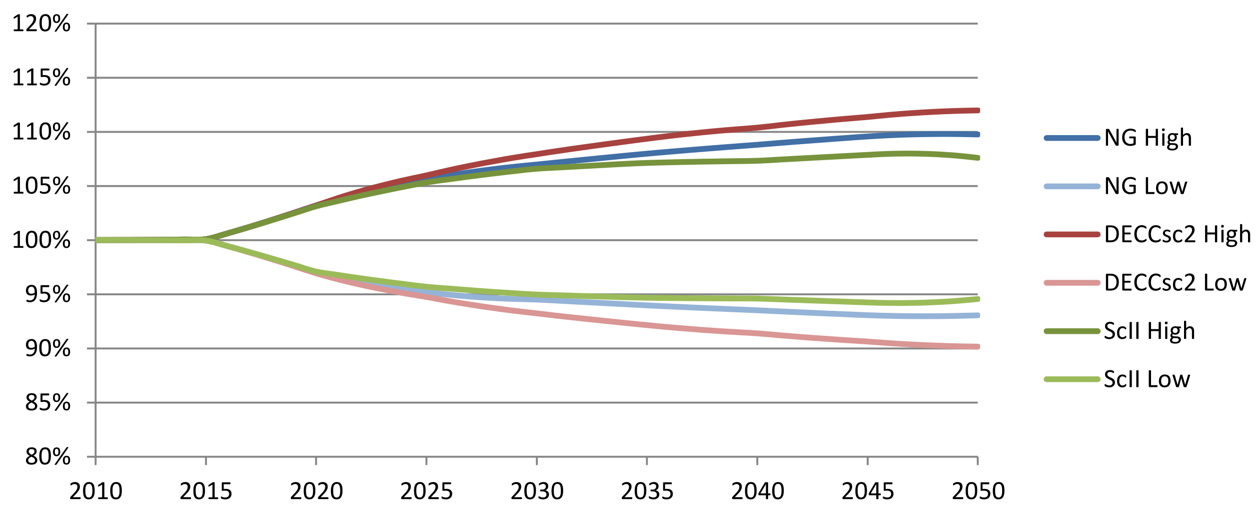

Figure 23. Deviation in Cost from Median Cost Scenario

The sensitivity of the overall electricity generation costs was also tested for different costs of interconnectors. The results show that a 20% reduction in cost of interconnectors would have a negligible impact for all pathways. The impact of an increase in cost of interconnectors was also analysed. As pathway ScII has the highest capacity of interconnectors, the highest cost of interconnectors from Table 3 was implemented for this pathway (labelled ScII_High) and compared with earlier results. Figure 24 presents the results from this analysis, which shows that a higher cost of interconnectors would not have a significant impact on earlier results.

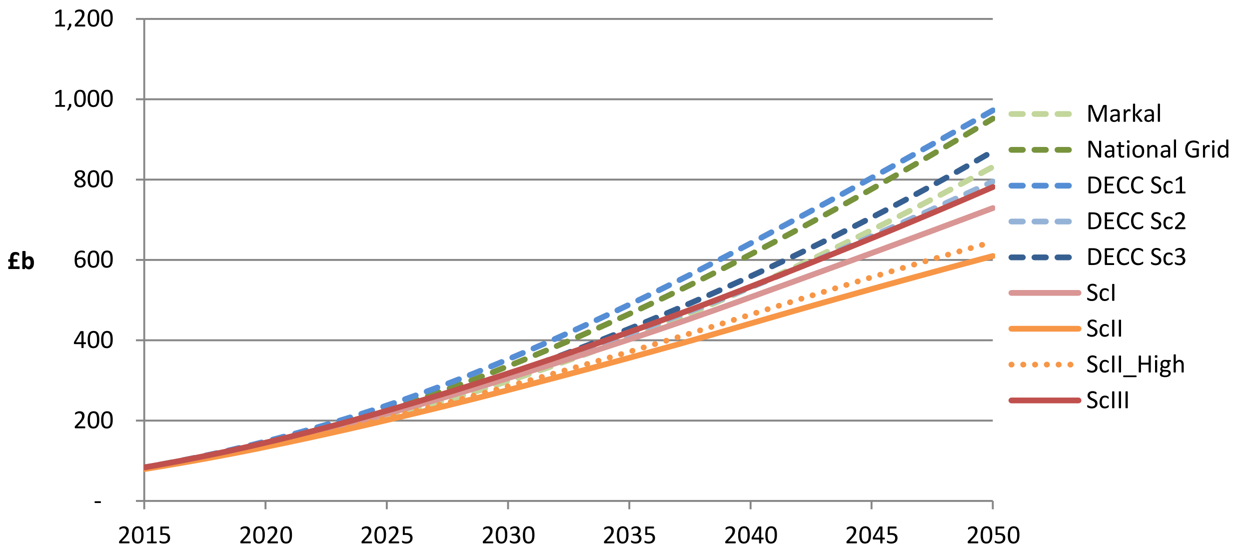

Figure 24. Cumulative Cost of Production

5 Discussion

The analysis carried out in this study shows that interconnectors are a feasible option for the UK to decarbonise the electricity sector. Results show that Scenario II, developed for the purpose of this study, with a mix of renewable generation technologies and interconnectors, achieves reduction in emissions faster than any of the other scenarios. Additionally, Scenario II maximises the reduction in CO_2 emissions per pound spent when compared to other pathways considered in this study, and can thus be considered as the most cost effective pathway. While it is not defined in the model where the capacity for interconnectors would originate from, the review in Chapter 2.7 showed that in addition to the capacity currently available there is significant potential for harnessing new resources.

The capacity additions considered by ENTSO-E in their *Ten-Year Network Plan* consists of interconnectors with a capacities between 700 MW and 1500MW, adding up to a total capacity of 15GW. Neither Spain nor Africa are considered in ENTSO-E portfolio and could thus add considerably to the total capacity. Further to the possibility for using higher capacity cables, up to 5 GW or 10GW, connecting to the hydropower resources of Iceland and Norway could be considered either for bulk transfer or balancing. Norway already has these resources available and while Iceland has a lower capacity of unharnessed resources it is currently supplying 75% (OECD, 2014) of its generation to aluminium smelters located around the country that could possibly be redirected for export in the future.

While bulk transfer is currently mainly being considered, variable two way interconnections could also serve for balancing as discussed in Chapter 2.7. If the UK electricity system were to consist mainly of intermittent renewable sources, such as wind and solar, interconnections to countries with more stable generation could allow for balancing between supply and demand when wind and solar are limited, e.g. during dark and still winter days. Wind and solar energy could thus be exported to countries such as Norway and Iceland, with higher amounts of reliable energy sources, when full generation capacity is achieved. The direction of electricity flow could then be switched to import hydropower when generation in the UK slows down. This mechanism would allow for hydropower resources to be stored while wind and solar is being utilized. Similar scenarios could be considered in the case of solar power imports from Africa which is a fairly consistent resource available throughout the year.

Current uncertainty relating to CCS and nuclear power, as discussed in Chapter 2, further supports the results obtained in this work. CCS has still not proven to be economically viable and with nuclear power projects being over budgeted and over scheduled, interconnection projects are a more viable option as the technology is known and developing fast. Interconnectors could thus allow for faster decarbonisation of the electricity sector than traditional pathways with wide scale deployment of CCS and new nuclear technologies, which aligns with reports discussed in Chapter 2.7. Additionally, interconnectors would also increase the resilience of the system since it is unlikely that electricity systems across Europe and Africa would all suffer a potential shock at the same time.

However, interconnectors are complex projects and as they connect two different countries, and islands in the case of the Great Britain and Iceland or Ireland, many stages and aspects of development have to be considered before implementation. This notwithstanding, as discussed in Chapter 1.1.4.1, EU and UK policies are being tailored to support further interconnections. Furthermore, electricity prices also influence the decisions on the feasibility of interconnections by transmission system operators. While electricity prices have not been discussed so far, the CfD mechanism introduced by the UK government and Parails (2010) argument supporting arbitrage trading in interconnections should stimulate transmission system operators.

5.1 Limitations

The analysis considers generation capacities, the potentials for interconnections and associated costs of development for the UK. However, the investments other countries would have to carry out in their electricity systems to be able to generate the additional capacity needed to meet the planned exports to the UK are outside of the scope of this analysis. Further the study assumes that the interconnectors are always available for supply and does not consider possible competitions over the capacity supplied by interconnectors.

Furthermore, while cost of several different technologies was covered in the technology review, these only give an estimate of the investment in each technology without consideration of investments different countries would have to carry out in transmission lines to connect new capacity to an existing electricity grid. Another limitation is related to the broad assumption of a single cost for the interconnectors but Table 2 demonstrates clearly that unit costs and losses change with the length of the interconnector.

As energy storage was out of the scope of this research it could be an additional limitation to the deployment of interconnectors and renewable capacity, as wind and solar capacities and deployment of backup generation would have new options when the possibility of storage is considered. Furthermore, electrification of heating and transport is not considered further then what is assumed in the MARKAL demand scenario and could thus be a limitation of the study that could be investigated further.

Further limitations are related to the lack of consideration for different political environments in countries suggested for interconnections and the possibilities for redundancies and public opposition. Redundancy could threaten the security of supply and thus contradict what has been stated about increased security. Additionally, the fact that official pathways were developed for different demand scenarios but modelled and compared using the same demand could affect the reliability of the results.

5.2 Further Work

Considering the limitations outlined above, further work should include a more detailed allocation of interconnector capacity. With more detailed allocation both distances and decision making processes and public acceptance in different countries can be considered in more detail.

With a better estimation of location and source of capacity, comparison between interconnectors and non-commercial technologies would be more accurate. Additionally, costs of generation technologies and future projections could be studied in more detail to allow for a better cost estimation. The same is valid for the cost of interconnectors and future development of this technology which should be considered in more detail to improve the accuracy of cost alternatives for interconnectors.

6 Conclusions

Official pathways proposing ways to decarbonise the UK electricity sector have a significant reliance on under deployed technologies, intermittent renewables requiring backup capacity and non-commercial technologies. Moreover, few of the considered pathways consider the possibility of low carbon electricity imports from other countries.

To see if interconnections, importing low carbon electricity, could help the UK achieve decarbonisation targets in a more cost effective way, three new pathways were developed and compared to existing pathways. All of the new pathways had a considerable capacity of interconnectors in addition to renewable and other low carbon sources. Official pathways used for comparison came from three different sources, the core UK MARKAL run, the Carbon Plan as implemented in the DECC Calculator and Rimmer's 2050 energy scenario developed for the National Grid. All pathways were modelled and estimated in the DECC calculator and then later modelled in more detail using LEAP.

Pathways were compared with regard to emissions and cost, and results showed that the scenarios involving a high capacity of interconnectors reduce emissions faster and for lower cost than those that rely on lower shares of the technology. The pathways with wide scale deployment of renewable generation technologies and interconnections resulted in the lowest cumulative cost and most reduction in emissions per pound spent on electricity generation.

Despite the limiting factors of this comparison, interconnectors could play a more significant role in decarbonising the UK electricity grid and are thus a feasible solution to lowering the UK's carbon footprint.

Increased interconnectivity between EU member states has been an aspiration of recent EU and national policies and reports have argued that increased security of supply can be achieved with increased interconnector capacity. The work shows the cost effective decarbonisation achievable with interconnectors that could be further evidence for both governments and transmission operators on the benefits of interconnectors.

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8 Appendices

8.1 High, Low and Median Cost Data

Table 6. Cost Scenarios

Technology	Tech type	Capital Cost [£/kW]			Fixed O&M [£/MW]			Variable O&M [£/MWh]		
		Low	Med	High	Low	Med	High	Low	Med	High
Hydro	NOAK		3,153.0			44,000.0				
	FOAK									
Geothermal	NOAK	2,246.0	4,540.0	6,600.0		36,000.0			11.0	
	FOAK									
Offshore Wind	R2	2,046.0	2,370.0	2,820.0		61,000.0			1.5	
	R3	2,549.0	3,000.0	3,650.0		67,000.0				
Onshore Wind	NOAK	1,221.0	1,532.0	1,910.0		15,000.0			3.0	
	FOAK									
Solar PV	NOAK	864.0	931.0	1,038.0		20,000.0				
	FOAK									
Tidal	NOAK	3,380.0	4,030.0	4,880.0		180,000.0				
	FOAK									
Wave	NOAK	3,600.0	4,400.0	5,480.0		180,000.0				
	FOAK									
Biomass	NOAK	2,016.0	2,431.0	4,538.0		96,000.0			4.4	
	FOAK									
Nuclear	NOAK	3,491.7	3,856.7	4,350.5	50,000.0	60,000.0	70,000.0	2.5	2.5	2.5
	FOAK	3,853.2	4,416.3	5,028.3	60,000.0	72,000.0	84,000.0	2.6	2.6	2.6
Gas CCS	NOAK	1,044.5	1,214.5	1,471.9	19,417.0	23,087.0	26,775.0	1.2	1.5	1.9
	FOAK	1,163.5	1,351.5	1,631.0	21,762.0	25,045.0	29,046.0	1.4	1.7	2.1
Coal CCS	NOAK	2,692.2	2,796.2	3,359.7	40,204.0	66,623.0	93,043.0	2.0	2.2	2.4
	FOAK	2,694.2	2,975.2	3,391.7	13,230.0	71,638.0	100,046.0	2.2	2.4	2.5
Gas	NOAK	496.4	581.4	664.0	18,026.0	21,954.0	25,882.0	0.0	0.1	0.2
	FOAK									
Coal	NOAK	2,862.7	2,862.7	2,862.7	33,280.0	33,280.0	33,280.0	4.5	4.5	4.5
	FOAK									

8.2 Cumulative Cost of Pathways

Table 7. Cumulative Cost of Pathways in 2030, median cost scenario [£m]

	Markal	NG	DECCsc1	DECCsc2	DECCsc3	ScI	ScII	ScIII
Capital Costs	62.0	78.2	101.0	72.2	57.6	81.6	76.1	76.3
Feedstock Fuel Costs	124.9	134.4	110.9	123.3	144.6	98.8	87.8	122.6
Fixed O&M Costs	104.1	114.9	132.4	108.2	104.5	118.3	106.3	112.0
Variable O&M Costs	7.3	7.9	8.1	8.3	7.6	7.0	5.5	6.3
Total	298.2	335.3	352.4	312.0	314.2	305.6	275.8	317.2

Table 8. Cumulative Cost of Pathways in 2050, median cost scenario [£m]

	Markal	NG	DECCsc1	DECCsc2	DECCsc3	ScI	ScII	ScIII
Capital Costs	308.0	345.6	419.9	368.9	236.3	314.0	260.0	279.9
Feedstock Fuel Costs	290.2	317.6	196.1	167.5	403.3	120.8	115.0	238.6
Fixed O&M Costs	211.2	264.6	333.1	231.9	208.2	276.2	222.5	246.5
Variable O&M Costs	22.1	23.8	23.0	26.8	22.4	18.0	11.9	16.3
Total	831.5	951.6	972.2	795.1	870.2	728.9	609.5	781.3

8.3 Cost Scenarios

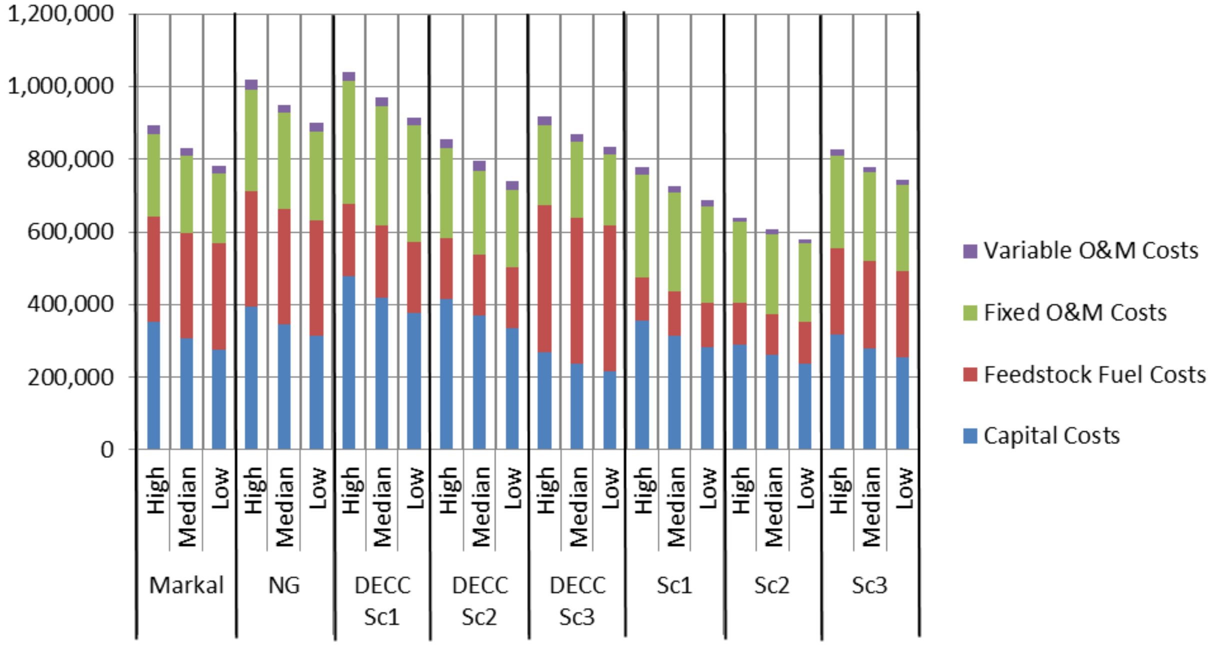

Figure 25. Cost Sensitivity Analysis on Production Cost