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PhD Civil Engineering

A Risk Based Approach for Trading Renewable Electricity

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Abstract

Growing energy demand and climate change due to increasing CO_2 emissions are two major global issues. The development of Supergrids, which involves connecting national energy supply grids together via interconnections, has been proposed as a measure to overcome these challenges. Supergrids arguably aid the implementation of other measures such as managing demand and development of renewable sources of energy, whilst it has its own benefits, perhaps, the most important one being its economic efficiency in comparison with generating electricity.

A key challenge for developing Supergrids is finding the most suitable countries with which to make an interconnection. This doctoral research aims to develop a risk-based theoretical framework for selecting the most appropriate country (ies) with which to make grid interconnections and trade renewable electricity. Quantitative risk analysis technique is used to compare candidate countries by taking into the account the various risks associated with the construction and maintenance of interconnections. The risks include: social, technical, economic, environment and political aspects.

The framework is demonstrated using the UK as a case study.

Dedication

To my wife
Sahar
For your support, patience and heart-warming words

To my family
I thank you for your constant support, reassurance and love over the years. Without you, the journey would not have been enjoyable, nor as fulfilling as it has been.

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Abbreviations

AC	Alternating Current
AHP	Analytical Hierarchy Process
AIS	Automatic Identification System
BBC	British Broadcasting Corporation
BritNed	Britain-Nederland
CCC	Committee on Climate Change
CCGT	Combined Cycle gas turbine
CCS	Carbon capture and storage
CHP	Combined heat and power
CSP	Concentrated solar power
DECC	Department of Energy and Climate Change
DP	Dynamic Positioning
FIT	Feed-in-Tariff
FST	Fuzzy Sets Theory
GDP	Gross Domestic Product
GHG	Greenhouse Gas
Gt	Gigatonne
GW	Gigawatts
HAZOP	Hazard and Operability study
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IRG	Infrastructure Risk Group
IMO	International Maritime Organization
LCC	Life Cycle Costs
MCS	Monte Carlo Simulation
MESH	Mapping European Seabed Habitats
MtCE	Million tonnes coal equivalent
NG	National Grid
NIMBY	Not in my backyard
NordBalt	Nordic - Baltic
NorGer	Norway - Germany
NorNed	Norway–Netherlands

NPV	Net Present Value
PERT	Program Evaluation and Review Technique
PI	Profitability Index
P–I	Probability–Impact
PV	Photovoltaic
P80, P50	80th (50^{th}) Percentile Cost
r	Discount Rate
RE	Renewable Electricity
RTE	Réseau de Transport d’Electricité
SAPEI	Sardinia - mainland Italy
SWIFT	Structured “what-if” Technique
VSC	Voltage Source Converters
WLA	Whole Life Appraisal
WLRCA	Whole Life Risk Cost Appraisal
WLC	Whole Life Costing
WNA	World Nuclear Association

1 INTRODUCTION

1.1 Background

Two major interlinked global issues face developed and developing nations both now and in the future; growing energy demands and rapid climatic changes. Most of what we do today within a well-functioning modern society (and its supporting economy) is impacted in one way or another by our thirst for energy. Unfortunately when sourced from fossil fuels it is to the detriment of the environment in which we live. Anthropogenic concentrations of CO_2 in the atmosphere have been increasing over the past century (the June 2014 concentration, 401 ppm, was about 43% higher than in the mid-1800s (OECD/IEA, 2012; Tans and Keeling, 2014)) and there is consensus amongst scientists that this is linked directly to our warming climates (Weitzman, 2015). The current level of CO_2 emissions can have a prolonged impact on the environment. For example, a study by MacDougall et al. (2013) suggests that even if anthropogenic CO_2 emissions were to cease immediately, CO_2 concentrations would continue to build in the atmosphere. Therefore cutting emissions by 60 to 80% needs to come much sooner than 2050, as enshrined in current UK policy.

This is even more pertinent when we consider continually growing global energy demands and the associated combustion of fossil fuels. These are a major source of CO_2 in the atmosphere currently and this demand for energy is projected to increase by one-third between 2010 and 2035 (OECD/IEA, 2011). This is due in no small part to the global rates of population growth allied with substantial economic development in new emerging markets (Yusaf *et al.*, 2013), e.g. China and India. The world population growth rate was approximately 1.8 per cent annually from 1980 to 2010 (The World Bank Group, 2014), whilst world total primary energy consumption increased by 2.59 per cent in the same time (EIA, 2013). For instance total energy consumption (coal, oil, gas, hydro-electricity) in China increased from 54 million tonnes coal equivalent (MtCE) in 1953 to 3,034 MtCE by 2014, making China the world's largest consumer (Crompton and Wu, 2005; Enerdata, 2015). In the UK, as another example, electricity demand is projected to increase by up to 40 per cent by 2030 (CCC, 2011). Undoubtedly around the globe electric power production industries are major producers of the world's greenhouse gas emissions (Moselle *et al.*, 2012).

In response to these challenges a requirement to replace fossil fuel power plants with 'low carbon' and renewable resources appears now to form a necessary linking thread through global energy policy. For example, the European Commission (2007a) agreed a set of binding legislation which aims to reduce by 20% (from 1990 levels) greenhouse gas emissions by 2020. This requires that the share of European Union (EU) renewable resources increases to 20%.

In the UK, government's policy drawn on two main approaches to tackle climate change and reduce the green greenhouse gas emissions (DECC, 2014b);

1. Reducing the demand for energy and to use energy more efficiently
2. Replacing fossil fuels and the associated power plant capacity and investing in low-carbon technologies

As part of this policy, the UK government in the next 10 years, intends to close more than 18 GW of non-renewable generating capacity, around 20% of current capacity, including 9 GW of the UK coal capacity (DECC, 2010; National Grid, 2011a). Decarbonising brings new challenges to the power systems as there are uncertainties related to developing the superseding technologies, for example the cost uncertainties and the security of supply (CCC, 2011). Furthermore, currently adopted power systems cannot rely on many renewables for the base energy load to meet the demand due in part to their intermittency.

An alternative is to change cultural consumption behaviour as part of a wider approach known as managing demand (Barbato *et al.*, 2011; Kohlbrecher *et al.*, 2011). There are a number of technologies which can be used to encourage behavioural change. For example Smart Meters and Smart Grids are two such technologies. The utilisation of Smart Meters involves introducing higher prices for peak times and to announce customers when peak time is reaching. This measure tries to minimise the unnecessary electricity consumption during peak hours which is more expensive to generate. In the UK most households will have smart meters installed between 2014 and 2019, although some energy companies had started to install smart meters before (DECC, 2013b). Smart Grids are a set of technologies that raise the intelligence of the electrical networks, including smart meters and communication devices, sensing and auto-correction of networks (Marques *et al.*, 2014b). Smart Grids advantages the interaction and responsiveness of the customers, and, in the long term, lowers peak demand, reduces overall plant and capital cost investments and potentially shelves the need for network upgrades (Siano, 2014).

Smart Grids provide useful real-time data to users including the economic cost (perhaps even value) of energy, whilst users can send data to the grid such as the energy consumption of each home appliance (Barbato *et al.*, 2011). These data can be used by the supplier for demand load management and to support residential users in shaping their energy demand profile.

Estimates of the energy savings from Smart Grids vary widely, from 0% to as much as 20% (Ehrhardt-Martinez *et al.*, 2010; Faruqui *et al.*, 2010) whilst two field studies (Ehrhardt-Martinez *et al.*, 2010; Houde *et al.*, 2013) show real-time feedback technology can produce reductions in electricity consumption of 5.7% and 12% respectively.

However, changing energy consumption behaviour is a long (and time consuming) procedure not least because it is challenging to prove to people the consequences (e.g. on the planet and on future generations) of their individual consumption behaviour. For instance, a British Broadcasting Corporation (BBC) poll (2004) showed that only just over half of the British population believed that changing their own behaviour would have an impact on climate change. This shows that such a demand based approach may not succeed alone and therefore needs to be used in combination with other approaches, such as supply supplementation through renewable electricity (RE) interconnections (Section 1.2).

1.2 Interconnections

Studies suggest that, based on theory, there are enough renewable resources (e.g. solar and wind) available around the world to meet the global energy demand and to dramatically decline our reliance on fossil fuels and other carbon emitting sources (Jacobson and Delucchi, 2011; WWF, 2011). However, what is missed and what is required in order to turn this theory into reality is the grids interconnection (i.e. with other countries). The Global Grid concept introduced by Chatzivasileiadis et al. (2013) shows that a globally interconnected network is technologically feasible and could be economically competitive when used to harvest remote renewable sources utilising high capacity long transmission lines.

A number of countries worldwide are adopting, or proposing, policies to encourage the development of such cross-border connections for the supply of energy. For example, in Europe the *"Supergrid"*, has been conceived and developed, to assimilate interconnected European renewable energy sources into a pan European grid and beyond. Although a precise definition for the term *"Supergrid"* does not exist, the concept was first introduced by Jacobsen and Delucchi (2009) and later adopted by Hirschhausen (2012) and will be used throughout this thesis.

A Supergrid consists of interconnected national alternating current (AC) grid networks. It integrates high-voltage direct (HVDC) cables/networks, as well as short cross AC border links, into existing low and high voltage AC networks.

Based on this definition Hirschhausen (2012) characterises Supergrids in terms of:

- Flexibility in system balancing;
- High capacity for power transmission;
- Geographically long distances.

Amongst their advantages, Supergrids enable the issue of the barrier of intermittency of renewables to be addressed. This is because the intermittency associated with multiple geographically dispersed sources is significantly reduced as when compared to that of an individual sites primarily due to different availability and demand patterns for using a variety of supply resources (Van Hertem and Ghandhari, 2010; Great Britain Parliament, 2011a; Chatzivasileiadis *et al.*, 2013; Elliott, 2013). Indeed, Hirschhausen (2012) and also Van Hertem and Ghandhari (2010) state that the development of Supergrids is an essential precursor for harnessing renewables effectively.

Another distinct advantage of such a system is that it improves the security of energy supply by providing parallel-multiple supply paths connecting countries across different time zones, with different electricity generating profiles, consumption demands and patterns (Van Hertem and Ghandhari, 2010; Hirschhausen, 2012). This offers a distinct array of benefits whereby the Supergrid can reduce the overall cost for generating electricity within the whole system thereby decreasing the requirement for other sources of spare energy capacity, which tend to be carbon emitting fossil fuels.

As for its implication, in December 2010 a ‘Memorandum of Understanding’ was signed by ten European states including the UK, making possible the transfer of renewable energy from northern marine and southern solar resources to European centres of population (Great Britain Parliament, 2011b). In 2011 the UK Energy and Climate Change Committee subsequently launched an inquiry to investigate the potential for building a European Supergrid (Great Britain Parliament, 2011b). In the first quarter of 2014 the UK generated 19.4 % of its electricity from renewable, with 2.7GW increase in installed capacities throughout 2013 (DECC, 2014a). In the same period the UK was a net importer of electricity from interconnections with France (3.6 TWh) and Netherlands (2.0 TWh) (DECC, 2014a).

1.2.1 Challenges in connecting countries

The concept of the European Supergrid is seen as part of the process of creating a single carbon reduced market for electricity across European Union member countries (European Commission, 2007b). In February 2011, the European Council agreed upon an ambitious objective to complete the single energy market by 2014, however, due to slow progress by member countries, this has been significantly delayed (European Union, 2014). One of the barriers to progress is the need for cross-border investment in energy infrastructure including the physical interconnections (Brancucci Martínez-Anido *et al.*, 2013; European Commission, 2014). It seems that the barriers for implementation of Supergrids and development of interconnections are primarily social and political, not technological or economic (Jacobson and Delucchi, 2011). The associated decision-making process is often a protracted procedure, for example on-going negotiations about developing interconnections have been continuing for over 10 years between France and Spain, and the UK and Norway. Part of the reason for such lengthy negotiations is because of the uncertainties involved. These include, but are not limited to: changes in energy policy of the countries concerned; the availability of spare electricity; security of supply issues; the comparatively lengthy construction period and the life-time of the physical interconnections (Eskandari Torbaghan *et al.*, 2015). Allied to those, an interconnection project is notoriously risky because two countries (at least), each with their own policies, are involved.

Governments, policy makers and private investors seek to adopt a cost effective, secure and 'low-risk' approach when considering developing interconnections. Ultimately this requires decisions to be made concerning the best countries to 'interconnect' with and share energy. For instance, in the UK finding potential countries for making the interconnection with the UK was part of the Parliament enquiry mentioned above. When so doing it is necessary to consider a number of social, technical, economic, environmental and political factors and the risks associated with each.

Such uncertainties could be addressed via a suitable risk assessment process that enabled identifying, better understanding and mitigating the potential impacts of risks (Flyvbjerg *et al.*, 2003; IRG, 2013). Utilising an appropriate risk assessment in this context would create a common language between all engaging countries that would help resolve disputes and shape a set of common priorities, thereby facilitating the overall decision-making process (Linkov and Ramadan, 2006). Early stage risk-assessment can significantly reduce the cost of projects by restricting unnecessary spend, especially of the contingencies allocated for cost uncertainty (IRG, 2013).

Risk and uncertainties have been addressed in energy related studies for many decades. For instance more than 40 years ago Salter (1973) described a probabilistic forecasting methodology where stochastic data and subjective probability estimates were used to achieve a probabilistically stated forecast at a future time frame (the year 2000) for electricity consumption of the U.S. With respect to interconnections however the risks and uncertainties of interconnections within the literature are less well developed. Whilst economists such as Parail (2010b) have introduced a probabilistic methodology to add economic uncertainty to the electricity trading via interconnections, this never extended to uncertainties associated social, technical, environmental and political aspect of developing and operating interconnections a shortfall which this thesis aims to fill. A number of studies have discussed the challenges of developing new interconnections between different regions and countries in relation to one of the aforementioned risk categories. However their primary focus is on one area of uncertainty. For example, economic considerations are dealt with by DKM (2003), Black &Veatch (2009) and Denny et al. (2010). Whereas technical aspects are discussed by Berdal Stromme (1998), Trieb (2006) and Georgiou et al. (2011). However, few studies appear to consider all of the aforementioned risk categories at the same time and no single study has been found to conduct a risk analysis on these interconnections at a pan-European scale.

This doctoral research project addresses this significant shortfall by proposing **a risk-based approach for selecting the most appropriate country (ies) with which to make grid interconnections and trade renewable electricity (RE).** A quantitative risk analysis technique is developed to compare candidate countries by taking into account the social, technical, economic, environment and political risks associated with the construction and maintenance of interconnections. The risk based methodology is demonstrated using the UK as a case study.

1.3 Aim and objectives

The aim of the research is to develop a theoretical risk based framework which can be used to select the most appropriate country (ies) with which to make electricity interconnections and trade renewable electricity. To achieve this, the research has the following key objectives:

1 Develop a framework which can be used to identify candidate countries for consideration

2 Investigate the surety of risk based technique for the project framework

3 Develop an economic model to explore the viability of the candidate countries

4 Verify the developed framework using the UK as a case study considering the risks impact on the economic viability of the screened candidate countries
    4.1 Project interconnection capacities between the UK and the candidate countries using the developed tool
    4.2 Develop the Whole Life Risk Cost Appraisal model for the UK and the candidate countries
    4.3 Conduct questionnaire and interviews utilising experts judgments on risks identification and risk semi-quantification
    4.4 Quantify the identified risks by simulating their impacts and probability of occurrence on the developed Whole Life Risk Cost Appraisal model
    4.5 Propose the most appropriate country or countries for making interconnection with the UK.

1.4 The Structure of the Thesis

To achieve the objectives listed above; this thesis is structured as follows:

1. The literature review in Chapter Two discussed the limitations of renewable energy technologies and the threats and opportunities associated with trading RE. The chapter also presents an overview of the Whole Life Appraisal (WLA) models and risk assessment techniques which could be employed to develop an overall risk assessment framework for assessing the potential countries.
2. A description of the research methodology is provided in Chapter Three which describes the method followed in this research to develop the theoretical framework and a case study to demonstrate the viability of the framework.
3. Chapter Four describes the stages taken in the case study for selecting candidate countries through an initial screening process, followed by a description of the process and data used to generate energy supply/demand scenarios.
4. The process utilised for identifying risks related to construction and operation of considered interconnections in the case study is described in Chapter Five.
5. The risk semi-quantification and quantification stages are presented in Chapter Six which includes the results of the case study.
6. A discussion of various aspects of the framework is given in Chapter Seven, whilst the conclusions and recommendations for further work are given in Chapter Eight.

The findings of this research have been published in two journal papers (International Journal of Energy Research and Proceedings of the ICE - Engineering Sustainability), one journal paper has been prepared to be submitted to Applied Energy Journal. The findings have also been presented and published within conference proceedings (i.e. The 3rd World Sustainability Forum, Basel, Switzerland), these can be found in Appendix A.

2 LITERATURE REVIEW

This chapter provides a critical review of the literature base related to the following areas: renewable energy technologies; trading RE; whole life appraisal method(s); and risk assessment techniques. Renewable energy technologies and trading RE are reviewed in order to justify the need for trading electricity via interconnections by showing the limitations of various renewable technologies. An introduction to whole life appraisal methods and risk assessments techniques, both of which were adopted within this study, is presented in this chapter. This includes a background to the techniques / methods, including a brief look at their development history and associated principles used therein.

2.1 Renewable energy technologies

In order to provide an initial stage of comparison between the various interconnections and renewable technologies for supplying electricity, the limitations of developing those technologies are described in this sub-section. The limitations are discussed under key drivers of change, commonly referred to under the STEEP acronym (i.e. Social, Technical, Economic, Environmental and Political categories), which allow adaptation of a similar qualitative approach for comparing various technologies. The technologies considered herein are; Marine - wave and tidal stream (2.1.1); Offshore wind (2.1.2); Onshore wind (2.1.3); Hydro (2.1.4); Pump storage (2.1.5); Biomass (2.1.6); CCS (2.1.7); and Nuclear energy (2.1.8).

2.1.1 Marine (wave and tidal stream)

Two physical properties that influence and constrain marine-based energy sources are energy density and occurrence which makes them an interesting source of energy when compared to similarly constrained sources such as wind and solar power (Langhamer *et al.*, 2010; Fadaeenejad *et al.*, 2014). Wave power along the European west coast, for instance, has the potential to meet all of the Western European electricity demand (Brooke, 2003). It is, however, a new technology at the demonstration phase (Kiranben and Suvin, 2011; MacGillivray *et al.*, 2014), and whilst progress in this area is being made it remains more expensive than alternative sources. The limitations according to the STEEP acronym are discussed below.

2.1.1.1 Social

The Energy Climate Change Committee (2012) raised concerns about the public acceptability of marine development for the UK. However, contra to this belief a study by Devine-Wright (2011) shows a predominantly positive and supportive public response to a tidal energy converter in Northern Ireland, and this is supported by the Sustainable Development Commission (2007) who found similar findings. However, a more recent study by Reilly et al (2015) suggests that it really depends on who you ask. For example, when fishermen on the island of Ireland were asked about their views towards the development of marine renewable energy projects 45% disagreed with development whilst only 40% agreed and 15% were neutral. This shows the importance of a sufficiently broad stakeholder group covering all sector of society.

2.1.1.2 Economic

Within the UK it is suggested that significant levels of investment are required for marine technologies in order to make them commercially viable (Great Britain Parliament, 2012). Additionally there is uncertainty regarding further investment capital in this area during the 2020s as less mature renewable technologies in this area unlike other alternative technology options accrue higher construction costs (O Rourke *et al.*, 2010; CCC, 2011; MacGillivray *et al.*, 2014).

In addition there are concerns that wave and tidal power establishments, independent of technique, will disturb most commercial fishing (Langhamer *et al.*, 2010; Reilly *et al.*, 2015). For instance, by installing 1000 linear wave energy converters 1 km^2 of fishing ground will be inevitably lost (Langhamer *et al.*, 2010). This not only has economic but also environmental consequences. In addition to social consequences already outlined.

2.1.1.3 Environmental

1. Physical Presence of Devices

The physical presence of new structures in marine ecosystems has fundamental impact on the habitat that lives within (Boehlert and Gill, 2010; Langhamer *et al.*, 2010; Lam and Bhushan Roy, 2014). Immovable and impassable wave devices, some of them take up significant areas as evidenced by examples such as Pelamis (Pelamis Wave Power, 2012) and Sea Dragon (Kiranben and Suvin, 2011), have the potential to interrupt the migration of surface inhabitants and therefore must be designed appropriately to minimise these effects (Boehlert and Gill, 2010; Langhamer *et al.*, 2010; Great Britain Parliament, 2012; Lam and Bhushan Roy, 2014). When considering sea life below water, devices such as rotors, cabling systems, anchors, provide new hard surfaces which may attract sea life and alter bottom feeding communities (Boehlert and Gill, 2010; Garel *et al.*, 2014). For instance, wave energy oscillating devices cause featureless sandy sedimentary habitats (Boehlert and Gill, 2010). Furthermore, pressure drop, contact with blades and cavitation can result in a 15 per cent rise in fish mortality per pass, despite the fact that most of the turbines are designed to be fish friendly (Kiranben and Suvin, 2011).

2. Dynamic Effects of Devices

There is the distinct possibility of wave energy technologies having impact on currents inadvertently resulting in energy reduction and alterations in sediment transport (Boehlert and Gill, 2010; Kiranben and Suvin, 2011; Garel *et al.*, 2014).

3. Chemical Effects

There is a substantially increased risk of chemical spills occurring especially for those devices that use a hydraulic fluid which can affect the water quality and may disturb seabed habitat and communities (Boehlert and Gill, 2010; Garel *et al.*, 2014).

4. Acoustic Effects

Construction and operation of marine renewable energy devices can disturb the acoustically diverse environment which is vitally important in animal communication, reproduction and orientation (Boehlert and Gill, 2010; Langhamer *et al.*, 2010; Kiranben and Suvin, 2011; Garel *et al.*, 2014).

5. Electromagnetic Effects

The network of cables used for transmitting electricity cause electromagnetic waves which are most likely to affect animals such as migratory fish, turtles and marine mammals that use magnetic fields, electric fields, independently or in combination for spatial location, orientation, or mate finding (Boehlert and Gill, 2010; Langhamer *et al.*, 2010; Garel *et al.*, 2014).

6. Climate Change

Table 1 presents the identified impact of climate change on Marine energy in northern Europe.

Table 1: Summary of climate change impacts on Marine energy and corresponding literature

Variables	Related impacts	Studies
Wind patterns (i.e. mean wind speed)	Altering wave regimes (i.e. mean wave height) Mean wave power density Plant capacity factor Energy cost	(Bacon and Carter, 1991; Harrison and Wallace, 2005; Wolf and Woolf, 2006; Lima *et al.*, 2014)
Atmospheric pressure	Increases mean wave height	(Bacon and Carter, 1993; Wang *et al.*, 2015)
Strong Storm	Increases of wave heights	(Wang *et al.*, 2004; Haigh *et al.*, 2014)
Sea level rise	Tidal energy resource changes Siting of associated on-shore infrastructure	(McCall *et al.*, 2007; Low carbon Research Institute, 2011; Hinkel *et al.*, 2014)

2.1.1.4 Technical

Intermittency is a technological barrier however it is possible to reduce its effect if wave power is considered in wind-dominated mix system, for example.

A well-developed grid is required in order to maximise the contribution of this technology, not least because the best wave and tidal resources are typically located in some of the most remote parts of the world (RenewableUK, 2011; Chatzivasileiadis *et al.*, 2013). Therefore not providing adequate infrastructure is a potential limitation which can be exacerbated by financial crises or insufficient backing from government.

2.1.1.5 Political

Løvdal and Neumann (2011) claim, via a global survey of companies in the marine energy industry, that internationalisation can be utilised as a strategy to overcome many of the marine energy industry barriers. However, lack of investment by local governments and an underdeveloped marine supply chain appear to be key criteria preventing the marine energy industry from fully realising its potential. This is particularly true for developed countries such as the UK, despite it being in one of the best locations worldwide for wave and tidal power generation in terms of both geography and expertise (Elliott, 2010). Supporting policies can have significant impact on the development of marine energy industry, however this requires supporting politics, and is not the case currently in Europe despite Europe being a leader in many other renewable technologies (Dalton and Ó Gallachóir, 2010).

Similarly, more recent publications such as Simas *et al.* (2015) also state that political barriers are a major factor limiting the progress of the marine renewable energy industry, and include: non-supportive policies in Europe, the complexity of consenting processes and the lack of dedicated legal frameworks.

2.1.2 Offshore wind

Despite having rapid recent growth in some countries such as the UK, with around 5GW of offshore wind in operation or under construction in January 2015 compared with 1,198 MW installed capacity in 2010 (Bilgili *et al.*, 2011; CCC, 2011; Offshore Wind Programme Board, 2015), this technology is in the primary phases of deployment and therefore more expensive than alternatives such as nuclear and onshore technologies (CCC, 2011; Offshore Wind Programme Board, 2015). The limitations are discussed below according to the STEEP acronym.

2.1.2.1 Social

Public acceptability regarding the development of the technology seems to be a major issue around the world. For instance Haggett (2011) and Kern *et al.*(2014) studies for the UK show that public does not automatically prefer offshore sites to onshore, and that moving offshore does not necessarily solve the challenges of accepting wind turbines by stakeholders. In one case in the US the following issues are mentioned by the oppositions: damage to marine life or environmental impacts, electricity rates, aesthetic, and impacts on fishing or boating (Firestone and Kempton, 2007). These issues resonate for the EU and other key regions around the world.

2.1.2.2 Economic

According to the CCC (2011) and Offshore Wind Programme Board (2015) reports for the UK, known as the world leader in offshore wind energy, further reduction in the technology cost is vital to achieve securing the required investment and support for new developments in this area. This is exacerbated by governments' stop-start investment cycles that is an unattractive proposition to investors who are looking for long-term business opportunities (CCC, 2011).

The cost of offshore wind turbines (levelised cost) in the UK has fallen over time from 140 £/MWh in 2010 to around 120 £/MWh in 2014 and it is projected to decrease to 100 £/MWh in 2020 (Offshore Wind Programme Board, 2015). However it is still higher than the nuclear and onshore technologies.

2.1.2.3 Environmental

1. Physical Presence of Devices

New structures above the water surface result in fundamental changes to the habitat and migratory patterns of seabirds and migratory birds (Exo *et al.*, 2004; Boehlert and Gill, 2010;

Johnston *et al.*, 2014). Resulting in disturbance to or even direct mortality (Garthe and Hüppop, 2004; Langhamer *et al.*, 2010). This is not helped by offshore wind energy devices which have vertical moving components.

The risk of short-term and long-term habitat loss for birds during construction and maintenance of wind turbines is also impacting (Exo *et al.*, 2004; Schuster *et al.*, 2015).

2. Dynamic Effects of Devices

Moving parts of offshore wind devices can cause problem for migratory birds known as blade strike (Exo *et al.*, 2004; Boehlert and Gill, 2010; Schuster *et al.*, 2015). Whilst it is not as common as people imagine its impact can lead to bird injury or even mortality.

3. Noise

The most significant acoustic effects associated with offshore wind farms occur during construction. These are identified as seismic survey and pile-driving with short-term impacts on marine mammals and possibly spawning fishes (DECC, 2009). The turbine noise may also cause disturbance to seabirds leading to habitat loss or change (Schuster *et al.*, 2015).

4. Climate Change

The identified impacts of climate change on wind energy in northern Europe are presented in Table 2.

Table 2: Summary of climate change impacts on wind energy in northern Europe and corresponding literature

Variables	Related impacts	Studies
Wind energy density	Changes in wind energy output	(Pryor *et al.*, 2005a; Pryor *et al.*, 2005b; Pryor and Barthelmie, 2010; Tobin *et al.*, 2015)
Geographic distribution	Availability of wind energy	(Pryor and Barthelmie, 2010; Tobin *et al.*, 2015)
Intra-annual variability	Availability of wind energy	(Pryor and Barthelmie, 2010; Tobin *et al.*, 2015)
Mean wind speeds	Decrease in wind energy output	(Pryor *et al.*, 2005b; Pryor and Barthelmie, 2010; Tobin *et al.*, 2015)
Wind speed extremes	Damage from extreme weather	(Pryor *et al.*, 2005b; Pryor and Barthelmie, 2010; Tobin *et al.*, 2015)
Sea ice	Decrease in maintenance costs	(Pryor and Barthelmie, 2010; Barstad *et al.*, 2012)

2.1.2.4 *Technical*

Offshore wind farms can be built closer to major cities which are located close to the sea. In comparisons to onshore farms they could require relatively shorter transmission lines. Although they need to be sited sufficiently far enough away to reduce visual and noise impacts (Bishop and Miller, 2007; Bilgili *et al.*, 2011; Mirasgedis *et al.*, 2014). However, offshore wind turbine is approximately 50% more expensive than onshore wind turbine (Bilgili et al., 2011). A more recent study in Germany by Ederer (2015) shows a similar rate between the cost of offshore and onshore turbines.

Weather condition may also cause some limitations for the construction, operation and maintenance of the wind turbines. The cost of construction may rise significantly by more expensive installation procedures and restricted access due to weather conditions (Pryor and Barthelmie, 2010; Bilgili *et al.*, 2011; Karan and Kazdagli, 2011). Limited access for operations and maintenance during operation caused by weather condition may also affect the availability of the wind farms.

2.1.2.5 *Political*

Pragmatic, ‘criteria based’ planning policy is identified by Toke (2011) as one of the main reasons why Britain is considered to be the leader in this industry, despite the existence of many planning pressures that hinder the drive for offshore wind power.

However, this needs to be considered against the fact that the development of the offshore wind energy is likely to depend heavily on consumer reactions to the expected price increases caused by the offshore wind power programme. Therefore political perseverance is required.

2.1.3 Onshore wind

The technology is well-established and being deployed worldwide; however support is still required for further development by governments and local authorities (CCC, 2011; Slee, 2015).

A significant barrier associated with wind generation is its efficiency. The maximum wind power extracted by an ideal wind turbine is 59.3% of the available wind power; which is known as the Betz limit (Irshad *et al.*, 2009). But in practical terms about 40% is regarded as the maximum achievable efficiency and even this only occurs at optimum wind speeds for each technology. Whilst there is such variation of the cut in and optimal operating speed between various models of turbine, the maximum efficiency is typically achievable at wind speeds of around 10 m/s (Wilson, 2007).

Therefore by looking at the frequency of wind speed in a country the possibility of achieving the claimed onshore wind capacity may be at the very least questioned. For example in the UK a study by Irshad et al. (2009) in 2008 showed that for the Edinburgh region the frequency of occurrence for the 10 m/s wind speed is low (just above 2%) whilst it is just for the specific region (Figure 1). Moreover, other studies such as: Deaves and Lines (1998), Pryor and Barthelmie (2010), Glass and Levermore (2011), Earl *et al.* (2012) and Watson *et al.* (2015) show similar result for the other regions in the UK, Denmark and part(s) of the EU. A study in India by Hossain *et al.* (2014), based on data from over 208 measurement sites, shows 0.033% frequency for 10 m/s wind.

Therefore, according to data provided in Figure 1 the probability of achieving the maximum efficiency, 40%, for the wind system in the UK, known as one of the leaders in the technology, is just around 2% in a year, which is quite challenging and therefore questionable in terms of supply meeting demand.

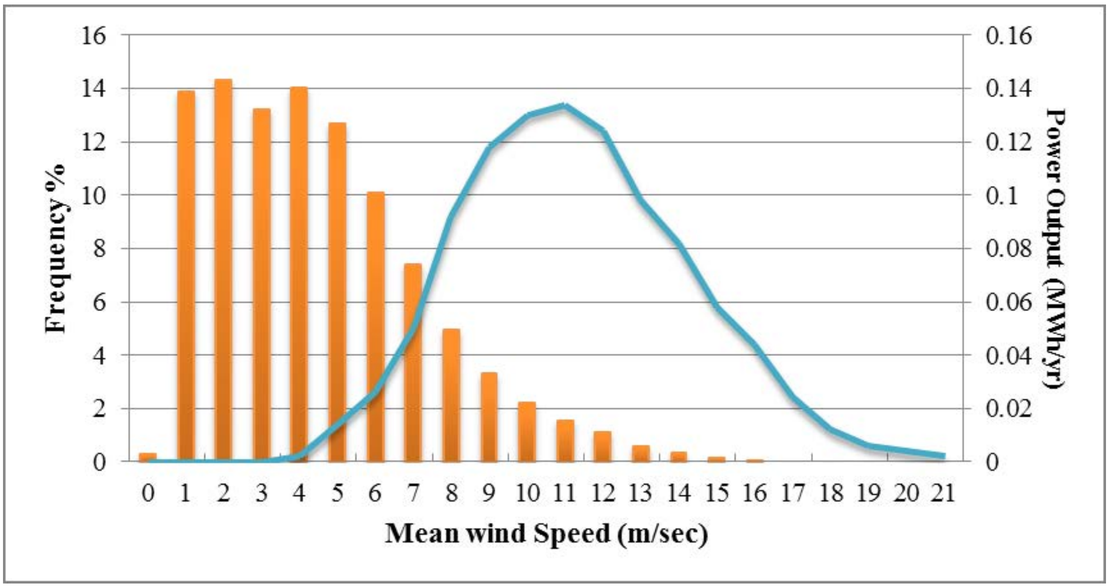


Figure 1: Wind Speed frequency in Edinburgh region for year 2008 (filled bars), source Irshad et al (2009). The line shows the power output as a function of wind speed for a similar wind climate and a 1 MW wind turbine in Denmark source Pryor and Barthelmie (2010).

The limitations of onshore wind technology are discussed below according to the STEEP acronym.

2.1.3.1 Social

Limited public acceptability of this technology also known as NIMBY (i.e. Not In My Backyard) is the main barrier of its development (Jones and Richard Eiser, 2010; Langhamer *et al.*, 2010; CCC, 2011; Burningham *et al.*, 2015). Visual and noise pollution (Bilgili *et al.*, 2011; Leung and Yang, 2012; Onakpoya *et al.*, 2015) might be a reason for this trend. In addition, low-frequency aerodynamic noise from wind turbines is rightfully or wrongfully related with sleep disturbances and hearing loss for people located in close proximity (Punch *et al.*, 2010). Incentivising potential users through slightly reduced electricity bills is a potential way forward; research suggests this could be around one per cent on the average household bill compared to investments on offshore wind (CCC, 2011).

2.1.3.2 Economic

Onshore wind has a relatively comparable cost to nuclear as a low-cost source of energy (Mott MacDonald, 2010; CCC, 2011; DECC, 2012a) and is therefore also likely to be cost-competitive when compared to gas CCGT, thought to be the lowest-cost source of energy by 2020 (Mott MacDonald, 2010; CCC, 2011; DECC, 2012a).

Unfortunately there is no evidence of a supporting framework for further investment in the technology in the UK (CCC, 2011; Slee, 2015). Nevertheless, development of onshore wind farms is limited simply by expensive land prices near major population centres (Bilgili et al., 2011; CCC, 2011).

2.1.3.3 Environmental

Noise and visual impact are two environmental pollutions which have been discussed earlier. In addition wind farms may pose a threat to nature conservation, through loss of habitat (Larsen and Madsen, 2000; Millon *et al.*, 2015), disturbance and displacement (Bright *et al.*, 2009; Van der Winden *et al.*, 2014) or direct mortality through blade collision (Johnson *et al.*, 2003; Bright *et al.*, 2009; Marques *et al.*, 2014a). Furthermore the other components of a wind farm such as high-power lines, windbreaks, roads and settlement are potentially disturbing habitats elements. Bright et al. (2009) states that the disturbance may happen in a number of ways;

a. Loss of nesting, foraging, roosting or moulting habitat,
b. Risk of decline in species productivity, and potentially survival rate.

Habitat loss is generally considered to be a relatively minor risk with some exceptions, these once again include disturbance displacement and mortality are of particular concern (Bright *et al.*, 2009).

Table 3 presents the identified impact of climate change on onshore wind energy.

Table 3: Summary of climate change impacts on wind energy in northern Europe and corresponding literature

Variables	Related impacts	Studies
Wind speed	Increase in winter wind speed and energy production (between 10–15% by UK 2080s) Decrease in summer wind speeds and energy production (up to 15% by 2080s)	(Harrison *et al.*, 2008; Chang *et al.*, 2015)
Mean wind speeds	Increase in average wind speed and energy output (1.3% averaged for 2080s)	(Harrison *et al.*, 2008; Chang *et al.*, 2015)

2.1.3.4 Technical

The main barriers associated with this technology are its intermittency and unpredictability in terms of energy production (Shuang *et al.*, 2010; CCC, 2011; Ayodele and Ogunjuyigbe, 2015).

In addition, onshore farms are located in remote areas, in part to avoid caused visual and noise pollutions, but also to maximise the benefit of areas with appropriate average wind speeds therefore, electricity loss caused by the requirements of long-distance transmission remains a significant costly barrier for the system (Bilgili *et al.*, 2011; Zeng *et al.*, 2015). This is exacerbated by the need for grid development which can raise the cost further and therefore pose barriers for investment. Notwithstanding a lengthy time delay can be expected when obtaining windfarm approvals (European Wind Energy Association, 2012).

Poor grid security and reliability combined with unstable wind power generation system exacerbates the situation are yet more barriers which may cause 10 to 12% power loss and therefore cause lower than expected energy output of the system (Yao *et al.*, 2011). Pei et al. (2015) report some bigger loss, over 50% in some short period, due to the same reason.

Forecasting wind speed is an uncertainty associated with wind energy in general, as one per cent error in wind speed has been known to lead to a three per cent error in energy output and when combined with the fact that there are between 0.6% to 30% uncertainties in predicting annual mean wind speed according to the predictions given by models quoted in the literature, certainty is not guaranteed (Prasad and Banasal, 2011). The uncertainties in forecasting wind speed depend on: the selected wind speed forecasting approach (i.e. model); anemometer wind speed measurement; the monitoring period; the historical period used in the analysis and the uncertainty in temperature and atmospheric pressure measurement (Prasad and Banasal, 2011). Therefore more accurate models and methods for forecasting, can help reduce the associated uncertainties (Prasad and Banasal, 2011; Nayak and Joshi, 2015). However, given the variability of natural environments this may be a long way off. Improvements therein would help in

- Attracting investors and enhancing marketing trading, and
- Optimizing scheduled maintenance.

2.1.3.5 Political

Concessionary policy towards the wind power industry adopted by many countries in the last decade, caused the wind market to develop rapidly, and therefore wind turbine technology has experienced an important and evolutionary development over this time (Leung and Yang, 2012; Sun *et al.*, 2015).

However this is not the case in all EU countries, for example Germany, as a leader of on-shore wind energy, is encountering many political challenges as adoption expands throughout the country. In several regions landscape disturbance of large scale windfarms is identified as the main reason for blocking their adoption and there are similar attitudes found elsewhere in the EU (Meyerhoff *et al.*, 2010).

Therefore governments' in many regions around the EU are supporting packages and direct subsidies such as feed-in-tariffs (FITs) which can be a fundamental requirement for the development of domestic small and medium scale wind turbines. However these are very sensitive to economic situations (see for instance Byrnes *et al.*, 2013; Dai *et al.*, 2016). Therefore the size of the tariffs can reduce over time, as has been the case in the UK, and these are strongly influenced by the policies of the powers that have been elected.

2.1.4 Hydro

The power of flowing water has been harnessed by humanity for many centuries as energy source for milling corn, pumping and driving machinery. There are three main types of hydroelectric systems currently in operation (Environment Agency, 2012):

- Storage; a dam impounds water in a reservoir that feeds the turbine and generator also known as Reservoir system.
- Pumped storage; include two reservoirs where at times of low demand, generally at night, electricity is used to pump water from the lower to the upper basin released through turbines to generate electricity when demand is high (e.g. Dinorwig in Wales).
- Run of river; use the natural flow of a river and divert water to a remote powerhouse containing the turbine and generator to generate electricity.

The limitations of the technology are discussed below according to the STEEP acronym.

2.1.4.1 Social

TNS (2003) Study demonstrates low levels of approval for hydro amongst the general public in the UK. This is mainly related to concerns, regarding visual impact and noise from the power plant(s). However a more recent study by Bracken et al. (2014) in the UK demonstrates a recent rapid expansion in micro-hydro schemes by public participation in their design, ownership or management.

2.1.4.2 Economic

The development of new hydro sites relies on fossil fuel costs (against which the cost for hydro generation can be offset) and the financial incentives which may be available for potential areas of development. This raises considerably risks and uncertainties.

2.1.4.3 Environmental

Although hydropower has many advantages over other energy sources in other areas, it carries with it just as many ‘potential’ environmental impacts and obstacles mostly caused by habitat alterations, in addition to benefits (see Table 4).

Table 4: Potential environmental benefits and adverse impacts of hydropower technology, source ORNL (2010) and Bracken et al. (2014)

Benefits	**Adverse Impacts**
No emission of sulphur and nitrogen oxides	Flood of wetlands and terrestrial vegetation
Few solid wastes	Emissions of greenhouse gases from flooded vegetation at some sites
Minimal impacts from resource extraction, preparation, and transportation	Conversion of a free-flowing river to a reservoir
Flood control	Replacement of riverine aquatic communities with reservoir communities
Water supply for drinking, irrigation, and industry	Displacement of people and terrestrial wildlife
Reservoir-based recreation	Alteration of river flow patterns below the dam Increasing flood risk by altering the conveyance of water through the river system Loss of river-based recreation and fisheries
Reservoir-based fisheries	Desiccation of streamside vegetation below the dam
Enhanced tail-water fisheries	Retention of sediments and nutrients in the reservoir
Improved navigation on inland waterways below the dam	Development of aquatic weeds and eutrophication
	Alteration of water quality and temperature
	Interference with upstream and downstream passage of aquatic organisms

Climate change impacts on hydro energy found from within the literature are presented in Table 5.

Table 5: Summary of climate change impacts on hydro energy and corresponding literature

Variables	Related impacts	Studies
Air temperature, precipitation, extreme weather events	Total and seasonal water availability (inflow to plant's reservoirs)	(Whittington and Gundry, 1996; Muñoz and Sailor, 1998; Whittington and Gundry, 1998; Harrison and Whittington, 2002; Lehner *et al.*, 2005; Fenger, 2007; de Lucena *et al.*, 2009; Hamlet *et al.*, 2010; François *et al.*, 2014)
	Dry spells	(Iimi, 2007; Vicuña *et al.*, 2008; Lise and van der Laan, 2015)
	Changes in hydropower system operation	(Schaeffer *et al.*, 2012; François *et al.*, 2014)
	Evaporation from reservoirs	

2.1.4.4 Technical

Advances in technology regarding the costs reduction, increasing efficiency and the reducing CO_2 footprint have significant impact on the developments of the technology in the future.

2.1.4.5 Political

Within the literature review study conducted here no political barrier to the development of hydro power was identified. The reason might be that most potential sites have already been developed within developed countries in the EU. However, as a recent study conducted in Greece showed perhaps it is merely because public opinion on the new development of small hydro plants is high, acceptability of the order of 80% is not uncommon (Kaldellis *et al.*, 2013). The similar trend is reported in the UK (Bracken *et al.*, 2014). Moreover the two are inextricably linked, i.e. public acceptance plays a major role on the landscape of political views in developed countries. Moreover it could help increase the share of power generation from renewable energy sources by helping to balance out the fluctuating supplies from wind and solar power. In this respect energy policy might therefore seek to increase the number of pumped storage plants around the world (Steffen, 2012; Saarinen *et al.*, 2015). Options for this are considered in more detail below:

2.1.5 Pump storage

As outlined previously this technology consists of two reservoirs where at times of low demand, generally at night, cheap electricity is used to pump water from the lower to the upper basin released through turbines to generate electricity when demand is peak or high (MacKay, 2009; Huggins, 2010; Environment Agency, 2012). Pumped storage system can switch on extremely fast, for instance Dinorwig power plant in the UK can switch on in 12 seconds, to reach 1.3GW power from zero, coping with any demand-fluctuations or wind-fluctuations (MacKay, 2009).

There are some new ideas for storing system such as building an artificial lake above the sea, with the sea being used as the lower lake (see Figure 2). The other idea is underground pumped storage, using flooded mine shafts or other cavities (Kousksou *et al.*, 2014).

Figure 2: Okinawa pumped-storage power plant, whose lower reservoir is the ocean with 0.2GWh energy stored, source iea hydro power (2013)

2.1.5.1 Limitations

The limitations associated with the development of the pumped storage are exactly the same as the one for hydro power (see Section 2.1.4).

2.1.6 Biomass

Biomass is any organic material that is available on a renewable basis and includes; forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, live-stock operation residues, aquatic plants and municipal and industrial wastes (Mott MacDonald, 2011). The limitations according to the STEEP acronym are discussed below.

2.1.6.1 Social

Haughton et al. (2009) reports the following social objectives identified through engagement with a range of stakeholders (public and private) in the UK:

1. Minimize transport movements;
2. Enhance rural quality of life;
3. Increase (or maintain) water availability;
4. Improve public enjoyment of the countryside;
5. Safeguard the historic environment.

All of the objects identified by Haughton et al. (2009) appear to have positive impacts, however there are other considerations and concerns that must be addressed. For example, OECD/IEA (2007) identifies concerns over public acceptance issues in many countries regarding tensions between organic waste recycling and the growth of energy crops, which must be profitable for the farmer. In addition considering must be given to the increasing competition with food production which also requires land (Adams *et al.*, 2011). Furthermore, adoption of a new phase of biomass (second generation which focuses on advanced ethanol production) has been decelerated in many countries due to the fact that several environmental and social issues linked to first generation biomass remain outstanding (Secko and Einsiedel, 2014). Chin *et al.* (2014) has also reported possible social acceptability issues caused by uncertainties associated with new crops and generally prefer traditional agriculture practices.

2.1.6.2 Economic

The following opportunities all of which have economic benefits are identified by Haughton et al. (2009):

1. Reduce energy costs to the consumer;
2. Increase amount of energy produced and used locally;
3. Enhance the local economies;
4. Enhance tourism potential;
5. Maximize waste management opportunities;
6. Enhance employment.

Conversely there are just as many dis-benefits, for example, studies by Adams et al. (2011) and Chin *et al.* (2014) suggest economic factors of projects to be the most critical barrier (and drivers) and this is mainly with regards to the cost (per tonne) of purchasing energy resources related to biomass. In addition financial support mechanisms for biomass are inappropriate and this is identified as another barrier for the development of the technology (Adams *et al.*, 2011). Government policy regarding this matter is a substantial hurdle to be overcome.

2.1.6.3 Environmental

Haughton et al. (2009) identify the following environmental objectives as positive impacts of the technology:

1. Enhance local landscape character;
2. Improve water quality;
3. Protect and improve soil resources;
4. Improve air quality;
5. Protect and enhance biodiversity [has been questioned by Chin et al. (2014) and Tan *et al.* (2008)];
6. Reduce greenhouse gas emissions [has been confirmed by Piroli *et al.* (2015)].

Climate change poses the biggest risk to achieving these positive impacts from adopting wider use of biomass systems and these are influenced by the aspects identified in Table 6.

Table 6: Summary of climate change impacts on biomass and corresponding literature

Variables	Related impacts	Studies
Air temperature, precipitation, humidity	Availability and distribution of suitable land Biomass yield and security of agricultural crops	(Brown, 2000; Fenger, 2007; de Lucena *et al.*, 2009; Persson and Höglind, 2014)

2.1.6.4 Technical

Flexibility in operation (i.e. not intermittent as long as fuel is available) provides biomass with a distinct advantage when compared to other intermittent renewable technologies such as wind energy. A new option for biomass technology in terms of climate mitigation is the theoretical potential of adding Carbon Capture and Storage (CCS – see 2.1.7) technology, introducing the prospect of negative emissions– in other words moving it from carbon neutral to carbon positive (Gough and Upham, 2011; Lomax *et al.*, 2015). In such a way this system takes advantage of biologically removing CO_2 from the atmosphere and at the same time producing biomass-based fuels to achieve decarbonisation of fuel use (Gough and Upham, 2011;

Lomax *et al.*, 2015). For the near future both the scale of the forestry and accessibility of CCS infrastructure pose risks for large-scale deployment of biomass (with CCS).

2.1.6.5 Political

The ecology of the plant is claimed to play a critical role in structuring the political adoption of biomass energy by van der Horst and Evans (2010).

This is known as Political ecology and is defined as the power structures that determine who has access to environmental assets and who does not within the developing world (van der Horst and Evans, 2010). Consensus therein is that security of supply is very influential within ecological and economic processes. An example would be the economic benefit gained when farmers grow a specific crop in a region rather than the appropriate crop for biomass energy. This poses a political challenge to make the biomass crop option economically beneficial. This would certainly be more challenging in a free market approach which favours minimum impacts of farm subsidies, regulations and other interventions [see Demirbas (2009) and Yang *et al.*(2014) for more discussions on free biomass market]. The production of biomass, however, can be facilitated through the agricultural policy of subsidising the farming of non-food crops (Demirbas, 2009; Yang *et al.*, 2014).

2.1.7 CCS

The technology involves the removal of CO_2 from the flue gas of fuel-fired power plants (coal or gas) and then its transportation and finally long-term storage in geological formations (CCC, 2011). The CCS system is expected to be 90% effective for capturing CO_2 emissions (Kharecha *et al.*, 2010; Alie *et al.*, 2015).

Storage capacity constraint and fuel (coal and gas) availability in future are two concern for the technology viability and availability. However, DECC (2012b) states that the offshore CO_2 storage locations, under the North Sea (Utsira formation, see Strachan *et al.*, 2011; Stewart *et al.*, 2014), can be extensively used for storage purposes. Two types of geological formations are considered to be appropriate for storing CO_2; deep saline aquifers and depleted oil and gas fields (see Figure 3). The idea embedded within this is to take advantage of a naturally occurring geology that has trapped CO_2, oil and gas for millions of years (ZEP, 2012; Harrington and Gillespie, 2015). Benson (2015) reports between 360 to 10,600 Gt global storage capacity and estimates it enough for accommodate hundreds of years at the current CO_2 emission rate.

The British Geological Survey (2012) has estimated that storage capacity in UK oil and gas field's amounts to at least 7.8 Gt and range of 24 Gt to 240 Gt for UK aquifers storage capacity. DECC (2012b) estimates that these storage capacities are enough for 100 years of CO_2 storage capacity at UK current rate of emissions from power generation.

CCS, however, is a dispatchable form of generation, whilst its quantity and timing can be controlled by grid operator as required to meet the variations in demand or the output of intermittent renewables (CCC, 2011). The CCC (2011) statement on CCS technology states that it is "Still (a) new technology and therefore highly uncertain". This recognises the concerns of 'storage capacity constraint' and 'fuel availability' as the two main issues associated with this approach.

Figure 3: Two types of geological formations suitable for storing CO_2, source ZEP (2012)

The limitations associated with CCS technology are discussed further below according to the STEEP acronym.

2.1.7.1 Social

Stigson et al. (2012) reports that the public's lack of knowledge or awareness on CCS means that there is relatively minor support for this approach compared to other renewable energy options. Moreover where awareness exists NIMBY tendencies become the main social concern. A more recent study by Ashworth *et al.* (2015) shows that public awareness of CCS remains low. Public opinion is therefore identified as the major risk of any new CCS development according to experiences from on-going or postponed potential storage projects (Greenberg *et al.*, 2011; Stigson *et al.*, 2012; Roeser and Pesch, 2015).

2.1.7.2 Economic

CCS sensitivity to fossil fuel price is identified as an economic barrier (CCC, 2011; Wang and Du, 2015). Furthermore, there is considerable uncertainty over capital costs as early-stage technologies are adopted. In addition it is likely that technology performance will lead to substantial cost variations on a project-by-project basis, making estimation of current and future costs hugely uncertain (CCC, 2011; Wang and Du, 2015).

Another group of economic risk relates to '*carbon price policies*' which is vital to support investment (Stigson *et al.*, 2012; Wang and Du, 2015). CCS is suggested as being very capital intensive, so any increase in the weighted average cost of capital will reduce the present discounted value of future profits (Newbery *et al.*, 2009; CCC, 2011).

2.1.7.3 Environmental

A study by Pehnt and Henkel (2009) shows an increase in cumulative energy demand and a substantial decrease in greenhouse gas (GHG) emissions for all CCS technologies. In part this is related to achieving negligible leakage in comparison with power plants without CCS. However when CCS is compared to renewable resources, unsurprisingly, it shows higher level of GHG emissions (Cuéllar-Franca and Azapagic, 2015). The CO_2 emissions produced by CCS occur at a much lower rate and are significantly delayed and therefore will have a much less negative impact on the environment (Pehnt and Henkel, 2009). Moreover, a considerable share of this CO_2 will be captured permanently due to chemical reactions and physical trapping (Pehnt and Henkel, 2009).

However additional detrimental effects need to be considered, for example, large volumes of degraded amine are common outputs of most CCS technologies that must be handled as hazardous waste (Bellona, 2012; Cuéllar-Franca and Azapagic, 2015). In addition if CO_2 leakage accidentally occurred this may harm local marine ecosystems around the injection point. This is related to the fact that huge volumes of leakage can replace oxygen in the water leading to lethal conditions (Bellona, 2012; Cuéllar-Franca and Azapagic, 2015).

As the technology uses gas and coal as the fuel at the moment the impact of climate change on CCS is similar to those on gas and coal. Table 7 presents the identified impact of climate change on oil and gas technology development. The identified impact of climate change on coal technology (Thermoelectric power generation) development is presented in Table 8.

Table 7: Summary of climate change impacts on oil and gas and corresponding literature

Variables	Related impacts	Studies
Extreme weather events	Disruptions of offshore extraction	(Burkett, 2011; Harsem *et al.*, 2011; Andreoni and Miola, 2014)
Extreme weather events, air/water temperature, flooding	Disruptions of on-shore extraction	
Extreme weather events, flooding, air temperature	Disruptions of production transfer and transport	
Extreme weather events	Disruption of import operations	
Flooding, extreme weather events and air/water temperature	Downing of refineries	
	Cooling water quantity and quality in oil refineries	

Table 8: Summary of climate change impacts on coal and corresponding literature

Variables	Related impacts	Studies
Air/water temperature	Cooling water quantity and quality	(Kopytko and Perkins, 2011; Schaeffer *et al.*, 2012; Andreoni and Miola, 2014)
Air/water temperature, wind and humidity	Cooling efficiency and turbine operational efficiency	
Extreme weather events	Erosion in surface mining	
	Disruptions of offshore extraction	

2.1.7.4 Technical

The future role of CCS is currently highly uncertain given the early stage of technology development. Therefore it is not surprising that facilities in operation today and where they do exist are fairly small and technologically uncomplicated (CCC, 2011; Stigson *et al.*, 2012).

Toxicity is a significant risk associated with these technologies (Stigson *et al.*, 2012; Cuéllar-Franca and Azapagic, 2015) therefore CO_2 observation as part of all storage phases needs to be considered.

Other technological risks are:

- Appropriate site selection based on available subsurface information (Imran *et al.*, 2014),
- Lack of a monitoring programme to detect problems (Imran *et al.*, 2014),
- Lack of a regulatory system and the appropriate use of remediation methods to stop or control CO_2 releases if they arise (IPCC, 2005; Liu et al., 2014)

2.1.7.5 Political

The "*political salience*" of CCS is reported high by Chaudhry et al. (2013) considering various technical, economic, and environmental uncertainties about the future of the technology. Chaudhry et al. (2013) focuses on the energy policy which includes stakeholders' perceptions of CCS in the U.S. This reveals negative associations being more frequently mentioned than positive attributes, with respect to technical, political and economic risks which appear to be more dominant than environmental or health-and-safety risks.

Another case study in Germany developed by Brunsting et al. (2011) shows that in the early days of development local politicians were strongly opposed to new CCS development. Contrastingly, the EU policy shows strong support for its development where 300 million Euros allowances were set aside within the EU emissions trading system's (ETS) New Entrants Reserve for funding CCS demonstration projects (Lerum Boasson and Wettestad, 2014).

2.1.8 Nuclear

Despite not being categorised as a renewable technology cannot be argued that nuclear has the potential to be a decarbonising option and therefore a direct competitor to other renewable technologies. Nuclear has been reported as the most cost-effective decarbonisation technology, possibly leading it to be cost competitive with unabated gas at a £32/tCO_2 carbon price in 2020 (CCC, 2011). Although changes in energy policy regarding supporting nuclear energy could threaten the availability of the technology, leading to the proposed construction of new nuclear plants being stopped. This is certainly the case in Germany where a nuclear-free policy was adopted following the Fukushima disaster (Stimpson and Lynch, 2011; Huenteler *et al.*, 2012; Park *et al.*, 2015). For the UK there is still uncertainty about whether to adopt nuclear, not least as many existing nuclear plants are being decommissioned.

The limitations of nuclear energy according to the STEEP acronym are listed below.

2.1.8.1 Social

Public acceptability is the major threat for any new nuclear power plant and site availability is undoubtedly a concern for areas being highlighted as having potential for new developments (Greenhalgh and Azapagic, 2009; CCC, 2011; Goodfellow *et al.*, 2011; Cooke, 2014; Shinoda *et al.*, 2014).

Pidgeon et al. (2008) conducted a study on the UK's public acceptability and suggests that a significant proportion of people may reluctantly accept nuclear power as a measure to tackle climate change. A research conducted in 2010 shows a slight increase in this trend being shown, although in this case only a minority expressed unconditional acceptance of nuclear (Corner *et al.*, 2011). However, another study by Ipsos MORI (2011), using samples of approximately 2000 people, showed a three per cent drop in support of the building of new nuclear power plant in Britain and four per cent increase in the number of oppositions in the period 2009-2011. More recently research shows that people who previously accepted nuclear energy in the UK have now become more uncertain after Fukushima disaster (Henwood and Pidgeon, 2015).

2.1.8.2 Economic

Elevated construction costs (related to tightened safety regulations) can be associated with new nuclear power plants and this may pose a significant risk for future development (CCC, 2011; European Commission, 2012). In addition where fears over safety or NIMBYism ensue, public demonstration (physical or vocal) can lead to delays (or cessation) in starting the project (Greenhalgh and Azapagic, 2009). For instance, negative public attitude in the UK had led to significant delays in Sizewell B project (O'Riordan, 1984; O'Riordan *et al.*, 1985) and cancellation of the Druridge Bay project (Baggott, 1998).

Allied to this is risk of finding capital investment (Greenhalgh and Azapagic, 2009; CCC, 2011; Harrison, 2014) and the cost of energy production, therefore, this requires provision of subsidies and or guarantees made by government (Thomas, 2010; Harrison, 2014).

2.1.8.3 Environmental

The Fukushima disaster in Japan and four previous major accidents in the history of nuclear power (see Table 9) raised many environmental (social and economic) concerns toward existing and increased use of nuclear technology (Smith, 2011; Steinhauser *et al.*, 2014). For instance, the Windscale accident had impacts on food products and consequently, three million litres of milk were discarded to avoid thyroid cancer, and Chernobyl caused at least 39 deaths, around 4000 to 6848 cases of thyroid cancer and evacuation of approximately 116,000 people (Smith, 2011; Steinhauser *et al.*, 2014).

Table 9: Major nuclear accidents, source Smith (2011) and IAEA (2011) for Fukushima INES category

Accident	Year	Country	Sector	INES category [a]
Windscale	1957	UK	Military	5
Kyshtym	1957	Soviet Union	Military	6
Three-Mile Island	1979	USA	Civilian	5
Chernobyl	1986	Soviet Union	Civilian	7
Fukushima	2011	Japan	Civilian	7

a) International Nuclear Events Scale: Category 5 = accident with wider consequences; Category 6 = serious accident; Category 7 = major accident.

Moreover spent nuclear fuel waste disposal (Greenhalgh and Azapagic, 2009; Christiansson, 2014) is a major concern for the technology (CCC, 2011; Grape *et al.*, 2014). As such the Committee on Radioactive Waste Management (CoRWM) (2006) recommends geological disposal as the best available approach for the long-term management of waste materials thereby allowing for safe storage whilst radioactivity decays naturally over time.

2.1.8.4 Technical

Long-term fuel, uranium, supply is a barrier for the technology; in simple terms there is a dwindling supply, however no fuel resource constraint is predicted to come to pass for the next fifty years (Knapp *et al.*, 2010; CCC, 2011). Although this all depends on whether more countries will push to advance their nuclear energy supply capabilities.

Safety concerns following the Fukushima disaster could play a major role for current and future public acceptance and associated government approvals (CCC, 2011; Shinoda *et al.*, 2014). However, contrary to this belief the 2008 White Paper on Nuclear Power ranks this risk as negligible (BERR, 2008b). The CCC (2011) report also draws from the findings of the European Commission suggesting a billion to one impact per reactor per year risk probability of a major accident with the meltdown of the reactor's core along with failure of the containment structure. Goodfellow et al. (2011) compared a selection of these probabilistic risk analysis results for some nuclear plants, such as HSE (2006) and US NRC (1975). The findings showed a significant reduction in calculated risk levels, three to four orders of magnitude over a period of 30 years.

Notwithstanding, these results from the CCC (2011) report further introduces the enormous earthquake and tsunami as the cause of the Fukushima disaster and indicates that the probability of natural disasters of this type and scale occurring in the UK is extremely minor, although not impossible. Furthermore Goodfellow *et al.* (2015) argue that involving the public in the design of nuclear power plants can improve public trust. However, more worrying highly probable concerns are raised in a study by Wilby et al. (2011) who highlight the risk of rising sea levels, higher sea temperatures and more extreme weather events over the next two centuries caused by climate change (see Table 10) [N.B. Cross reference with Table 7 will highlight other impacts of climate change that could be influential on nuclear power, such as Thermoelectric power generation)].

Possible future review may significantly tighten the safety regulations for nuclear and certainly technological advancement now means that the waste produced is a fraction of that from early power plants adopted in the 1960's. However all of this comes at an economic price and safety fears undoubtedly raise the construction and waste storage costs to minimise risk potential.

Table 10: Climate change impacts on evaluating nuclear sites, source Wilby *et al.* (2011)

Strategic siting assessment criteria	**Potentially affected by climate change**
Demographics	×
Proximity to military activities	×
Flooding	√
Coastal processes	√
Proximity to hazardous industrial facilities	×
Proximity to civil aircraft movements	×
Internationally designated sites of ecological importance	√
Nationally designated sites of ecological importance	√
Areas of amenity, cultural heritage and landscape value	×
Size of site to accommodate operation	×
Access to suitable sources of cooling	√

2.1.8.5 Political

Nuclear energy might have the highest sensibility to politics among all sources of energy. This is due to two key fundamental reason, these are:

- Firstly international concern over the widespread increases of Uranium enrichment in developing countries and associated possibilities of non-peaceful usages and therefore global stability (see for instance Lewis, 2013)
- Secondly the health and safety concerns and associated public acceptability regarding new nuclear developments in developed countries especially after the Fukushima disaster (see Kim *et al.*, 2013; Csereklyei, 2014). In many cases, as highlighted in the text this brings with it the possibility of a political U-turn regarding the future usage of nuclear (similar to Germany with its newly adopted 'no-nuclear' policy) (see Walker and Henry, 2013)

2.1.9 Summary

In general this section has shown that there are various barriers, limitations and uncertainties associated with the developments and implications of all renewable technologies. Under the categories considered for each of the technology options proposed there are couple of issues that resonate between all of them which pose a real threat for both development and adoption both now and in the future. For instance '*public acceptability*' (for most of them, e.g. Wind energy and nuclear), '*technical issues*' related to remote new developing sites without required infrastructures (i.e. long-distance transmittance, and also renewables intermittency, variability and cyclic nature). The next section, therefore, looks at the advantages associated with a very different approach to renewable energy that allows for trading of RE. By developing interconnections in this way many of the barriers and uncertainties associated with renewables' will be overcome hence facilitating their development and adoption. The next section outlines this approach in further detail.

2.2 Interconnections

This section describes some other features of interconnections in more details building on the discussion of this topic area which can be found earlier in background section of the research.

2.2.1 Economic viability

The economic viability of the Supergrid is considered by many authors as the primary driver to its success or failure (DKM, 2003; Black &Veatch, 2009; Denny *et al.*, 2010). Ultimately this requires cognizance for the cost of alternative supply technologies. Figure 4 shows these in £/MWh (2013 costs) for the UK (Mott MacDonald, 2010). It can be seen that the least costly investment in 2013 was gas followed by onshore wind and then nuclear (the figures are in line with recent studies such as CCC (2013)). Whilst Gas has a relatively low capital cost investment it is not a renewable source and for decarbonisation (via CCS technology) to be included costs increase significantly (CCC, 2011; CCC, 2013). For onshore wind the lack of inexpensive land near major population centres allied with the visual intrusion caused by large wind turbines has hindered their adoption (Bilgili *et al.*, 2011; CCC, 2011; Onakpoya *et al.*, 2015). Therefore it is not surprising that nuclear has been claimed to be a vital part of a future reliable, low carbon energy supply mix for the UK (Lynch, 2010; CCC, 2011; CCC, 2013). If we then consider the cost (in £/kW) of nuclear set against the cost for recently built interconnection between UK and Netherlands (BritNed) the capital investment was significantly less (Table 11). These cost implications of sourcing renewable sources in this way is a dominant influencing factor for decision makers when considering a Supergrid.

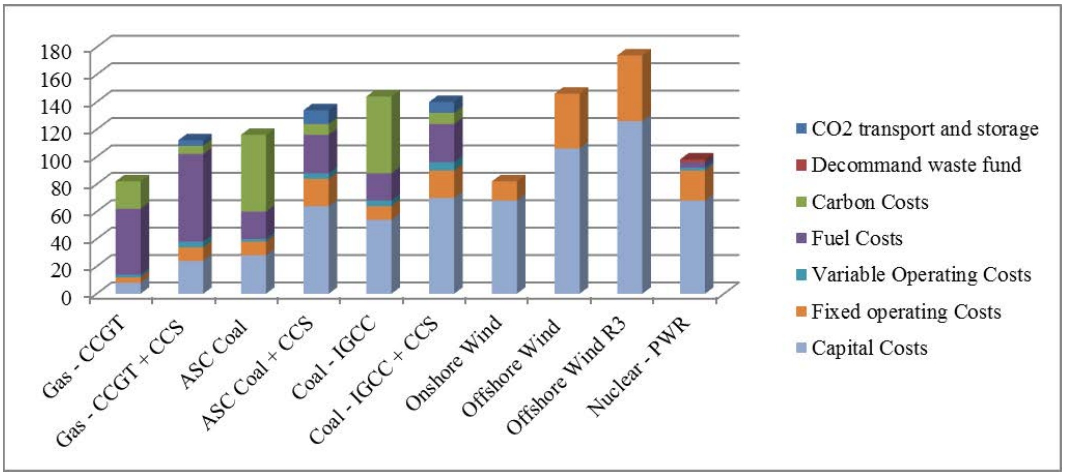


Figure 4: Levelised costs of main technologies for projects started in 2013: £/MWh, source Mott MacDonald (2010)

Table 11: Capital cost of nuclear plant VS interconnection

Source	Cost (£/KW)	Reference
Nuclear Plant	3,200	Thomas (2010), Harrison (2014)
BritNed interconnection	545	BritNed (2011)

A different approach to estimating economic viability of such a system can be found in Chatzivasileiadis et al. (2013) who compares directly the cost of interconnections with all the available renewable resources. The authors conclude that the economic viability of interconnections is highly likely and well within the acceptable limits that investors and customers alike are willing to pay (i.e. €0.0166 to €0.0251 per delivered kWh cost for a 5500 km, 3 GW seabed cable compared to the cost of renewables in 2020 to start from $0.04/kWh to a maximum of $0.13/kWh). If this can be achieved once constructed things can only improve, not least because the cost of technologies typically decrease over time (as costs reduce through the adage of ‘learning by doing’) and through increasing economy of scales (Battaglini *et al.*, 2010). However, nuclear power is one of the few technologies which tended to become more expensive with time (Neij, 2008; Cooper, 2009; Battaglini *et al.*, 2010). Therefore, as a direct alternative to existing approaches importing (and also exporting) RE could be economically beneficial alternative for the UK and any other countries outside the EU. This approach is well exampled by Williges *et al* (2010) who considers diversifying investment of renewable sources (e.g. concentrated solar power - CSP) in least cost North African countries as a cost effective solution. However, this then poses further question, for example, will a truly diversified renewable market, lead to an overall improvement in stability of electricity prices (Schaber *et al.*, 2012a; Klinge Jacobsen *et al.*, 2014) and will it allow for more, or less penetrability? Will this be hindered by the over-integration of seemingly disparate market(s)? What would be the impact of increasing the geographical market and potentially the number of competitors on the target market (Malaguzzi Valeri, 2009; Nooij, 2012; Torriti, 2014)? The argument is not straightforward and would require, at the very least, investment from two, but preferably multiple countries. This recognizes the fact that sources of renewable energy (e.g. marine technologies and wind farms (Hirschhausen, 2012)) may be located away from the centres of demand necessitating long-distance transmittance. These pose technical challenges (Berdal Stromme, 1998; Trieb, 2006; Georgiou *et al.*, 2011; Canelhas *et al.*, 2015), including energy losses and have associated economic costs - a function of cable distance, type (e.g. AC or DC) and location (i.e. underground, seabed or overhead) (see Section 2.2.3 for more information on DC and AC cables). An important parameter is the economic cost of carbon (see section 6.2.3.2) and how renewable energy will be traded in the future. For example, Italy already plans to enhance its renewable targets by importing electricity produced from renewable sources outside of its boarders (European Union, 2009; Kovalyova, 2010; Martínez-Anido *et al.*, 2013). According to the European Union (2009) directive "guarantees of origin" have the function of proving to a customer that a given share or quantity of energy was produced from renewable sources – this should avoid the possibility of double accounting in any given country.

Chatzivasileiadis et al. (2013) also present the costs of five existing (and planned) seabed HVDC cables (see Table 12). NorNed is the longest seabed cable to date, between Norway and Netherlands (ABB, 2005). SAPEI is currently the deepest seabed cable in the world, connecting Sardinia with mainland Italy (Terna, 2009). BritNed connects the UK with the Netherlands and has been in operation since April 2011 (BritNed, 2011). NorGer, between Norway with Germany, is still in the planning phase, with estimated project completion in 2015 (Chatzivasileiadis *et al.*, 2013). NordBalt is also in planning phase, which connects Sweden with Lithuania, linking the Baltic electricity market with the Nordic and the European market, to be completed by 2016 (Chatzivasileiadis *et al.*, 2013). Chatzivasileiadis et al. (2013) findings confirms the viability of HVDC cables for long distance transmissions considering both distance and cost of the projects.

Appendix B provides further illustrations of other economic opportunities associated with interconnections using the UK as an example.

Table 12: Costs of HVDC seabed projects, source Chatzivasileiadis *et al.* (2013)

	NorNed	SAPEI	BritNed	NorGer	NordBalt
Voltage (in kV, DC side)	±450	±500	±450	450–500	±300
Capacity (MW)	700	1000	1000	1400	700
Length (km)	580	435	260	570	450
Maximum sea depth (m)	410	1600	n/a	410	n/a
Total Cost (in millions)	£493.66	£617.07	£493.66	£1151.87 (±30%)	£452.52
Cost without converters (in millions)	£246.83	£370.24	£246.83	£559.48 - 1250.60	£222.15
Cost/km (in millions)	£0.43	£0.85	£0.95	£0.98 - 2.20	£0.49

2.2.2 Security of energy supply

Ensuring security of future supplies poses an equally challenging prospect. Undoubtedly a lower risk is posed in this respect through adoption of a large grid system where multiple supply paths exist in parallel (Van Hertem and Ghandhari, 2010; Hirschhausen, 2012). The same philosophy underpins the adoption of any national grid system - as preferable to having multiple local dispersed grids (Parr, 2012). The Supergrid just takes this concept to the next scale. It could be argued that the importation of RE via a Supergrid provides an effective solution for reducing the dependency on long-distance imported fossil fuels from sometimes unstable countries whilst enhancing security of energy supply (Battaglini *et al.*, 2010; Hirschhausen, 2012; Katinas *et al.*, 2014; Kishore and Singal, 2015). For example, in 2014 some 7% of the electricity generated in the UK (around %30 of total gas imported) was sourced from Algeria, Egypt, Nigeria, Qatar and Trinidad and Tobago [it was around 16% in 2010] (DECC, 2011b; DECC, 2015). Although it also raises the question of whether importing electricity will ultimately bring a new kind of dependency and therefore pose new kinds of threats to security of supply (see Zeller, 2009; Ochoa and van Ackere, 2015). Battaglini *et al.*(2010), for example, recognizes the importance of selecting a "good government" (e.g. Norway) to guarantee that the imports are secure and beneficial for both sides – so governance issues along with clear policy guidance are paramount to its success (or failure).

Renewable energy generation output (e.g. wind, hydro and solar) is naturally variable and unpredictable. Therefore, balancing these issues out is seen as one of the main requirements for the seamless integration of renewable energy supply sources (Van Hertem and Ghandhari, 2010; Chatzivasileiadis *et al.*, 2014). In addition RE once generated needs to be used because it is technically inefficient and costly to store (Koponen *et al.*, 2008; Achenbakh, 2010; Chatzivasileiadis *et al.*, 2014; Torriti, 2014). It could be argued that Security of supply is improved (i.e. intermittency becomes less of an issue) within the Supergrid network because of the geographical dispersion of supply sources (Battaglini *et al.*, 2010; Great Britain Parliament, 2011a; Schaber *et al.*, 2012b; Torriti, 2014). This allows for the disassociation of localised weather systems (Van Hertem and Ghandhari, 2010). For example, in Europe, wind energy from the UK can be partially balanced with solar energy from Spain or Northern Africa (e.g. Sahara desert) or hydro power from Scandinavia or the Alps. In so doing the Supergrid reduces the requirement for back-up generation (Aboumahboub *et al.*, 2010; Great Britain Parliament, 2011a; Chatzivasileiadis *et al.*, 2014).

Security of supply issues are further reduced due to the intricacies of ‘time-zoning’. For instance, there is at least one hour difference between the UK and other North Sea bordering countries and this will facilitate offsetting peak demand requirements in each country during the day (Van Hertem and Ghandhari, 2010; Chatzivasileiadis *et al.*, 2014). This argument is enhanced further when considering the differences in lifestyles and various end-uses uses for electricity around the EU - which of its own brings added flexibility and improved security to the grid during peak hours.

However, there are some studies questioning the significance of the impact of this parameter on the revenue of interconnections such as Parail (2010b) whose model shows only 0.1% drop in BritNed revenue by assuming Britain and Netherlands in the same time zone.

Notwithstanding these advantages it should be recognized that a ‘common mode failure’, should it occur, would impact the entire DC Supergrid and could feasibly stop all power transfers - potentially leading to generation imbalances (Van Hertem and Ghandhari, 2010; Hirschhausen, 2012).

2.2.3 HVDC VS HVAC

There are some technological barriers associated with interconnections more importantly electricity losses, which emphasise the importance of selecting the best available technology to minimise them. High-Voltage Direct Current (HVDC) is proposed as an alternative solution for the long distance transmission problems associated with the traditional technology, High-Voltage Alternating Current (HVAC), regarding cost and electricity losses (Van Eeckhout *et al.*, 2010; Van Hertem and Ghandhari, 2010; Chatzivasileiadis *et al.*, 2014). However, electricity loss is still a technological barrier for trading electricity. Two parameters therefore require further consideration; these are cost and transmission loss, of both (HV)AC and (HV)DC technologies. In terms of the first consideration the study by Van Eeckhout et al (2010) provides very clear results in this respect. The authors compared the total costs of these systems, the results of which are presented in Figure 5. It is worth pointing out that total cost consists of investment costs, annual costs of the losses and the maintenance of the transmission system.

Figure 5: Comparison of costs for HVAC and HVDC cables, source Van Eeckhout *et al.* (2010)

Figure 6: Total losses of a DC system versus losses of an AC system, source Santacana et al. (2007)

The figure shows that HVDC technology is not economically feasible for the distance less than 80km compared to HVAC (see Figure 5). In contrast Van Hertem and Ghandhari (2010) suggest a much shorter distance, up to 40 km, would be required to achieve a break-even point for traditional AC systems.

In terms of the second consideration, Santacana et al. (2007) compares the total losses of a 400kV DC system with a 400kV AC system for different distances. Figure 6, shows that DC has lower transmission losses over long distances (>250km) compared to AC technology. Although it highlights also that AC has lower transmission losses over shorter distances (<250km). The ABB (Asea Brown Boveri*)* Company achieved 3.7% losses in Norway–Netherlands (NorNed) interconnection project with DC system (ABB, 2005). The connection distance in this respect was 580km. Furthermore, another company, Siemens, claims that the losses of its HVDC line (e.g., ±800 kV) is less than 3% for every 1000 km (Siemens, 2015). This suggests that a 6000 km HVDC line with the current technology has a better efficiency than pump storage or compressed-air energy storage (Chatzivasileiadis *et al.*, 2014).

DC, therefore, is an enhanced system for long-distance transmission and whilst the largest losses are related to transmission distance of DC there are also losses related to converters which change DC to AC. The range of losses within the convertor is reported to range between 0.6 to 1.7 per cent depending on the type of convertor (Van Hertem and Ghandhari, 2010; Chatzivasileiadis *et al.*, 2013). The loss of electricity is, still, a barrier of DC system, although, this will be improved with time as it is still a continuously developing technology (Van Eeckhout *et al.*, 2010; Larruskain *et al.*, 2014; Vobecky *et al.*, 2015).

Whilst many technical reasons for adopting a DC network exist, there are also non-technical reasons behind selecting DC over AC technology. For example, DC technology offers cables that cause no visual intrusion (unlike above ground pylons) and produce no varying electromagnetic fields (Van Hertem and Ghandhari, 2010). Therefore the approach has much less problems with licensing and construction compared to a traditional AC system (Van Hertem and Ghandhari, 2010). Furthermore, DC technology is more suitable for seabed cables by allowing a fast and relatively cheap cabling as fewer joints are needed (Buijs *et al.*, 2011).

By considering two case studies, within Europe and within the U.S.A and an empirical analysis of ongoing transmission projects, i.e. Supergrids between Europe and the Mideast and North-Africa, Hirschhausen (2012) suggests that HVDC is an appropriate technology for developing the transmission infrastructure.

2.2.4 Summary

As presented in the previous sub-sections, there are various threats and opportunities associated with trading RE via interconnections. Notwithstanding, with further research and effective implementation these risks could be dealt with effectively. For the most part it appears that there is a solid evidence base that describes clearly the many opportunities and advantages for trading electricity via interconnection. In many respects such an approach would help address some of the drawbacks associated with renewable technologies as they are currently being implemented on an *ad hoc* independent country-by-country basis.

2.3 Whole Life Appraisal

2.3.1 Terminology and definitions

Whole Life Appraisal (WLA), also known as Whole Life Costing (WLC), Cost in Use and Life Cycle Costs (LCC) technique, is utilised in this research as a foundation for risk analysis of the various proposed candidate countries. This section reviews the literature on this approach introducing the technique and its various applications.

Flanagan and Jewell (2008) describe that the terminology has changed over the years from "cost in use" to 'LCC' and further to 'WLC'. The authors then provided yet more terminology defining the new term as '*Whole Life Appraisal – WLA*'.

The WLA concept in regards to a pan European super grid deliberates of all relevant costs and revenues associated with the interconnection over its service or design life (Flanagan and Jewell, 2008). It considers the initial capital cost and the running cost of the interconnection and expresses these costs in comparable manner by applying the discounting technique over a time horizon (Flanagan and Jewell, 2008).

The ISO Standard 15686-5 (2008) and also Langdon (2007) help in making a distinction between these approaches and highlight the key differences between the expressions WLC and LCC. They make it explicit that WLC is equivalent to LCC (plus external cost). However, it is admitted that sometimes all terms are being used interchangeably and this poses risks with accurate cross comparisons of projects. The Standard states that "life cycle costing - LCC" should be used to describe a limited analysis of a few components (i.e. the cost calculations themselves) whereas WLC should be adopted as a broader term, which covers a wide range of analyses.

Due to the fact that discussions about terminology causes much confusion in this field this study adopts the WLA definition by Flanagan and Jewell (2008) (highlighted in italics earlier). The literature shows that the most appropriate method for WLA in construction industry is net present value (NPV), the associated discussion by Levander et al. (2009) is presented in Appendix C. As such it is not surprising that when considering studies of the tools adopted in WLA for such projects Kishk et al. (2003) and Kim *et al.*(2014) found that NPV was the most extensively employed method. When dealing with an exhaustible budget or limited capital for developing a new interconnection a further analysis on NPV is suggested which is prioritising interconnections that give the highest NPV per invested pound known as profitability index (PI) (Brealey *et al.*, 1991; Helbæk, 2010).

2.3.2 Applications

WLA can be used as a decision making method, management techniques as well as a maintenance guide. As it declared by Park (2009), WLA is not a new concept, it has been used as a tool since the 1960s and it has become best practice in construction procurement in the last decade (Sorrell, 2003). Due to the increasing complexity and dynamics of construction projects, various aspects, (i.e. time, cost, and quality) need to be considered across the whole life of a constructed asset (Park, 2009).

The main cost saving application of the technique is not only with respect to new projects, but also existing assets (Flanagan and Jewell, 2008). An example of applying WLA on an existing asset is the evaluation of new double or triple glazing for a building, where various parameters such as costs of materials, installations, as well as long term energy savings need to be taken into account.

ISO (2006) states a number of principal benefits associated with application of the WLA technique, these are:

1. *Reduced ownership costs*; by consider operating expenditures before making decisions, the whole supply industry takes a different approach to quality and service.
2. *Reduction of the risk of operating expenditure*; by enabling high operating expenditure elements to be identified at an early stage.
3. *Changing the criteria for option selection*; [WLA provides criteria which can be directly linked to increased asset value and hence improved profitability over the asset life cycle. In contrast traditional criteria for selecting options would have been based upon available technology or lowest price which did not necessarily lead to maximum value for the asset.]
4. *Establishing a framework within which to compare options at all stages of development*

5. *Providing a mechanism by which major cost drivers can be identified, targeted and reduced*

Despite being an application of investment appraisal, WLA does not use some of the more commonly adopted methods, such as payback period. The following sentence from Flanagan and Jewell (2008) states the reason why. "*Money today is not the same as money tomorrow*". The technique which expresses future costs and revenues into present value is called "discounting" (Flanagan and Jewell, 2008).

2.3.3 Limitations

The poor utilisation of the method has been accredited to the (Ibrahim *et al.*, 2010);

a. Complexity of the process,
b. Cost of implementation,
c. Scarcity of reliable historical data,
d. Lack of standard methodology and framework,
e. And the limitations of existing analysis tools.

Of these, scarcity of data is stated as the most challenging since hardly any meaningful interpretation can be made without reliable data (Ibrahim *et al.*, 2010). Subsequently, numerous research have been conducted to mitigate the data scarcity problem by utilising subjective data (Ibrahim *et al.*, 2010; Ammar *et al.*, 2013). Kishk and Al-Hajj (2000) and Ammar *et al.* (2013) proposed an algorithm for the evaluation of subjective data based on Fuzzy Set Theory (FST) based on availability, tangibility and uncertainty. Whilst Boussabaine and Kirkham (2008) outline a methodology for WLC of mechanical and electrical services using Monte Carlo simulation. Ibrahim et al. (2010) adopts a different algorithm which utilizes expert judgments in the absence of reliable historical data. A method mixing the two later approaches is used in this study but as it is mentioned by Manewa et al. (2009) the subjectivity and bias are shortfalls of any approach using professional judgments. Taking this into consideration this challenge within this research has been to address this with a suitable approach. Chapter 3 describes this in more detail.

Moreover, despite conducting numerous research in the area of economic analysis, the practical application of WLA is still being explored (Manewa *et al.*, 2009). Almost all descriptions available for the technique confirm its ability to measure the cost and benefits of a facility, however; the hidden costs or benefits associated with social and environmental issues are not considered. Perhaps the absence of a framework for collecting and storing such related data is one of the reasons for its absence (Levander *et al.*, 2009; Robinson *et al.*, 2015) or perhaps it is merely because economics has historically been (and may remain as) the overarching driver.

Life cycle methods have had limited application, despite its acknowledged importance, and this is due in part to the uncertainty associated with the maintenance and operational cost data (Levander *et al.*, 2009; Flanagan, 2015). That said initial cost estimations cannot be determined easily and reliably, for the simple reason that they do not extend extensively into the future – where changes occur. Levander et al. (2009) deliberate that a risk analysis should be carried out after any WLA model has been developed to address the uncertainty associated with future. As such a broadly similar approach is adopted in this study. The next section, therefore, describes the general concept of the risk assessment the detailed steps of which are described in Chapter 3.

2.4 Risk assessment

Mega projects, such as a pan-European Supergrid are considered as risky businesses due to their complexity, construction time duration and involvements of various disciplines and stakeholders. Allied to this, an interconnection project is notoriously risky because two countries (at least), each with their own policies, are involved. In the past these risks have led to several European projects being postponed for decades (e.g. France-Spain and UK-Norway). A report by Infrastructure UK (IRG, 2013), a unit within the UK Treasury, has undertaken a review of the cost of infrastructure projects in the UK and how this cost can be reduced. The group's research looked at the management of cost risk and uncertainty throughout the project lifecycle and recommends that leading organisations should seek to underpin early stage risk assessment in order to significantly reduce the cost of projects. In part by restricting unnecessary spend, especially of the contingencies allocated for cost uncertainty.

Selecting the most appropriate country with which to make an interconnection, as part of the initial stage of the project, without taking into account the risks and uncertainties cannot be desirable. Apart from engagements of two countries (at least) the other uncertainties will be directly related to, or influenced by, project complexity, construction time (10 years for some seabed interconnections), duration of asset use (40 years or more, see Chatzivasileiadis *et al.* (2013)), inaccuracy in cost estimation and the involvement of various disciplines and stakeholders (Flyvbjerg *et al.*, 2003).

Unfortunately, the construction industry has a poor reputation in risk analysis when compared with other industries such as finance or insurance (Laryea, 2008; Taroun, 2014). Although risk assessment steps have been studied widely, it has been reported as a controversial issue (Baloi and Price, 2003; Taroun, 2014). When considering quantitative and semi-quantitative risk assessment the main challenge for interconnections is data collection, both for assessing impact and probability of risks. This is paramount as construction projects are very often one-off enterprises (Flanagan and Norman, 1993). This issue has led the construction industry to rely only on subjective methods to deal with risk (Taroun, 2014). To overcome this challenge individual knowledge, experience, judgement and rules of thumb should be structured to facilitate risk assessment (Dikmen *et al.*, 2007).

Modelling the risks' probability of occurrence and impact in order to assess the risks is one of the widely used functions of risk assessment. However, the Probability–Impact (P–I) model was subject to criticism with suggestions to improve it. The literature review conducted by Taroun (2014) shows that researchers have investigated different theories, tools and techniques for aiding risk assessment. However, he identified a clear gap between the theory and practice of risk modelling and assessment.

Therefore, it is vital to understand the actual practice of risk analysis and review the development of risk modelling and assessment in order to use the technique effectively in the developed framework and the case study. As a result, the literature review contained herein looks at the history of risk assessment followed by considerations for recent developed techniques and improvements.

2.4.1 Risk assessment history

Risk analysis is not new in construction industry. The development of the Program Evaluation and Review Technique (PERT) was established in the 1950s for tackling uncertainty in project duration (Taroun, 2014). However, the origins of risk management is claimed to go back to as early as 3200 BC in the Tigris-Euphrates valley (Baker *et al.*, 1999). One of the functions of a group people there was to act as risk consultants by identifying the important dimensions of the problem, propose alternative actions, and collect data on the likely outcomes (Baker *et al.*, 1999). The terms "risk analysis" was first used by Hertz (1964) who adopted computers for generating probability distributions of investment projects rates of return. Edwards and Bowen (1998) state that these statistical methods were initially used and were subsequently replaced by Monte Carlo Simulation during the 1970s (see 2.4.1.1) and fuzzy set theory (see 2.4.1.2).

In the 1980s '*risk'* began to be taken more seriously and became embedded as a project feature, as such the term *'Risk Management'* became a well-established project management technique (Taroun, 2014). One of the earliest attempts to structure project risks and identify their sources in a coherent way is presented by Chapman and Cooper (1983) who first introduced the "*Risk Engineering*" approach. This approach integrates different tools and techniques such as the PERT in addition to decision trees, which can be used for combining risk events and producing probability distributions of activities and project durations.

2.4.1.1 Monte Carlo simulation

Simulation is the science of designing a model which acts in the same way as a real system and has similar effects and/or outputs (Flanagan and Norman, 1993). Many systems are too complex for being modelled and undoubtedly this leads to considerable uncertainties. However, Monte Carlo technique can be used for evaluation therein by considering the inputs as random variables, running a number of calculations (so-called simulations) and sampling the input in order to obtain possible outcomes of the wanted result (BSI, 2010). The precise origin of the name is not agreed, but there is general consensus that its roots are related with the games of chance played in the casinos of Monte Carlo (Johansen, 2010).

When the technique was first developed, the number of iterations required for Monte Carlo Simulations (MCS) made the process slow and time consuming, but advanced computers and theoretical developments have made processing time almost insignificant for many applications. As Johansen (2010) describes MSC employs random quantities to provide estimates of deterministic quantities rather than estimating random quantities in a deterministic manner. The simulation considers the fact that all risks and uncertainties can be expected to vary simultaneously and describes the parameters subject to uncertainty by probability distributions (BSI, 2010).

Monte Carlo methods were developed for dealing with numerical problems, although the implementation of the method was complex in the early years of development (for instance see Hastings, 1970). Diekmann (1983) presented one of the earliest attempts of modelling risk using MCS for producing a probabilistic estimate of project cost which suffered from inaccuracies. Later Beeston (1986) provided improvements whereby MCS generate more accurate estimates of risk. A new model by combining MCS and PERT [PERT is used to estimate the probability of completing a project or individual activities by any specified time (Cottrell, 1999)] was introduced by Hull (1990) to assess proposal risks from cost and duration perspectives. Other developments of the method were conducted by E Diekmann (1992) and B

Huseby and Skogen (1992) in two different studies. Each study was sorted to combine influence diagramming and MCS, in order to account for (and then assess) dependencies that existed between different risks. The MSC was used later by Dawood (1998) for estimating an activity or project duration using risk model. A more recent established stochastic method, based on MCS methodology, was developed by the Washington State Department of Transportation for estimating project cost, was presented by Molenaar (2005). The author uses the range cost output to convey project costs by stating that the range estimating output better represents the uncertain nature of project costs prior to design engineering comparing to traditional methods of providing a point estimate. This method was adopted in this study to generate and consider ranges for outputs of the WLA model. This is a suitable approach not least because in financial decision-making processes and techniques, a ‘single’ value is required with a desired achievement possibility assigned. Although there must be recognition that risk assessment can be used to generate a single value from a range of possible final capacities, it requires characteristically subjective judgement without standardisation (IRG, 2013).

BSI (2010) describes a number of statistical methods such as Markov and Bayesian analysis which could have been used instead of the MCA chosen for this research. The Markov analysis is not helpful for the analysis of interconnections risk as it is more appropriate for the analysis of repairable systems where the future state of a system depends only upon its present state and probabilities of the state of the system moving from one state to another depend on the present state. Bayesian analysis however might be used as an alternative to Monte Carlo analysis. Bayesian statistics differs from classical statistics (and is similar to the Monte Carlo) in that is does not assume that all distribution parameters are fixed, but that parameters are variables. Bayesian statistics have been utilised widely for: medical diagnosis, image modelling, genetics, speech recognition, economics, space exploration and in the powerful web search engines used today (BSI, 2010). The inputs are similar to the inputs for a Monte Carlo mode. Bayesian analysis uses Bayes’ net to show the dependencies and interactions between various components which is used to estimate the risk probability. Defining all interactions in Bayes nets for complex systems is one of the drawbacks of the method. Expert judgment was also needed to provide the knowledge of a multitude of conditional probabilities.

2.4.1.2 Fuzzy Set Theory

Probability theory based tools and MCS continued to control risk assessment In the 1980s (Taroun, 2014). However, Fuzzy Sets Theory (FST) was not introduced until a decade later and provided a viable alternative for dealing with subjectivity in construction risk assessment (Zimmermann, 2001).

The concept of FST was developed by Lotfi Zadeh in 1965 to represent the uncertainty. Zadeh (1965) defines a fuzzy set as a class of objects with a variety of grades of membership and each object is graded a membership ranging between zero and one. One stands for complete belonging and zero stands for complete non-belonging. Hence, the key difference between FST and the traditional set theory (known as crisp set theory) is the partial belonging to a set comparing to a complete belonging or complete non-belonging to a set in the crisp set theory (Liu *et al.*, 2002).

Kangari and Riggs (1989) deliberates the usage of FST in risk assessment by presenting an objective evaluation of the advantages and limitations of FST for assessing construction risk. FST different theories were investigated during the 1990s to account for the special nature of construction risk, and in the last decade risk assessment became a hot research topic.

Since 2000, FST has become the principal approach for handling complex obstacles where subjectivity is involved (Taroun, 2014). Baloi and Price (2003) reviews various techniques and methodologies for assessing risk and concluded that FST was a key tool highly relevant for the construction industry. Zhang and Zou (2007) combined the strengths of FST and Analytical Hierarchy Process (AHP) technique, which is used to structure a large number of risks, for assessing risks in joint venture construction projects in China. However, Taroun (2014) believes that both techniques have limitations and these are not necessarily overcome by utilising them together.

2.4.2 Recent developments and findings

Some previous attempts to combine all of these various techniques have been repeated in the last few years. For instance, Nieto-Morote and Ruz-Vila (2011) combined the strength of AHP and FST, similar to Zhang and Zou (2007) study, in order to address the complexity and subjectivity of construction risk assessment. They used linguistic terms to assess risk probability and impact and to assess the mixture of quantitative and qualitative data. The most notable differences between their approach and other fuzzy risk assessment methods are the use of an algorithm to handle the inconsistencies in the fuzzy preference relation when pair-wise comparison judgements are necessary. Cheikh et al. (2013) also introduces a new mathematical model based on FST for selecting the preferred investment options.

Aven and Krohn (2014) question the reliability of current definition of probability by using the Fukushima Daiichi nuclear disaster in Japan in March 2011 as a case study. They show that the disaster happened because of categorising the risk as acceptable by ranking the magnitude of the tsunami as unlikely. They concluded that in order to assess and manage such events. A process that goes 'beyond' probabilities is therefore needed allowing a broader risk perspective to be achieved. They suggest a combination of the High Reliability Organisations method with ideas from the quality management.

In this research the risks related to the construction and operation of interconnections cannot be disassociated from uncertainties of energy projections. Therefore the next section looks at these in more detail.

2.4.3 Uncertainty in energy projections

A variety of methods have been adopted around the globe by many researchers to analyse future energy supply/demand and model associated risks (where definition and probabilistic assignment can be achieved) and uncertainties (where description without probabilistic assignment can be achieved), see for example Luo *et al.* (2014), Song et al. (2013) and Kearns et al. (2012). More than 40 years ago Salter (1973) described a probabilistic forecasting methodology in which stochastic data and subjective probability estimates were used to achieve a probabilistically stated forecast at a future time frame (the year 2000) for electricity consumption of the USA. The probabilistic (rather than deterministic) approach allowed for quantification of relative risks associated with alternative energy strategies to be highlighted, which could then be converted to planning decisions. More recently, similar analyses have been used to allocate probabilities to uncertainty regarding future temperature(s) and their impact on energy supply and demand in the USA when implementing cryogenic carbon dioxide capture (Hamlet *et al.*, 2010).

In contrast, researchers in the UK have identified risks and uncertainties associated with four different future scenarios (i.e. low carbon dioxide, low carbon dioxide resilient, reference and resilient), adopting analytical tools (e.g. Markal, Wasp and CGEN) in order to build a resilient UK energy system (Chaudry *et al.*, 2011). Therein probabilities were not attached to energy scenarios, but a methodology for implementing such a procedure was described in detail (see Morgan and Keith, 2008, p196).

With respect to interconnections various deterministic techniques and methods for calculating capacities are increasingly being introduced and adopted (e.g. Denny *et al.*, 2010; Georgiou *et al.*, 2011; Timilsina *et al.*, 2015). However, it appears that literature on the risks and uncertainties of interconnections is much less well developed. While economists such as Parail (2010b) have introduced a probabilistic methodology to add economic uncertainty to electricity trading by way of interconnections, this has not been extended to uncertainties associated with generating surplus electricity. In simple terms they do not take into account other uncertainties such as social, technical, environmental and political, a shortfall which this piece of research aims to address.

Taking all of these in combinations as outlined within the methodology (Chapter 3) it is possible to provide a much broader assessment for interconnections. In order to achieve this focus has been on adopting a probabilistic approach for estimating surplus electricity.

The theoretical framework presented in this thesis goes a significant way towards filling a gap in knowledge and allows risk assessment to be undertaken in the appraisal stage of a project. This is a significant step towards assessing the most appropriate country that the UK should interconnect with (and thus also identifying the least suitable partner countries).

3 METHODOLOGY

The literature review demonstrated that there has been no definitive piece of research to develop a risk-based framework which, despite the recognised need, can be used to select the most appropriate country (ies) with which to make electricity interconnections. To address this shortfall, this chapter presents the research methodology developed to establish a new theoretical framework to identify and assess risks associated with interconnections. The chapter consists of three discrete parts:

(1) Research Methodology (Section 3.1); which describes the methodology used to conduct the research;

(2) Theoretical Framework (Section 3.13.2); which explains the theories and factors which must be considered together in order to select the most appropriate country with which to form an interconnection; and lastly

(3) Application of the theoretical framework (Section 3.3); which describes the process used to apply the developed framework to a case study.

3.1 Research Methodology

An overview of the research methodology which is described herein is shown in Figure 7. At the outset of the research the aims and objectives were identified which facilitated the development of a general methodological approach to the research. A comprehensive literature review was carried out to; i) better understand available renewable energy technologies and the process of trading electricity via interconnections; and, ii) identify and assess whole life cycle analysis approaches and risk assessment methods. A risk-based framework was then developed based on the findings from the literature. Subsequently with the involvement of experts specific aspects of the risk-based framework were augmented and tested via a case study. In parallel to the development of the theoretical framework, in order to generate future energy supply/demand scenarios, which could be used for assessing the capacity of interconnections, a prototype tool was developed. The aforementioned stages are described further below:

1. Review of relevant literature on renewable energy technologies. This was carried out to understand the benefits of interconnections regarding enhancing harnessing renewables. Thereafter, trading electricity via interconnections and risk associated with inter-

connections were studied in detail. This part of the research has been fully described in Chapter 2.

2. Select appropriate assessment techniques. The literature was reviewed to identify the most suitable techniques to be used within a risk-based framework, for selecting the most appropriate country with which to make an interconnection. The focus was on identifying suitable techniques which could be used within a risk-based WLA approach. The literature review helped to identify, understand and investigate the components of the risk-based framework. Chapter 2 deals with this aspect of the research.
3. Development of the risk-based framework. The framework was developed based on a WLA approach which utilised the Net Present Value (NPV) technique to rank candidate countries with which to make an interconnection. The NPV technique was couched within a risk based framework to enable uncertainties associated with costs and benefits to be considered. The framework is described more fully below.
4. Prototype tool. A prototype tool was developed to generate energy supply/demand scenarios and to assess the capacity of interconnects.

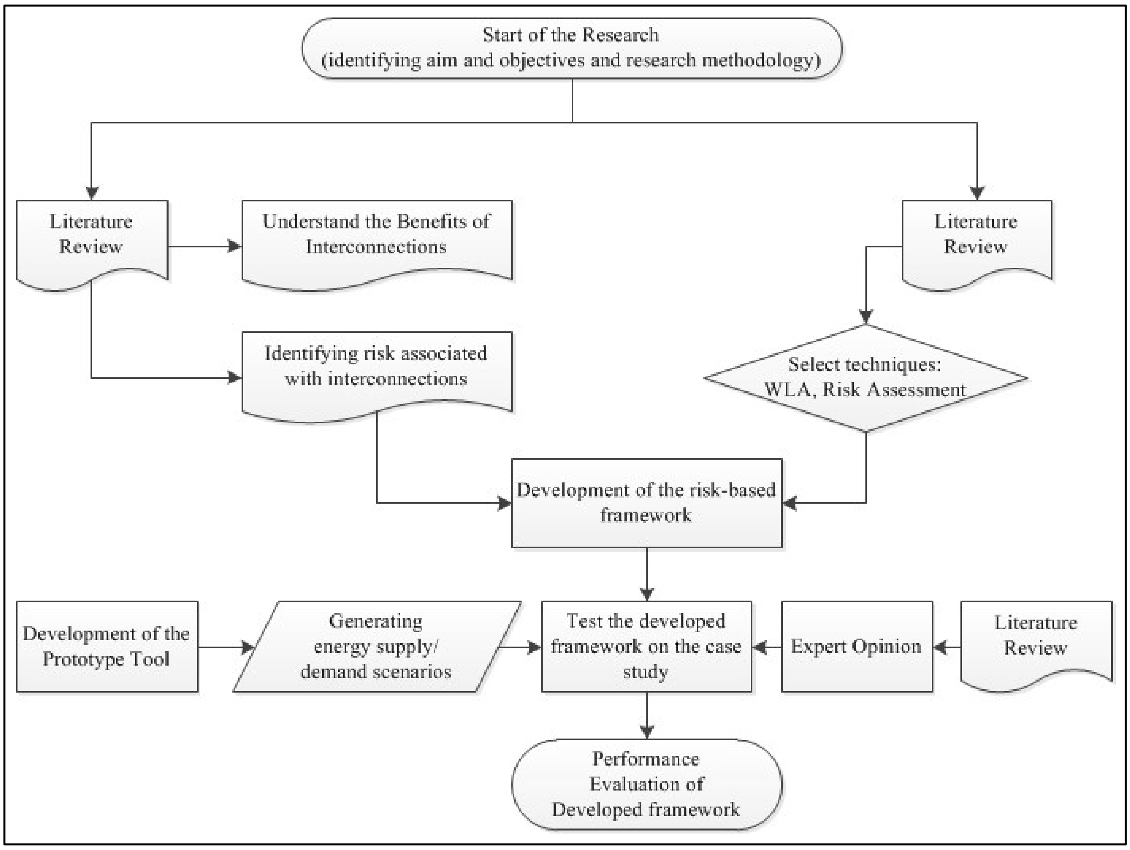


Figure 7: Research Methodology

5. Evaluation of the performance of the developed framework via a case study. The developed framework was demonstrated via a case study (based on the UK) in order to assess the risk costs of making interconnections with the UK's neighbouring countries.
6. Use of expert opinion in the case study. Data collection process in the case study was conducted by utilising expert opinion to augment a literature review. This process has been fully described in Section 2.

3.2 Theoretical Framework

Three main factors are considered in order to select the most appropriate countries with which to establish an interconnection. These are:

1. Meeting energy demand
2. Minimising the CO_2 emissions and
3. Minimising the cost risk of making interconnections

The first two factors can be considered in terms of the availability of RE in the candidate country. Therefore the ideal for an interconnection would be to choose the country (ies) with the maximum RE availability and minimum cost of establishing an interconnection. A simple approach therefore could be to select the country with the maximum current RE share and with the minimum length of interconnection as a proxy for construction cost. However, there are risks associated with both the availability of RE and the construction cost(s) which have to be considered in order to make a reliable decision. In addition, relying on the current availability of supply has high risk and uncertainty when considering typical construction and lifetime durations of 10 and 40 years respectively for some interconnections. To address these concerns, a framework, illustrated in Figure 8 and consisting of three main stages was explored and developed in this research. The stages for consideration were:

Stage 1: Selecting candidate countries (see Section 3.2.1)
Stage 2: Whole life Appraisal –WLA (see Section 3.2.2)
Stage 3: Risk assessment (see Section 3.2.3).

These are now described in detail.

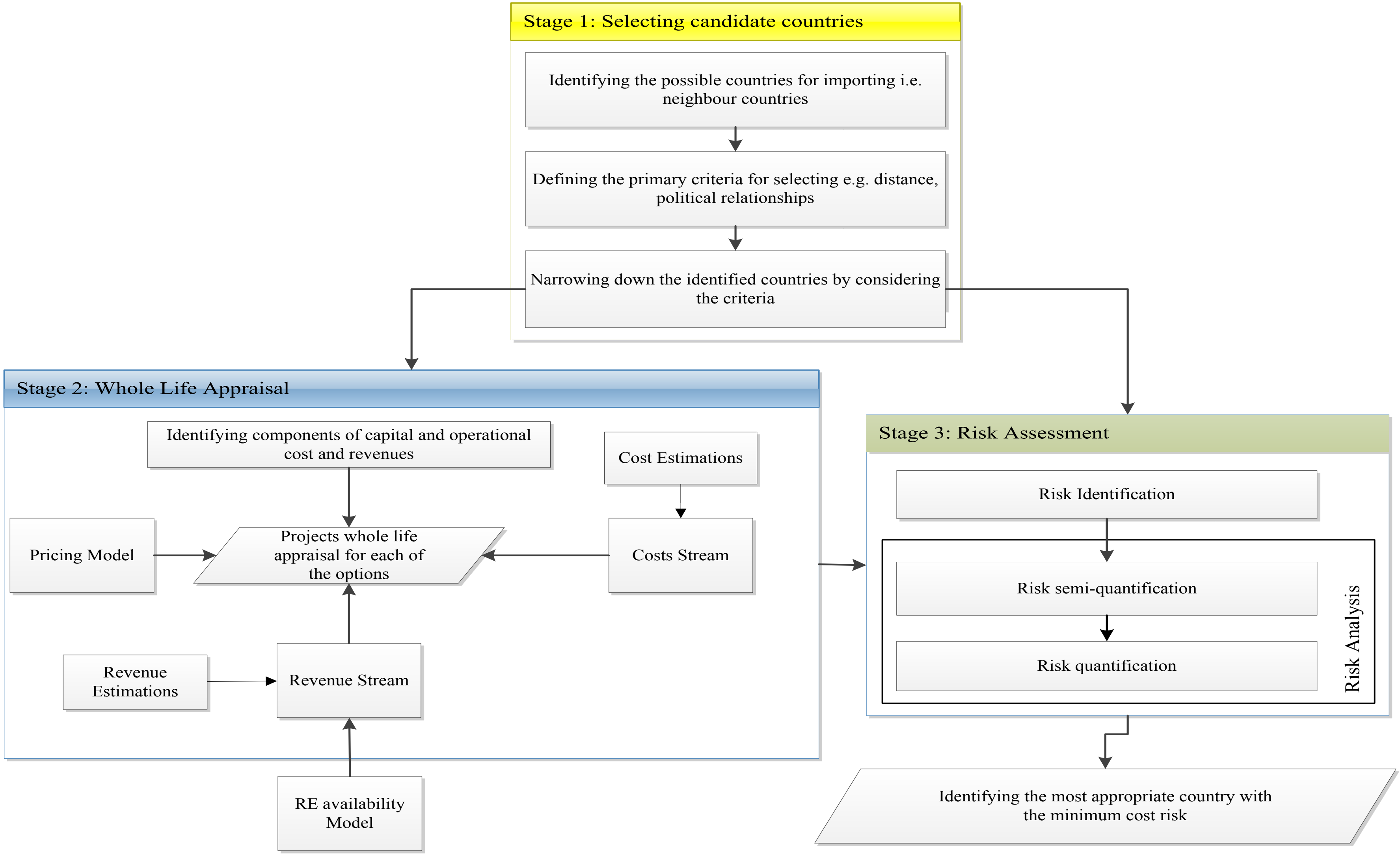


Figure 8: Theoretical framework for selecting the most appropriate country (ies) with which to make an interconnection

3.2.1 Stage 1: Selecting candidate countries; Initial screening

This stage is used to carry out a pre-screening exercise by which unsuitable countries can be identified and excluded from further analysis. This is required due to various political, economic and/or social situations and conditions which may affect any related decision. For example, a potential electricity producing country with major political conflicts would be precluded from further consideration at this stage and at this time. That is not to say that future consideration could not be made if the situation were to change. This stage is therefore used to identify the specific consideration and to apply them.

In contrast the selection criteria for other countries could be more technical or economic in nature. For instance, considering countries only within a specific radius of a country (as cost proxy related to the distance over which an interconnection needs to be made). In order to obtain the required information to carry out technical or economic evaluations, published information could be augmented with the opinion of various stakeholders such as politicians, scientists and economists.

Another criterion considered herein for selecting candidate countries is related to CO_2 emission savings. The emissions associated with the interconnection include that embodied within the infrastructure (including the cables) and that associated with maintenance, i.e. short term and long term emissions. By comparing the life cycle emissions of the cable per kilometre (which is a function of the type of cable) with the emissions from the various electricity generation technologies with the same capacities a threshold in terms of kilometre can be calculated. This approach was considered to be appropriate and subsequently was applied to the case study.

3.2.2 Stage 2: Whole life appraisal (WLA)

This stage considers Whole Life Appraisal. As outlined in the Literature Review chapter (Chapter 2) WLA is a useful technique for making an effective choice between various competing options and has been used, as part of the overarching framework for comparing candidate countries.

The requirements of the WLA used in this research were (developed from Flanagan and Jewell, 2008):

1. Identification of an overall time period or whole life of the interconnections
2. Collecting the costs and revenues associated with the interconnections

3. Considering only those costs and revenues which have direct impact on the project. Therefore, there is no need to consider for example the jobs which can be generated by construction of the interconnections.
4. Considering the effect of time on the interconnections;
    a. The impact of inflation
    b. The fact that the money spent or received in the future is worth less than the money spent or received today (utilising discount rate)

The discount rate used for project appraisal is an after-tax rate of interest that must be earned (expected to be earned) on investment costs over the period, whilst many firms use an ideal cost of capital as their discount rate (Dennis-Escoffier and Fortin, 2007). This requires careful consideration when making comparisons across members states (within this study) because the ideal cost of capital can differ annually and by country depending on cost of debt and equity. The other factor which influences the choice of an appropriate discount rate is inflation which varies by country.

Three source of data are required to ensure that the WLA is appropriate and accurate (Flanagan and Jewell, 2008), these are;

1. Experts
2. Modelling techniques and
3. Historical data.

As WLA of an interconnection can be complex, it was decided in this research to adopt a simplified approach consisting of its essential component parts. This included consideration of the impact of the integrated (or interconnected) market on the level and volatility of electricity prices (Pricing model). This model takes into account the parameters such as changes in fuel prices (oil, gas and coal) and penetration of renewables such as wind energy (see Parail, 2010b as an example). A second model was developed to forecast the availability of RE and the demand (RE availability model) in both involved countries. The model reveals the demand for the imported RE and the amount of the spare RE for being traded for all countries considered. The availability of RE for both involved countries is used to estimate the appropriate scenarios for the interconnection's revenue. A further model is required to forecast the costs of the interconnections including the construction and maintenance of the system (Cost stream).

The cost estimation (and also the other revenue streams) should be recorded to avoid double counting for risk costs, so for instance, if the uncertainties related to pricing of RE is already considered in the WLA model it should not be quantified separately in the risk quantification stage as a risk.

The development of an ideal WLA model, including the aforementioned components, requires a team of experts in various disciplines including economics and the associated technologies.

3.2.3 Stage 3: Risk assessment

One of the main purposes of utilising risk assessment is to provide evidence-based information and analysis to make informed decisions regarding the choice of candidate countries. Some of the benefits of applying this concept, include the ability to (BSI, 2010):

1. Understand the associated risks and their potential impacts on the cost of interconnections
2. Provide information for the decision makers regarding risks
3. Compare the risks in alternative countries
4. Provide information that will help evaluate whether the risk should be accepted when compared to pre-defined criteria.

Risk assessment consists of three stages (BSI, 2010):

1. Risk identification (Section 3.2.3.1),
2. Risk semi-quantification (Section 3.2.3.2) and
3. Risk quantification (Section 3.2.3.3)

These stages are used to provide an understanding of risks associated with construction and maintenance of interconnection, their causes, consequences and their probabilities. The risk semi-quantification and risk quantification stages are collectively known as risk analysis (BSI, 2010). Each of these is now described in detail.

3.2.3.1 Risk identification

The process of finding and recognising risks is known as risk identification (BSI, 2010). The aim of this stage is to identify what might happen or what circumstances might exist that might affect the output and achievements of building interconnections and trading RE.

Three main methods are used to identify risks namely (BSI, 2010):

a) Evidence based methods; such as check-lists and reviews of historical data
b) Systematic team approaches; where a team of experts follow a systematic process to identify risks by means of a structured set of prompts or questions

c) Inductive reasoning techniques such as Hazard and Operability study (HAZOP).

Methods (a) and (b) were used for the case study to avoid subjectivity that may occur by adopting only one of the methods and to achieve adequate validity and reliability (see Section 3.3.6.1 for the limitations associated with qualitative methods). Inductive reasoning techniques were not selected as they can be very time-consuming and a detailed analysis requires a high level of documentation (BSI, 2010).

3.2.3.2 Risk semi- quantification

In this stage understanding of the risk is developed further in order that it provides an input to decisions on dealing with risks in the quantification stage (BSI, 2010). In other words risk semi-quantification determines the consequences and their probabilities for identified risks drawn from Stage 1. These are then combined to determine a level of risk.

The process includes mapping identified risks to the activities of both building and maintaining interconnections. In such cases a risk can have multiple consequences and can affect multiple activities. There are various techniques and methods available for these analyses and more than one technique may be required for complex applications (BSI, 2010).

In this process an estimation is made of the range of potential consequences that might arise from an event, situation or circumstance, such as electricity blackout, and their associated probabilities, in order to measure the level of risk. Semi-quantitative methods use integer rating scales for consequence and probability and combine them to produce a level of risk.

The British Standard Institute (BSI) (2011) defines risk as the probability or threat of an event on a system. Accordingly, the base measure of risk is commonly evaluated in terms of the likelihood, or probability, of an event occurring by the magnitude, or impact, of the event (BSI, 2010):

$$Risk = (probability \times impact) \tag{1}$$

This is the approach adopted within this study where levels of risk are expressed in the most suitable terms for that type of risk and in a form that aids risk evaluation such as a probability distribution over a range of consequences.

3.2.3.3 Risk quantification

In this stage quantitative analysis is used to estimate practical values for consequences and their probabilities. These are used to produce values of the level of risk in specific units (BSI, 2010). There are however some barriers for conducting the full quantitative analysis such as; lack of data or influence of human factors or when the effort of quantitative analysis is not required. In such circumstances, which was not the case in this research, a comparative semi-quantitative or qualitative ranking of risks by specialists, knowledgeable in their respective field, may still be effective (BSI, 2010).

Chapman and Ward (2004) discussed that an effective risk assessment is necessarily a qualitative identifying process early on and a more quantitative evaluating process later on. Following this process, results of the qualitative method, risk identification, was used within this study to develop and inform the quantitative risk analysis, (see Bergman, 2008; Creswell and Creswell, 2009). A mixture of qualitative and quantitative methods were, therefore, utilised in order to allow for a better understanding of the problem rather than using either method alone (Creswell and Clark, 2010). The mixed method adopted within the framework is demonstrated in Figure 9.

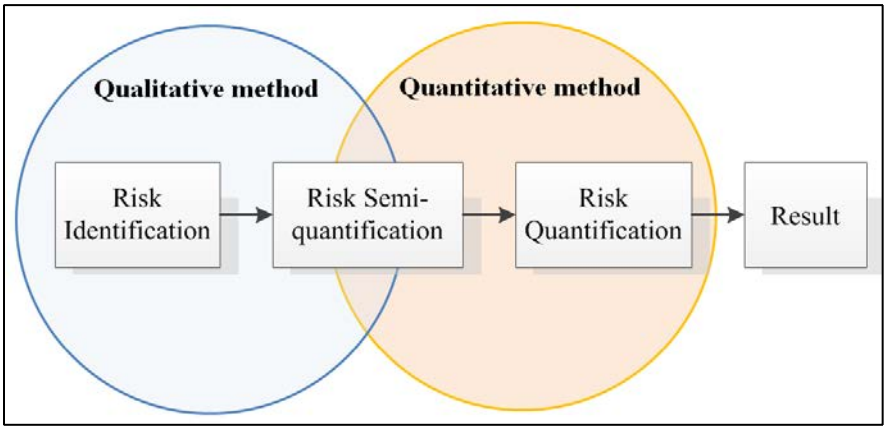


Figure 9: The method used in the case study

The mixed method was adopted within the risk assessment process in order to provide a robust comparison between various candidate countries for making interconnections. This is described in detail for the case study in Chapter 6.

In brief, the qualitative method adopted within this study is used to describe a situation or problem by establishing the variation in the situation without quantifying it (Kumar, 2010). As such integral to the aim of this adopted method is to collect a range of viewpoints on a subject or an event from various participants (Creswell, 2009; Denzin and Lincoln, 2011).

In contrast a quantitative approach, is used to add an exact value on the magnitude of the variation related to these viewpoints (Kumar, 2010). This is a useful method for testing, verifying or comparing options (Creswell, 2009).

3.2.4 Selecting the most appropriate country (ies)

The last stage involves comparing estimated levels of risk between various countries, in order to select the best options with minimum cost risk.

3.3 Application of theoretical framework

This section illustrates how the theoretical framework has been applied to a case study which considers the prospects of the UK trading RE via interconnections with a number of other European countries. The associated process is illustrated in detail in Figure 10. Chapters 4, 5 and 6 describe the outcome of the case study.

3.3.1 Initial screening

Within the process of initial screening distance is considered to be a major driver of cost regarding both construction and maintenance of an interconnection as it directly links to cable cost (including cable installation) which is the most costly component of an interconnection construction process (Chapter 6.2). The operation cost is mainly due to electricity loss which is exacerbated by having longer distance transmission.

The UK currently has a stable relationship with its neighbouring countries, therefore political consideration was not deliberated as a criterion for the initial screening of candidate countries. However, in risk analysis stage all other criteria including political were considered.

Lifecycle CO_2 emissions, as an important environmental factor, were also considered as a criterion in the case study for the initial screening, the details of which are presented in Section 4.1.1.

3.3.2 Whole life appraisal

Within the process of whole life appraisal cost streams (Section 3.3.2.1) and revenue streams (Section 3.3.2.2) were developed drawing from historical data and expert opinion for data collection where applicable.

3.3.2.1 The cost stream

Expert judgment and historic data were used for developing the cost stream. A literature review was conducted for collecting the relevant historic data. Then a group of experts was consulted to verify and augment the findings.

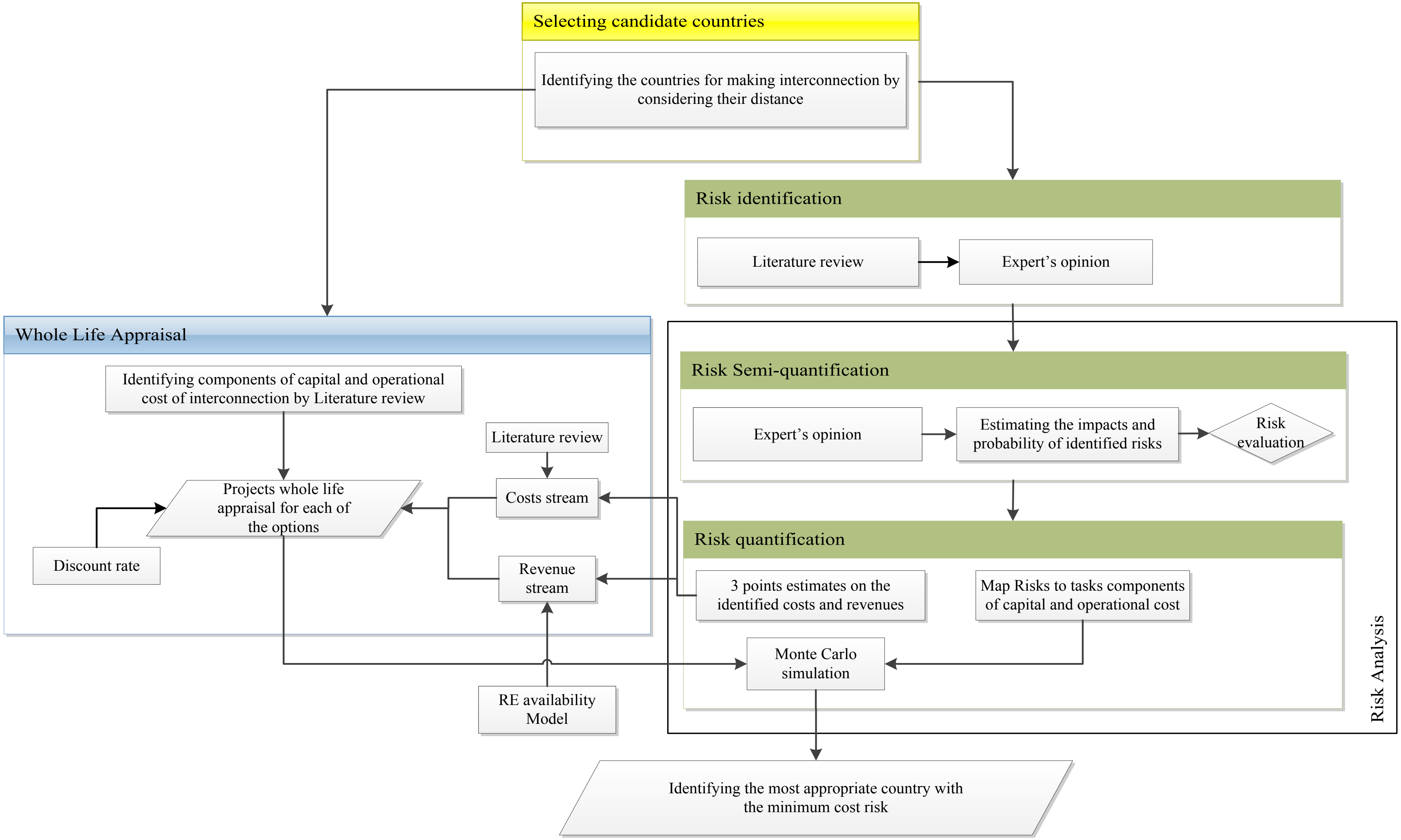


Figure 10: Application of theoretical framework

3.3.2.2 The revenue stream

As discussed above there was a need to project the availability of RE in both involved countries to assess the capacity of an interconnection (in terms of GW of energy as well as its availability in terms of GWh and a percentage of capacity). A scenario based approach was used in this research for RE availability projection (for further details see Section 4.2). In brief scenarios analysis is the development of descriptive models for how the future energy mixture might turn out and is a useful tool to help decision-makers visualise the future (BSI, 2010; Boyko *et al.*, 2012). There are many projections (some of which involve trend analysis) developed within a range of studies considering a number of countries' future energy supply. For example in the UK Ault et al. (2008), Barnacle et al. (2012), Poyry (2008), CCC (2012) look at UK future energy needs over the coming decades. Therefore the challenge for this study was to identify and adopt the most suitable projection. Therefore a literature review was conducted to find the extreme possible scenarios which led to developing a tool. The aim of the tool was to provide a range of energy supply / demand scenarios. Section 4.2.1.1 describes the developed tool in more detail.

The energy supply / demand scenarios were used to estimates the availability of RE during the whole life of interconnections. Having calculated available RE in this way, a literature review was used to estimate the future price of RE in order to complete the revenue stream. Expert judgment was used to verify the approach and augment the information obtained.

3.3.3 Risk identification

A qualitative method was used in the case study to identify risks related to construction and operation of interconnections. The literature review was utilised to identify major categories of risks associated with seabed interconnections thereafter this was augmented by canvassing the opinion of a group of experts. In line with British Standard (BSI, 2010) and best practice the identified risk(s) were categorised according to key drivers of change:

1. Social (S)
2. Technical (T)
3. Economic (E)
4. Environmental (E)
5. Political (P)

These five categories of risks, known as STEEP factors (Morrison, 2006; Hunt *et al.*, 2012), are often used during a project's feasibility analysis stage (Millington, 2000;

Thompson, 2005; John W. Brockhouse and Wadsworth, 2010). The categorisation of risks into STEEP factors is practical as well as simple and comprehensive (Khumpaisal *et al.*, 2010). An example of identified risk(s) for an interconnection is illustrated in Table 13. These risks are assigned as construction and operation risks.

Table 13: Example of identified risk for an interconnection project

	Risk category	Example of Identified risk	Applicable to seabed cable only
Construction risks	Social	Public acceptability	
	Technical	Loss of Dynamic Positioning (DP)	√
		Earthquake	
		Seabed topography	√
		Anchoring damages, kinks and loading/re-loading	√
		Seabed contamination	√
		Unforeseen ship wrecks and other submarine debris	√
		Fishing activities and ship anchoring	√
	Economic	Uncertainty in cost estimation (quantity and rates)	
		Supply chain; contractor	
		Solvency of contractor	
		Inflated bid price	
		Cost of material	
	Environmental	Disturbing habitats and ecosystems	
		Climate change	
	Political	Changes in energy policy of candidate country, regulatory	
Operational risks	Social	Demonstrations caused by raised price	
	Technical	Availability of electricity from renewable resources	
		Earthquake	
		Fishing activities and ship anchoring	√
		Climate Change	
	Environmental	Disturbing habitats and ecosystems	
	Economic	Increase in prices of imported electricity	
	Political	Changes in energy policy	
		Security of renewable energy supply	
		War	

3.3.4 Risk semi-quantification

To evaluate the risk exposure to the project, each risk was semi-quantified according to its probability and impact. This stage included an estimate derived using a scoring approach on an integer scale. Risk scoring was used to rate the identified risks using similar criteria so that they can be compared objectively.

A semi-quantification risk matrix (consequence/probability matrix) was used to rank identified risks on the basis of prioritising them according to their exposure. Furthermore the process allowed for a filtering process by which risks that needed more detailed analysis could be identified (see Figure 11). A qualitative approach was used to develop a set of criteria, as shown in Figure 11, which could be used by the experts (who may not be used to risk analysis or simply did not have a quantitative judgment (the alternative option in the risk matrix) or knowledge in order to assist in obtaining the probability of an event occurring and its resultant impact.

BS (2010) introduces three general approaches to estimate probability and consequences namely:

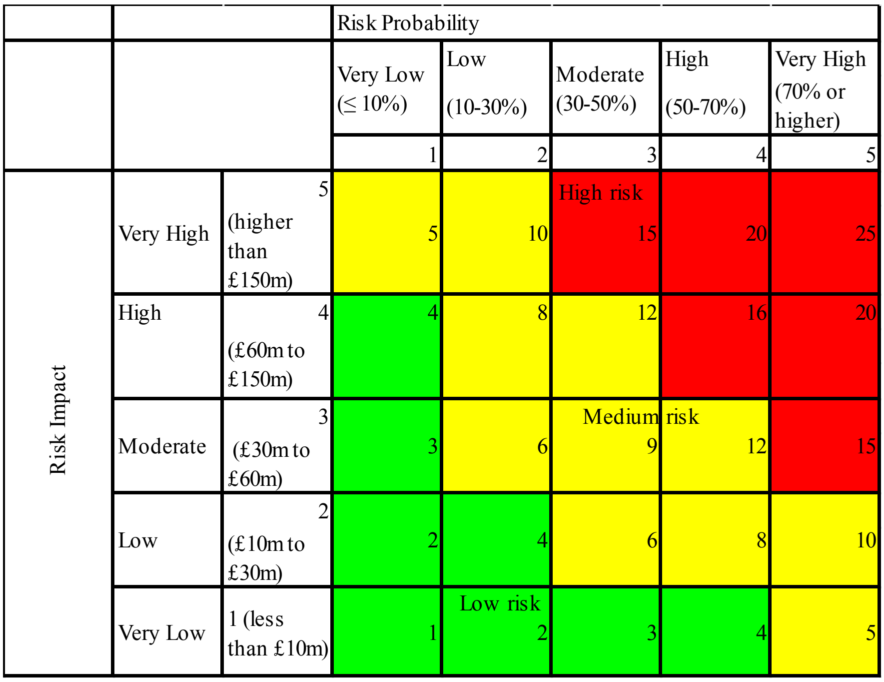
a) Use of relevant historical data
b) Probability forecasts using predictive models
c) Expert opinion in a systematic and structured process.

Where no historical data or developed probability models were available risk probability and impact was estimated in this study using expert opinion. Subjective estimates of probability ranges may be applied in this way when appropriate data is not available (Chapman and Ward, 2004). In some cases relevant past experience is available but the appropriate data may not have been collected, may not exist in required quantity or detail or may not have been collected accurately (Chapman and Ward, 2004).

Within this approach an expert is defined as an individual who has some degree of training, experience and/or education greater than general population (Flanagan and Norman, 1993). In order to avoid any possible bias which is a disadvantage of using experts' opinion, experts with different backgrounds were selected. Section 3.3.5.2 presents more information on the participants' background.

There are various techniques available for eliciting expert judgment such as the Delphi technique, paired comparisons and category rating (BSI, 2010). However, in this research it was decided to use a structured interview to collect the expert judgment on probabilities and consequences of risks. Structured interview was selected as it has been recommended by BSI (2010) for dealing with risks with a low level of time and cost related to conducting the method, information availability and the complexity involved, which all meet the requirements of the case study (see Section 3.3.5).

A matrix (see Figure 11) was employed as a screening tool to identify the most significant risks and to exclude less significant or minor risks from further quantitative analysis. The purpose was to ensure that the quantitative risk analysis focussed on those which were deemed most important.



			Risk Probability				
			Very Low (≤ 10%)	Low (10-30%)	Moderate (30-50%)	High (50-70%)	Very High (70% or higher)
			1	2	3	4	5
Risk Impact	Very High	5 (higher than £150m)	5	10	High risk 15	20	25
	High	4 (£60m to £150m)	4	8	12	16	20
	Moderate	3 (£30m to £60m)	3	6	Medium 9	risk 12	15
	Low	2 (£10m to £30m)	2	4	6	8	10
	Very Low	1 (less than £10m)	1	Low risk 2	3	4	5

Figure 11: Risk matrix, source Eskandari Torbaghan *et al.* (2015)

The risk identification and semi-quantification stages described above were elicited by means of structured interviews and questionnaires to identify the risks and to estimate the impact and probability of the risks. The questionnaire and backgrounds of the experts who participated in this study are described in the next section.

3.3.5 Expert opinion

Expert opinion can be used in a systematic and structured process for data collection in a risk assessment process. Expert judgements should draw upon all relevant available information including historical data in that process. There are a number of formal methods suggested by BSI (2010) for obtaining expert judgement providing an aid to the formulation of appropriate questions and include the use of questionnaires, structured interviews, brainstorming and the Delphi technique. The attributes and relative merits of these with respect to risk identification and semi quantification are described in Table 14 (BSI, 2010).

The attributes of the methods are described in Table 14 in terms of:

- the extent of resources required in terms of time and level of expertise, data needs or cost,
- the nature and degree of uncertainty of the risk assessment based on the amount of information available and what is required to satisfy objectives,
- complexity of the problem and the methods needed to analyse it.

Of the techniques presented in Table 14, Scenario analysis, Function analysis and Statistical methods groups require historical data (i.e. at the minimum for the probability) and as those historical data were unavailable for the case study they were excluded as an option. Of the remaining four methods, brainstorming, the Delphi and structured "what-if" (SWIFT) techniques could not be utilized as they require a team of experts to work collaboratively which was not achievable for this PhD study. Therefore the structured interview was adopted to facilitate risk identification and semi-quantification. The structured interview process was implemented by using a questionnaire described below.

As shown in Table 14, structured interviews are recommended for dealing with risks with a low level of time and cost related to conducting the method, information availability and the complexity involved, which all meet the requirements of the case study.

This section provides the types of questions asked within the questionnaire as well as the backgrounds of the experts who participated in this study. Reliability of the questionnaires results regarding the semi-quantitative stage are also discussed in this section.

Table 14: Attributes of a selection of risk assessment tools, source BSI (2010)

Type of risk assessment technique	Description	Relevance of influencing factors		
		Resources and capability	Nature and degree of uncertainty	Complexity
SUPPORTING METHODS				
Structured Interview and brainstorming	A means of collecting a broad set of ideas and evaluation, ranking them by a team. Brainstorming may be stimulated by prompts or by one-on-one and one-on-many interview techniques	Low	Low	Low
Delphi technique	A means of combining expert opinion that may support the source and influence identification, probability and consequence estimation and risk evaluation. It is a collaborative technique for building consensus among experts. Involving independent analysis and voting by experts	Medium	Medium	Medium
SWIFT (Structured "what-if")	A system for prompting a team to identify risks. Normally used within a facilitated workshop. Normally linked to a risk analysis and evaluation technique	Medium	Medium	Any
SCENARIO ANALYSIS				
Fault tree analysis	A technique which starts with the undesired event (top event) and determines all the ways in which it could occur. These are displayed graphically in a logical tree diagram. Once the fault tree has been developed, consideration should be given to ways of reducing or eliminating potential causes / sources	High	High	Medium
Event tree analysis	Using inductive reasoning to translate probabilities of different initiating events into possible outcomes	Medium	Medium	Medium
Cause-and effect analysis	An effect can have a number of contributory factors which may be grouped into different categories. Contributory factors are identified often through brainstorming and displayed in a tree structure or fishbone diagram	Low	Low	Medium
FUNCTION ANALYSIS				
FMEA	FMEA (Failure Mode and Effect Analysis) is a technique which identifies failure modes and mechanisms, and their effects. FMEA may be followed by a criticality analysis which defines the significance of each failure mode, qualitatively, semi-qualitatively, or quantitatively. The criticality analysis may be based on the probability that the failure mode will result in system failure, or the level of risk associated with the failure mode, or a risk priority number	Medium	Medium	Medium
STATISTICAL METHODS				
Bayesian analysis	A statistical procedure which utilizes prior distribution data to assess the probability of the result. Bayesian analysis depends upon the accuracy of the prior distribution to deduce an accurate result. Bayesian belief networks model cause-and-effect in a variety of domains by capturing probabilistic relationships of variable inputs to derive a result	High	Low	High

3.3.5.1 Questionnaire

The questionnaire was designed in a spreadsheet format to obtain the following types of data during a structured interview session:

1. Risk Identification
2. Estimating impact and probability associated with identified risks (risk semi-quantification stage)

The questionnaire was checked and evaluated through a pilot study which was used to correct and enhance the structure, content and format of the questionnaire. Interviews were selected for data collection rather than sending the questionnaire to provide the opportunity for the conductor to describe the identified risks in more details and also to explain the risk assessment procedure in order to obtain more reliable answers from experts. The one-to-one communication facilitated by this method allowed for an in-depth consideration of the associated issues.

1. Risk Identification

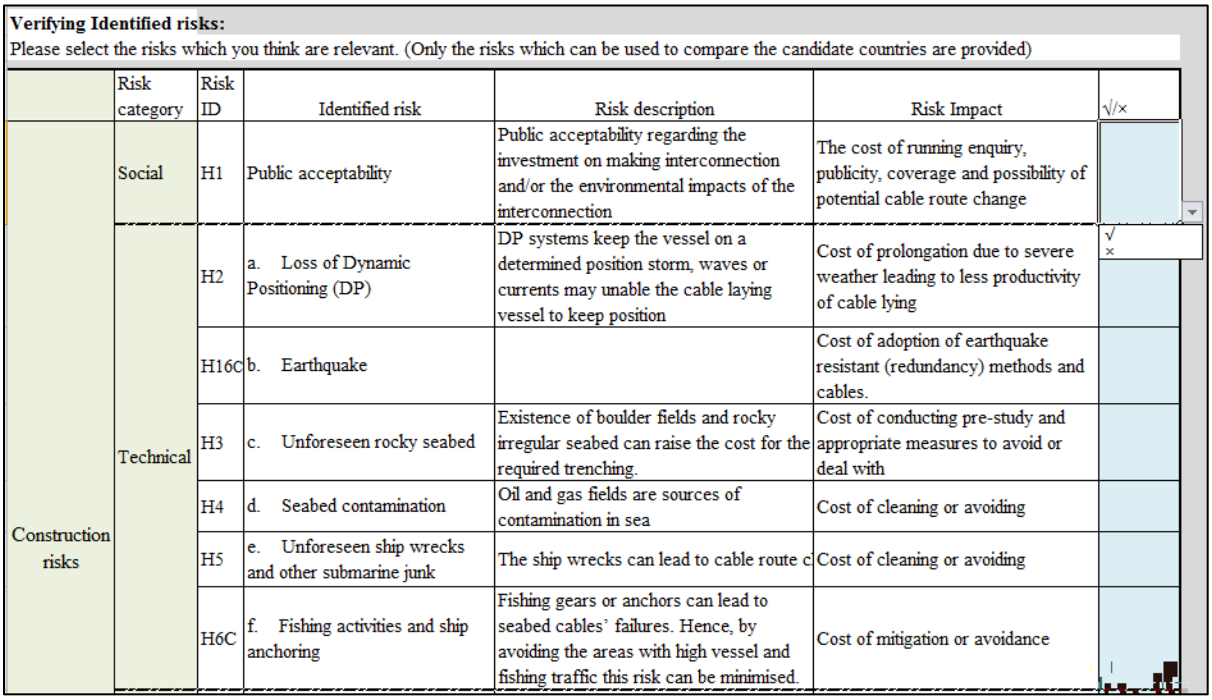
Risks associated with construction and operation of interconnections were initially identified from the literature review and were found to focus on threats and opportunities associated with interconnections (Section 5.1).

The experts were given the following options during the first part of the interview process:

a. To confirm the risks identified from the literature review, which they believed could be used to compare the candidate countries (Figure 12) [see Section 5.1 for the list of identified risks from literatures.]
b. To identify new risks. These new risks were considered afresh by the next expert to be interviewed and could at this stage be accepted or rejected.

This process was carried out sequentially amongst the experts so that new risks were considered by the next interviewee, and if they were confirmed they were included in the pool of risks (Figure 13).

The procedure revealed valuable data from experts' experiences which were not available in the literature. The identified risks were described in Section 5.2.

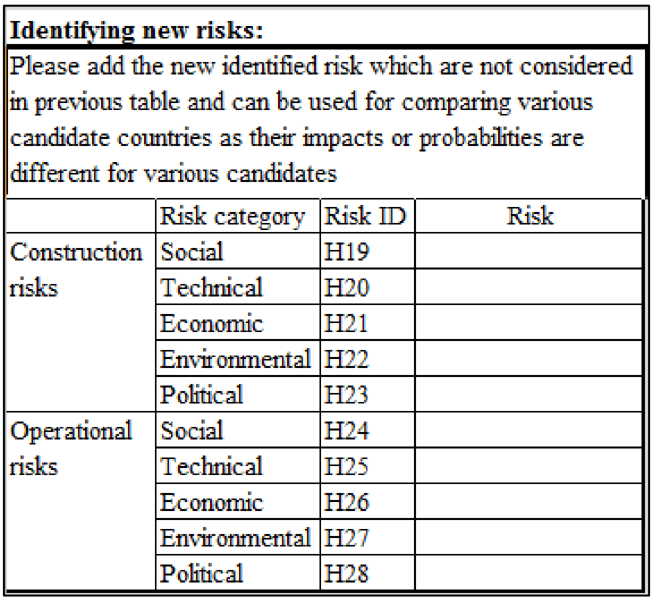


Verifying Identified risks:

Please select the risks which you think are relevant. (Only the risks which can be used to compare the candidate countries are provided)

	Risk category	Risk ID	Identified risk	Risk description	Risk Impact	√/×
Construction risks	Social	H1	Public acceptability	Public acceptability regarding the investment on making interconnection and/or the environmental impacts of the interconnection	The cost of running enquiry, publicity, coverage and possibility of potential cable route change	
	Technical	H2	a. Loss of Dynamic Positioning (DP)	DP systems keep the vessel on a determined position storm, waves or currents may unable the cable laying vessel to keep position	Cost of prolongation due to severe weather leading to less productivity of cable lying	√ ×
		H16C	b. Earthquake		Cost of adoption of earthquake resistant (redundancy) methods and cables.	
		H3	c. Unforeseen rocky seabed	Existence of boulder fields and rocky irregular seabed can raise the cost for the required trenching.	Cost of conducting pre-study and appropriate measures to avoid or deal with	
		H4	d. Seabed contamination	Oil and gas fields are sources of contamination in sea	Cost of cleaning or avoiding	
		H5	e. Unforeseen ship wrecks and other submarine junk	The ship wrecks can lead to cable route c	Cost of cleaning or avoiding	
		H6C	f. Fishing activities and ship anchoring	Fishing gears or anchors can lead to seabed cables' failures. Hence, by avoiding the areas with high vessel and fishing traffic this risk can be minimised.	Cost of mitigation or avoidance	

Figure 12: Snapshot of the risk identification spreadsheet (identified risks from literatures)



Identifying new risks:

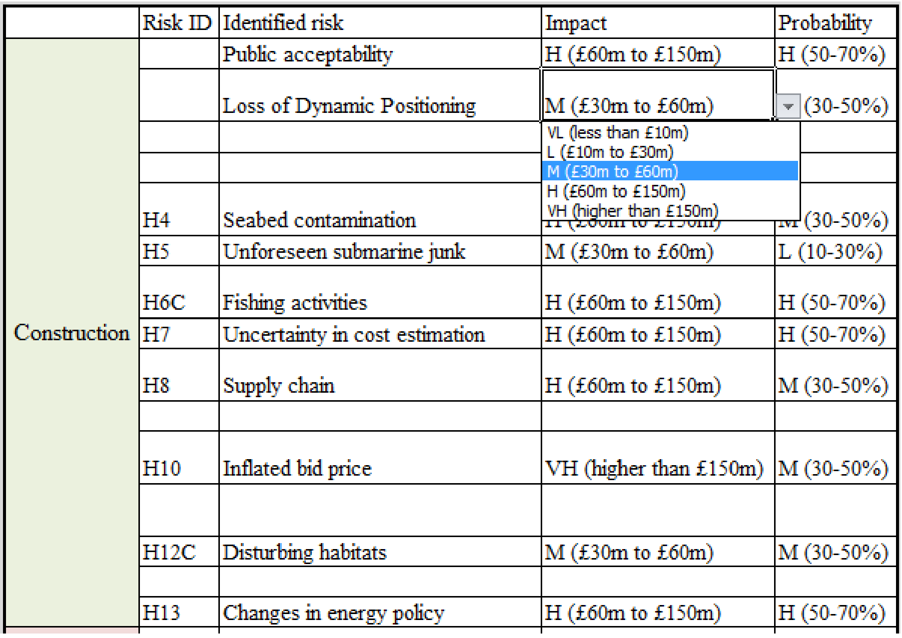
Please add the new identified risk which are not considered in previous table and can be used for comparing various candidate countries as their impacts or probabilities are different for various candidates

	Risk category	Risk ID	Risk
Construction risks	Social	H19	
	Technical	H20	
	Economic	H21	
	Environmental	H22	
	Political	H23	
Operational risks	Social	H24	
	Technical	H25	
	Economic	H26	
	Environmental	H27	
	Political	H28	

Figure 13: Snapshot of the risk identification spreadsheet (adding new risks feature)

2. Risk semi-quantification

After the risk identification process the experts were asked to estimate the impacts and probabilities associated with each identified risk using the linguistic terms "very high", "high", "medium", "low", "very low". Each linguistic term had associated with it a range of numerical values (e.g. "high impact" was given a cost range of £60 m – £150 m. Figure 14 demonstrates the process.



	Risk ID	Identified risk	Impact	Probability
Construction		Public acceptability	H (£60m to £150m)	H (50-70%)
		Loss of Dynamic Positioning	M (£30m to £60m)	(30-50%)
	H4	Seabed contamination	H (£60m to £150m)	M (30-50%)
	H5	Unforeseen submarine junk	M (£30m to £60m)	L (10-30%)
	H6C	Fishing activities	H (£60m to £150m)	H (50-70%)
	H7	Uncertainty in cost estimation	H (£60m to £150m)	H (50-70%)
	H8	Supply chain	H (£60m to £150m)	M (30-50%)
	H10	Inflated bid price	VH (higher than £150m)	M (30-50%)
	H12C	Disturbing habitats	M (£30m to £60m)	M (30-50%)
	H13	Changes in energy policy	H (£60m to £150m)	H (50-70%)

VL (less than £10m)
L (£10m to £30m)
M (£30m to £60m)
H (£60m to £150m)
VH (higher than £150m)

Figure 14: Snapshot of the speadsheet used for semi-quantification

The data obtained from the experts was used in a risk matrix to calculate risk levels. The matrix was presented in a spreadsheet during an interview to help the interviewees understanding the procedure (Figure 11).

Following current industry practice, probability is defined within the following ranges shown in Table 15, with very low and very high allocated less than 10 per cent of the overall range and over 70 per cent respectively.

Table 15: The ranges for probability used in semi-quantification stage

Probability
Very Low (≤ 10%)
Low (10-30%)
Medium (30-50%)
High (50-70%)
Very High (70% ≤)

The risk impacts for each candidate country were presented as five ranges based on a percentage of the construction cost of the interconnection to that country. The percentages allocated for each range are provided in Table 16.

During the interview when experts assigned an impact and probability to the risk, they were asked to give their rationale for so doing. This has done to limit the bias associated with the selections and to make sure the selection was based on previous experiences in most cases.

Table 16: Illustration of risk impact and the associated range used in semi-quantification stage

Rank	Low range (%)	High range (%)
Very Low		1
Low	1	3
Medium	3	7
High	7	15
Very High	20	

3.3.5.2 Interviewees

In total over one hundred experts from continental Europe, who have specialist skills and knowledge in electricity generation and distribution, were contacted through email correspondence. Of these, 20 agreed to partake in the research, representing 8 different countries (Table 17a). These included those working in electricity generating and distribution companies, design engineering consultants, academic researchers of note in their field (including energy policy specialists, electrical power engineers and economists), policy makers and government advisors. The respondents were subsequently grouped into five broad categories: Academia, Grid operators, Government advisors, Private developers and Suppliers as shown in Table 17b. A discussion of the number and background of the experts who participated in the research, and whether they may be considered to be representative, is provided in the discussion chapter (Section 7.2.4).

As can be seen in Table 17 most of the experts had been interviewed are from the UK with an academic background (9 and 8 people respectively). As for the background only one expert was interviewed from a supplier or contractor group which was due to two factors. Firstly they were very conservative about the confidentiality of data and even the university's guarantee was not enough to convince them to participate. Secondly the main suppliers or contractors related to cables and interconnections are from Continental Europe and their representatives in the UK were found to have a marketing background but not the technical which was required to answer the questionnaire.

Table 17: Breakdown of Experts consulted according to country (a) and Category (b), source Eskandari Torbaghan et al. (2015)

Countries	Number of participants
UK	9
Netherlands	2
Italy	1
Belgium	3
Sweden	1
Ireland	2
Germany	1
France	1

(a)

Category	Number of participants
Academia	8
Grid operator	4
Government advisor	5
Private developer	2
Supplier	1

(b)

3.3.6 Risk quantification

Building on the estimates of risk contingencies for capital expenditure and operational excellence risk ranking generated based on experts' judgment. The risk quantification process was utilised on the output of the WLA stage. This resulted in the discounted operational and maintenance relevant costs and revenues which in culmination form a cost risk model (Section 6.2).

Risk impact and probability were modelled by statistical distributions and a Monte Carlo Simulation run(s) that provided an estimate of the risk contingency and defined dominant contributors. For the purposes of this research the @Risk^{TM} software (Palisade Corporation, 2012) was selected to run the simulation. The philosophy behind this was that it is a widely available, convenient to use, flexible, unstructured software system that can help quantify, display and combine risks and uncertainty parameters (Chapman and Ward, 2004; Brandimarte, 2014; Naedele *et al.*, 2015; Rubio *et al.*, 2015).

The mixed method, which combined qualitative and quantitative methods (described in Section 3.2.3.3), adopted herein is more commonly termed as a triangulation approach used to check the viability of the research and to overcome subjectivity (Burns, 2000; Bergman, 2008; Creswell, 2009). This is important to mitigate against exclusive reliance on one method which may bias the researcher's overarching picture (Burns, 2000). In this research the subjectivity associated with identified risks was assessed in semi-quantification stage, this was then used for quantifying the impacts. An identified risk with a negligible (or non-identified) impact was not considered in the risk quantification stage. In addition, two other methods of triangulation were used in the case study, which are discussed along with the limitations (and mitigation approaches) associated with these qualitative and quantitative methods in the following sub-sections (3.3.6.1 and 3.3.6.2).

3.3.6.1 Limitations of qualitative method and mitigations

Inadequate validity and reliability is a major concern of qualitative method(s), due to its subjective nature (Burns, 2000). By conducting a rigorous questionnaire with a range of participants active within the energy sector from different disciplines, the author consents that triangulation was achieved and the problem of subjectivity was sufficiently addressed. This is a view held by other authors (Bergman, 2008). For example, only risks which were identified by at least two of the participants in the risk identification stage were considered for further analysis. This triangulation approach was adopted in order to avoid any bias. The exception to this rule was where a strong evidence base of literature supported its adoption for further consideration. In addition to this, a member-checking approach could be used by taking the final list of identified risks back to participants to check the accuracy of the qualitative findings and to avoid any personal bias (Creswell, 2009).

Other limitations relate to the time required for data collection, analysis and interpretation which require a well-established time-table and plan for research (Burns, 2000). Therefor the research plan adopted herein, allowed for appropriate extra lead in time for these qualitative tasks, this included expected lag time between tasks, to cover any associated issues (Harris and Roberts, 2003).

3.3.6.2 Limitations of quantitative method and mitigations

There are associated barriers for adopting a quantitative approach which relate to the subjectivity involved within the analysis (Aven, 2011). An issue that could lead to structural bias and false representation, where the analysis outputs actually reflects the view of those involved in the analysis only, including the questionnaire participants and the researcher (Silverman, 2009). However, by mixing a qualitative approach as adopted within this research, this issue can be addressed (Creswell *et al.*, 2003). Further details of how this was done within this research are discussed in Chapter 6.

3.3.6.3 Monte Carlo Simulation (MCS)

MCS has been identified by the British Standards Institution as strongly applicable for risk evaluation (BSI, 2010). Within this research the computer programme, @Risk^{TM}, was used to generate sets of random numbers for use in testing various cost risk scenarios (Flanagan and Norman, 1993). Simulation here involves risk analysis using the statistical experiment. [A full description of the simulation is discussed is Section 6.2.4]. In brief this requires a large number of theoretical NPVs (the output of WLA method) to be generated within the simulation in order to reflect the various plausible outputs of the actual cost risk of interconnections (BSI, 2010). Each simulation, known as an iteration, was undertaken by replacing a risky variable with a random number drawn from the probability distribution used to describe that variable (Flanagan and Norman, 1993; BSI, 2010). Typically at least 1000 iterations are performed which then can be used to generate a frequency distribution for the whole cost(s) (Flanagan and Norman, 1993). Thereafter, the generated statistical data were utilised to generate cumulative frequency curves and to extract the NPV which will not exceed a certain probability; 80 per cent is adopted within the case study reported here. The risk quantification process provides a range of possible final risk costs, cumulative frequency curves. Unfortunately this is incompatible with our aim to compare the various candidates, although the range, over which this occurs, does help inform the robustness of the associated decision(s) when used in comparison with single-point estimation(s). In general the single figure to be considered in the decision criteria will be a central value at the early stages, for example the P50 is adopted as being the 'most likely' value from a three point estimate (IRG, 2013). However, it is important to use the range to provide a feel for the full breadth of uncertainty that exists. The move from a range of possible final risk costs to single number is a matter of judgment as the risk analysis is characteristically subjective, not least the process for reaching a single value (IRG, 2013).

For the case study the 80 per cent was selected in line with Primavera Risk Analysis (Oracle, 2009) software to show a high probability. This is a value supported by Network Rail who use to find developments (IRG, 2013). P80 is the output of an approach known as "percentiles" which is a measure of confidence for the probability of the final cost being less than P80 (IRG, 2013). In other organisations it might be considered less efficient to allow a higher probability for re-authorising expenditure. Therefore within the UK the Highways Agency, London Underground and Heathrow airport adopt P50, also known as the median (IRG, 2013).

More details of the process of applying the MCS technique are provided in the case study (Section 6.2.4). Some general strengths and limitations of the simulation (BSI, 2010) are:

I. Strengths
  - can model any distribution in an input variable;
  - are relatively simple to develop and can be extended;
  - any influences or relationships arising in reality can be represented, including conditional dependencies;
  - sensitivity analysis can be applied [which was applied for the case study]
  - models can be easily understood as the relationship between inputs and outputs is transparent;
  - provides a measure of the accuracy of a result;

II. Limitations:
  - it relies on being able to represent uncertainties in parameters by a valid distribution
  - large and complex models may be challenging to the modeller
  - the technique may not adequately weigh high-consequence or low probability events

3.4 Summary of the Methodology

In order to select the most appropriate countries with which to establish an interconnection the development of the theoretical framework has been explained. In brief this comprised of three elements; (1) selecting candidate countries, (2) WLA and (3) risk assessment. In relation to (3) this chapter has described the three components of a risk assessment procedure, namely: risk identification, semi-quantification and quantification. These sequential stages required to understand the associated risks and their potential impacts on the cost of interconnections are described. While a number of approaches are available to estimate probability and consequences of identified risks, using expert opinion was identified as the most appropriate approach for this research.

The applicability and usefulness of theoretical framework was tested via a case study which considered the risks of the UK forming an interconnection with a number of neighbouring countries (Chapters 4 to 6).

4 CASE STUDY: SELECTING CANDIDATE COUNTRIES

This chapter and the following two chapters describe the UK case study implementation of the methodology described in Chapter 3.

The case study described in this chapter consisted of an initial screening process to identify candidate countries and a scenario analysis to generate energy scenarios which were used to assess the capacity of the interconnections between the UK and the candidate countries. Thereafter, a whole life appraisal technique was developed to assess the risk cost of the UK developing interconnections with the identified candidate countries (Section 4.3).

4.1 Initial screening

The process of identifying candidate country started with a pre-screening stage by which unsuitable countries were identified and not considered for further analysis. The initial screening process, as introduced in Section 3.2.1, considers political, economic, technical and or social situations and conditions. However, distance (economical factor) and CO_2 emissions (environmental and technical factors) were only identified as important criteria for the initial screening process (Section 3.3.1).

Distance is a major driver of cost regarding both construction and maintenance of an interconnection and was therefore used as a criterion for identifying countries for further analysis (see Section 3.3.1). For the case study therefore it was decided to consider countries within a distance of 800 km (measured from nearest boarder to nearest boarder) from the UK, and only those countries with the possibility to connect to the UK directly without the need to build the interconnection through other countries. For example, Luxembourg was not considered for the case study, as there would be a need to build an interconnection from it through Belgium or France. Iceland was also excluded from the considered countries as its distance to the UK mainland is over 800 Km. However, it should be noted that Iceland could be a potential option for the UK if the high capital costs, needed for building an interconnection, could be sufficiently offset by its access to renewable energies such as geothermal and hydro (Hammons *et al.*, 1993; Karlsdóttir, 2013). The identified countries are shown in Table 18. The nine candidate countries were; Belgium, Denmark, France, Germany, Ireland, Netherlands, Norway, Spain and Sweden. The interconnections were assumed to be used for both importing and exporting renewable electricity when possible.

Table 18: Identified countries

	Countries	Min distance to the UK (km)
1	Sweden	800
2	Spain	700
3	Denmark	580
4	Norway	460
5	Germany	380
6	Netherlands	170
7	Belgium	98
8	Ireland	85[a]
9	France	40

[a] Distance by sea

4.1.1 CO_2 emission

The lifecycle CO_2 emissions of a cable forming an interconnection were used as a measure of the viability of the interconnection. This was achieved by comparing, for an assumed cable energy capacity of 1000 MW, the emissions of an interconnection cable to each candidate country with the current level of emissions from each of the 14 current existing UK energy sources. This allowed the viable (sustainable) length of an interconnection to be calculated in terms of lifecycle CO_2 emissions when compared to generating the same amount of electricity from current UK energy sources. To achieve this it was necessary to determine the emissions of both the cable and those of the current UK energy sources.

Data provided by Jorge et al. (2012) was used to determine the emissions of seabed cables over the lifetime of the interconnection (see Table 19). Jorge et al. (2012) considered emissions for the production of materials, installation, maintenance, and the decommissioning of seabed cables. The emissions from cable manufacturing (i.e. assembly of components) were not included in their study since they make up a very small fraction of the total emissions (less than 0.03% of the total when calculated for transformers). For cables in general Jorge et al. (2012) show that transmission losses represent over 96% of the total emissions and the impact of manufacturing are very small. The majority of the processes (such as the production of steel and copper) considered by Jorge et al. (2012) reflect the European context, which may be different for other technological or regional environments.

Table 19: Breakdown of HVDC cable emissions per km (ton CO_2 eq), source Jorge et al. (2012)

Process	Emissions (ton CO_2 eq)/km
Cable	140
Installation	1.5
Maintenance	2.5
End-of-life	-11
Total	133

The end of life of the cable contributes negatively to the total emissions (Table 19) as it includes recycling of metal parts, which outweigh other end of life processes, such as transportation activities.

It should be noted that Jorge et al.'s (2012) study is based on a number of assumptions and does not consider several parameters such as the cable's capacity. The CO$_2$ emissions associated with the current UK energy sources were obtained from a number of studies as shown in Table 20.

An example of the calculation for wind energy is as follows: the maximum length of an interconnection cable producing the same amount of emissions as a 1000 MW of wind energy is given by:

$$\text{Length of cable with equal emissions (Km)} = \frac{\text{Wind energy } CO_2 \text{ emissions } (tCO_2 \text{ eq})}{\text{HVDC cable emissions per km } (tCO_2 \text{ eq/km})} \tag{2}$$

$$= \frac{25 \times 1000 \text{ (tCO2 eq)}}{133 \text{ (tCO2 eq)}} = 188 \text{ km}$$

Of those countries considered, only Belgium, France, Ireland and Netherlands meet this criterion (Table 20).

Table 20: CO$_2$ emissions of various power generation technologies per 1000 GMW and the length of a cable of the same energy capacity producing the same level of emissions

Technologies	CO$_2$ Emissions (KtCO$_2$ eq)	HVDC cable emissions per km (tCO2 eq)	Length of cables with equal Emissions (Km)	Countries within given distance from the UK
Coal	9303 [1]	133	69,947	All of the 9 countries given in Table 18
Gas	8672 [1]		65,203	
Oil	6079 [1]		45,707	
CHP	3820 [2]		28,722	
Coal + CCS	930 [3]		6,992	
Gas + CCS	867 [3]		6,519	
Geothermal	799 [1]		6,008	
Nuclear	449 [1]		3,376	
Hydro	301 [1]		2,263	
Biomass	224 [1]		1,684	
Solar PV	150 [1]		1,128	
Pumped Storage	47 [4]		353	Belgium, France, Ireland, Netherlands
Marine	44 [5]		331	
Onshore Wind	25 [1]		188	
Offshore Wind				

[1] Kharecha *et al.*(2010), [2] Matthes *et al.*(2005), [3] Kharecha *et al.*(2010) CCS system is assumed 90% effective for reduction of CO$_2$ emissions, [4] Weisser (2007), [5] Douglas *et al.*(2008)

It can be seen from Table 20 that even very long distance interconnections can be environmentally viable when compared to several renewable resources. Interconnection with only four countries currently however may be considered viable for replacing pump storage, marine and wind energy in terms of CO$_2$ emissions.

4.1.2 Assumptions

All interconnections between the UK and the candidate countries were assumed to be seabed cables made from the same material and to the same standards in order to make the comparison simple. However there are other options available for some countries. For instance, the interconnection to France can be built through the Channel Tunnel (E&T, 2011) and that with Ireland the link could be via an overhead cable from Northern Ireland.

The interconnections between the nine candidate countries and the UK were assessed by their cost risk in the case study. The capacity of an interconnection is one of the main uncertainties when estimating its overall cost risk, and the following section describes the method used for assessing the interconnections capacities by generating future energy scenarios.

4.2 Scenario generation and assessment of interconnection capacities

As with any new approach, there is a range of risks associated with developing interconnections, not least the availability of surplus electricity for exportation between various candidate countries. While the future is never certain, the process of generating a range of possible capacities for these interconnections should be considered as a necessary precursor for mitigating risks within decision-making processes. In facilitating this objective, this section proposes a step-wise methodological framework for assessing the probabilities of achieving surplus capacity provision by using a newly developed tool for proposing a range of energy supply/ demand scenarios in conjunction with the @Risk^{TM} assessment tool (presented in Appendix D). The develop tool and the methodology described here were used in the case study. The approach adopted within this section provides a robust framework for risk assessors to improve upon single-point estimation in order to understand better the possibilities for supply and demand that might occur.

The rest of this section describes the methodology used for scenario generation using the developed tool (Section 4.2.1) and steps used for developing two extreme scenarios tion 4.2.2). Assessment of interconnection capacities using a risk assessment approach is presented in Section 4.2.3.

4.2.1 Scenario Generation

In this step (informed by future projection scenarios) it was necessary to generate a range of capacities for energy supply/demand. When considering two interconnected countries, this then allowed calculation of 'spare' electricity capacity that can be traded in either direction. Three steps were required.

4.2.1.1 Step 1: Developing an Excel-based future scenario tool

There is a plethora of electricity supply mixes and/or energy demand projections, hence complicated decision-making procedures require in-depth consideration of the various scenarios that are being developed. This requires a high level of knowledge that is available only within a team of experts that are well versed on the various techniques of future scenarios analysis. Alternatively, what was missing was a tool that acts as a database for existing energy supply/demand scenarios and allows the user to look up existing scenarios or mix existing scenarios for a country, leading to a range of new possibilities and to allow alternative approaches to be considered. Such a tool has been developed in this research and has been used for the case study. For the case study around 50 studies were incorporated within the database of the tool, each of which provides various supply/demand projection scenarios according to a range of countries' renewable and non-renewable supply technologies.

The developed tool has three main components.

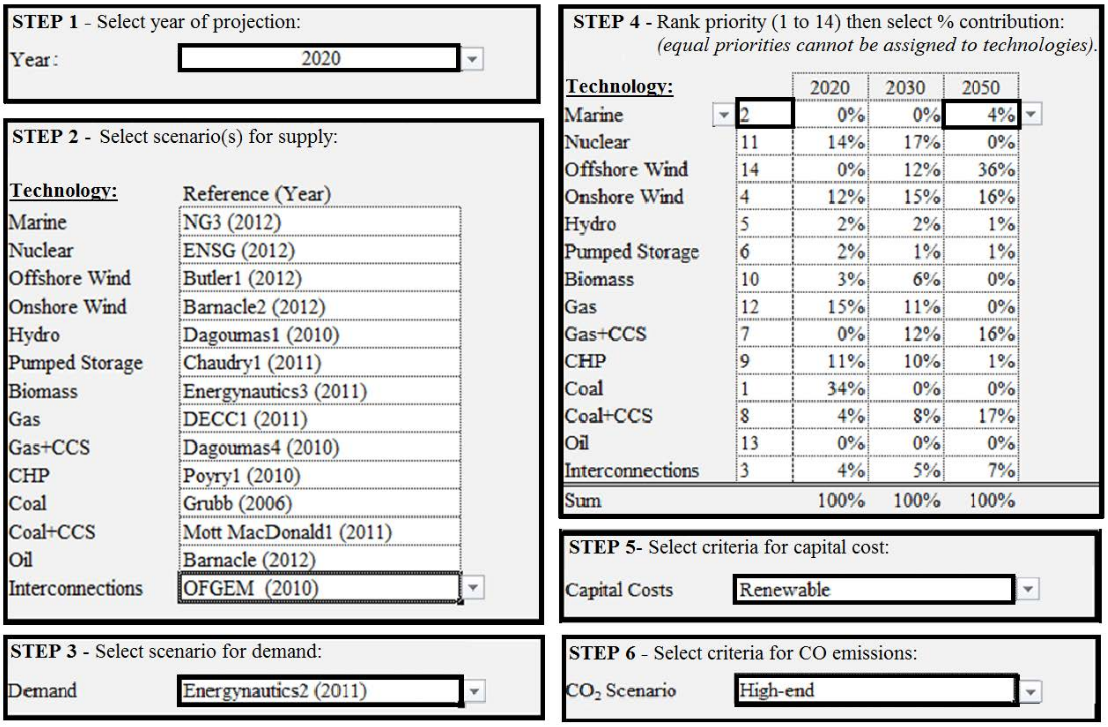
STEP 1a - Year of projection

Three options (i.e. 2020, 2030 and 2050) were considered that are sufficiently far enough in advance of today to allow for short medium and long term decisions to be made. Moreover they are in line with where national and international policy requirements have been drawn up.

STEP 1b - Electricity generation technologies

Fourteen likely future macro-scale technologies were added to the tool based on categories stipulated by National Grid (2011a) (Figure 15). PV systems are excluded from the list as they are considered micro-scale for domestic use in the UK (case study) and there is no solar farm in the country at the moment. It is possible to select one source or multiple sources within the tool (Figure 15).

For each of the considered technology and for each considered country it was required to add scenarios. In total some 50 scenario sources were added (Section 4.2.2) and this list can be added to for future use as more scenarios become available. In so doing the tool can remain relevant and upgradeable for decision-makers both now and in the future. In terms of interconnections over 23 scenario studies are included within the tool (Figure 16).



STEP 1 - Select year of projection:

Year: 2020

STEP 2 - Select scenario(s) for supply:

Technology:	Reference (Year)
Marine	NG3 (2012)
Nuclear	ENSG (2012)
Offshore Wind	Butler1 (2012)
Onshore Wind	Barnacle2 (2012)
Hydro	Dagoumas1 (2010)
Pumped Storage	Chaudry1 (2011)
Biomass	Energynautics3 (2011)
Gas	DECC1 (2011)
Gas+CCS	Dagoumas4 (2010)
CHP	Poyry1 (2010)
Coal	Grubb (2006)
Coal+CCS	Mott MacDonald1 (2011)
Oil	Barnacle (2012)
Interconnections	OFGEM (2010)

STEP 3 - Select scenario for demand:

Demand: Energynautics2 (2011)

STEP 4 - Rank priority (1 to 14) then select % contribution:
(equal priorities cannot be assigned to technologies).

Technology:		2020	2030	2050
Marine	2	0%	0%	4%
Nuclear	11	14%	17%	0%
Offshore Wind	14	0%	12%	36%
Onshore Wind	4	12%	15%	16%
Hydro	5	2%	2%	1%
Pumped Storage	6	2%	1%	1%
Biomass	10	3%	6%	0%
Gas	12	15%	11%	0%
Gas+CCS	7	0%	12%	16%
CHP	9	11%	10%	1%
Coal	1	34%	0%	0%
Coal+CCS	8	4%	8%	17%
Oil	13	0%	0%	0%
Interconnections	3	4%	5%	7%
Sum		100%	100%	100%

STEP 5- Select criteria for capital cost:

Capital Costs: Renewable

STEP 6 - Select criteria for CO emissions:

CO_2 Scenario: High-end

Figure 15: STEP 1 to 6 in excel based scenarios tool, source Eskandari Torbaghan *et al.* (2013)

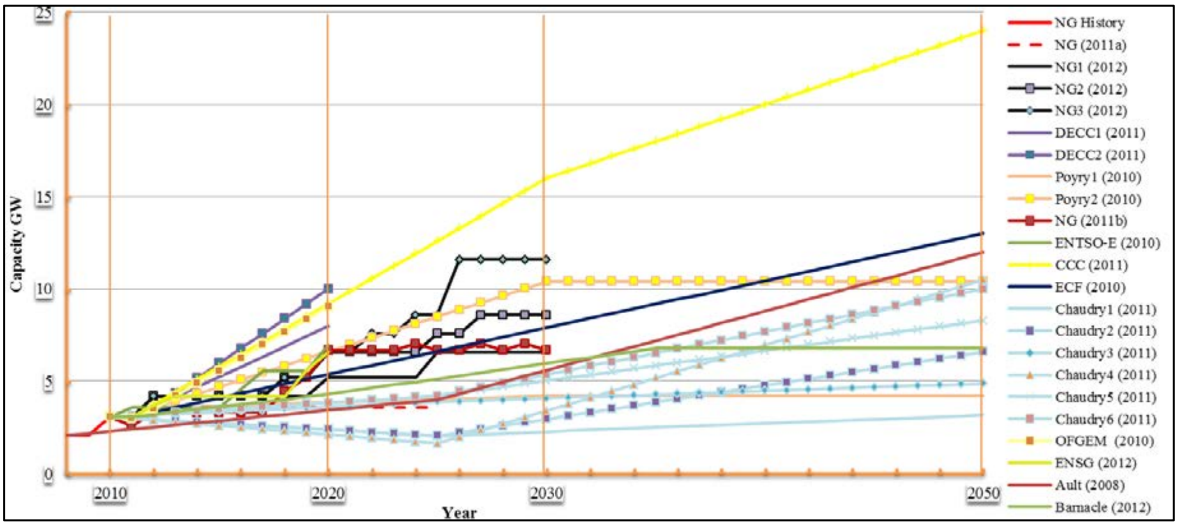


Figure 16: Considered studies for projecting the share of interconnections, source Eskandari Torbaghan *et al.* (2013)

It is possible through the use of the tool to identify the highest achievable (projected) share of interconnections within the UK up to 2050. As it is shown in Figure 16 the highest capacity of interconnections is projected by CCC (2011), around 25 GW, and this is more than twice other projections – this is because they declare relatively small costs associated with interconnection compared to generation costs and they perceive increased interconnection, even in scenarios with low renewable generation, with European and Scandinavian systems. The current capacity of interconnections in the UK is around 4.15 GW (National Grid, 2014).

STEP 1c - Energy demand scenarios

Energy demand scenarios were added to the tool for each considered country. The tool balances the demand option with the supply option (this includes additional spare capacity required within the network – see later).

4.2.1.2 Step 2: Ranking technologies

All the technologies, selected within the tool, were assessed in terms of their lifecycle emissions and load factors (i.e. likely availability due to external conditions such as wind, sunshine, water flow rates and so on). Multiplying lifecycle emissions by the load factor leads to a pollution factor by which the technologies can be ranked from the most emitting (12) to least emitting (1), as shown in Table 21 (see Eskandari Torbaghan et al. (2013) for more details). It should be noted that, for the purposes of this study, carbon dioxide capture and storage (CCS) is not considered a renewable technology as it requires fossil fuel for its implementation.

Table 21: Technological influences for scenario development, source Eskandari Torbaghan *et al.* (2014)

	Lifecycle emissions*: tCO_2-eq/GWh	Load Factor** %	Pollution Factor (A×B)	Ranking
Technology	A	B	C	D
Onshore Wind	9.5	30	3	1
Offshore Wind	9.5	30	3	1
Pumped Storage	36	15	5	2
Marine	20	25	5	2
Solar (PV)	17	30	17	3
Biomass	48	53	26	4
Hydro	86	40	34	5
Nuclear	57	90	51	6
Gas + CCS	110	90	99	7
Coal + CCS	118	90	106	8
CHP	474	92	436	9
Oil	771	90	694	10
Gas	1100	90	990	11
Coal	1180	90	1062	12

*References used for each technology: CHP (Matthes *et al.*, 2005), Pumped storage (Weisser, 2007), Marine (Reeves and Watson, 2011), CCS (Kharecha *et al.*, 2010), others (Kharecha *et al.*, 2010)

**Load factors are adapted from (ENVIROS Consulting Limited, 2006; Douglas *et al.*, 2008; Ipakchi and Albuyeh, 2009; DECC, 2011c)

This step made it possible to prioritise the technologies within the tool (1 to 14) based on their pollution factor. The prioritisation then used to combine different technologies to form various energy/demand scenarios. In other words a technology with high priority (1) was considered to be the preferred option for the energy scenario (Coal is assigned 1 in Figure 15). The tool automatically indicates % share of supply that is available / required from each technology for 2020, 2030 and 2050. The % assignment is based on two criteria:

1. Firstly, the technology availability, which depends on the selected scenario study chosen in STEP 1b; Equation 3 is applied to each selected technology:

$$\text{Technology (\%)} = (\text{Projected capacity}) / (\text{Selected demand projection} \times (1 + \text{Plant Margin})) \tag{3}$$

2. Secondly, the percentage selected *ibid*. For example if coal is Priority 1 with a 34 % share selected (Figure 15), 66 % is then available for Priority 2 to 14. If marine is then selected as Priority 2 with 0 % then 66 % is still available for Priority 3 to 14 etc.

[Plant margin is defined as: the amount by which the total installed capacity of directly connected power stations and embedded large power stations and imports across interconnections exceeds the demand and is often expressed as a percentage of the peak demand (National grid, 2013). The plant margin is used in a grid to meet any demand fluctuation, scheduled and unscheduled maintenance of power plants and also the renewables intermittency. Therefore, the estimation of plant margin is complicated and requires consideration of various parameters and will change according to the overall share of renewables. For simplicity in this research a fixed value of 40 % is selected based on historical values from the National Grid.]

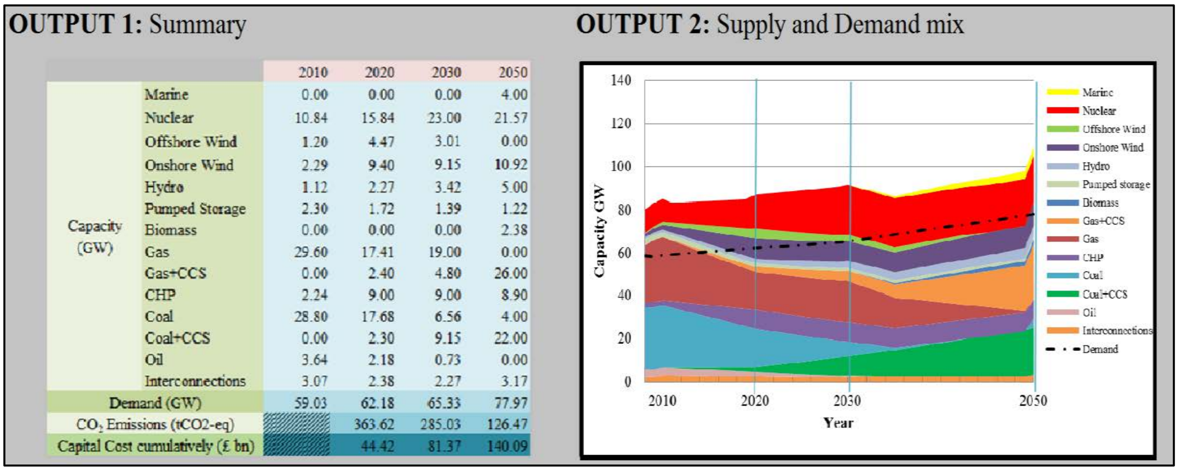
Step 2 helped ascertain (based on existing scenario studies) what possible future mixes of supply might be available in order to meet projected demands.

4.2.1.3 Step 3: Developing scenarios

The presented method and discussed data were used in the developed tool to generate energy/demand scenarios (Section 4.2.2).

Figure 17 shows the output of the developed tool, Output 1 provides a summary of the supply potential (in GW) for each technology and the total demand in 2010, 2020, 2030 and 2050 (related emissions and cumulative capital costs are also provided but were not used for this research). The trends can then be seen in Stacked-Area charts in Output 2.

The following section described the two scenarios which were developed and used in the case study.



OUTPUT 1: Summary

		2010	2020	2030	2050
Capacity (GW)	Marine	0.00	0.00	0.00	4.00
	Nuclear	10.84	15.84	23.00	21.57
	Offshore Wind	1.20	4.47	3.01	0.00
	Onshore Wind	2.29	9.40	9.15	10.92
	Hydro	1.12	2.27	3.42	5.00
	Pumped Storage	2.30	1.72	1.39	1.22
	Biomass	0.00	0.00	0.00	2.38
	Gas	29.60	17.41	19.00	0.00
	Gas+CCS	0.00	2.40	4.80	26.00
	CHP	2.24	9.00	9.00	8.90
	Coal	28.80	17.68	6.56	4.00
	Coal+CCS	0.00	2.30	9.15	22.00
	Oil	3.64	2.18	0.73	0.00
	Interconnections	3.07	2.38	2.27	3.17
Demand (GW)		59.03	62.18	65.33	77.97
CO_2 Emissions (tCO2-eq)		▨	363.62	285.03	126.47
Capital Cost cumulatively (£ bn)		▨	44.42	81.37	140.09

OUTPUT 2: Supply and Demand mix

Figure 17: Scenarios tool outputs, source Eskandari Torbaghan *et al.* (2013)

4.2.2 Development of extreme scenarios

Based on these data, the tool was subsequently used to develop two differently themed scenario sets – renewable scenarios and fossil fuel scenarios. Due to the fact that historical data show that at least 10 years are required for the design and implementation of interconnections, Strbac *et al.* (2013) report an average of 5 years for construction and 5 years is assumed for pre-study and design, the year 2030 was selected (this refers to Step 1.a above, tion 4.2.1.1). Table 22 presents for the list of technologies, number of scenarios and corresponding references used to generate those two scenarios (steps 1.b and 1.c Section 4.2.1.1).

4.2.2.1 Renewable Scenarios

This scenario set seeks to 'maximise the use of renewable energy in order to reduce CO_2 emissions while minimising reliance on fossil fuels'. Using this ethos, ten individual scenarios were developed (i.e. one for the UK and one for each of the nine candidate countries, Appendix D). These scenarios were developed assuming that energy supplies therein are sourced from the available renewable technologies of each country (i.e. those ranked 1 are adopted first, followed by those ranked 2 and so on, Step 2: Ranking technologies Section 4.2.1.2). The share of each supply technology for each country from 2010 to 2030 is presented in Figure 18. For clarity, the final breakdown of supplies for 2030, which was used in Section 4.2.3, is presented in Figure 19.

Table 22: List of technologies, number of scenarios considered and corresponding references (the superscript numbers) for UK and each candidate country, source Eskandari Torbaghan et al. (2014)

Technologies	UK	Sweden	Spain	Norway	Netherlands	Ireland	Germany	France	Denmark	Belgium
Marine	**20** [1-9]	**3** [5]	**6** [5, 10, 11]	**3** [5]	**8** [5, 10, 11]	**8** [5, 10-13]	-	**6** [5, 10, 11]	**5** [5, 10, 11]	-
Offshore Wind	**26** [1-4, 6, 9, 14-17]	-	-	-	**6** [18, 19]	**3** [12, 13, 20]	**4** [21]	-	-	-
Onshore Wind	**14** [1, 2, 6, 9, 15, 16]	-	-	-	**9** [5, 10, 11, 18, 19, 22]	**8** [10-13, 20, 22]	**9** [5, 11, 21]	-	**11** [5, 10, 11, 18, 22-24]	**11** [5, 10, 11, 25, 26]
Wind	-	**12** [5, 10, 11, 23, 27]	**7** [5, 10, 11, 18, 28]	**11** [5, 11, 23, 27]	-	-	-	**7** [5, 10, 11, 18, 22]	-	-
Hydro	**22** [1, 4-9, 16, 29]	**7** [5, 10, 11, 27]	**7** [5, 10, 11, 28]	**8** [5, 11, 27]	**6** [5, 10, 11, 19, 22]	**6** [5, 10, 11, 13, 20, 22]	**8** [5, 11, 21]	**6** [5, 10, 11]	**6** [5, 10, 11]	**5** [5, 10, 11]
Pumped storage	**8** [1, 4, 6, 7, 30]	-	-	-	-	**1** [20]	**2** [21]	-	-	-
Biomass	**15** [1, 2, 5, 6, 9, 29]	**10** [5, 10, 11, 27]	**9** [5, 10, 11, 28]	**5** [5, 11, 27]	**9** [5, 10, 11, 19, 22]	**7** [5, 10, 11, 13, 20, 22]	**9** [5, 11, 21]	**7** [5, 10, 11]	**7** [5, 10, 11]	**9** [5, 10, 11, 25]
Solar (PV)	-	**7** [5, 10, 11]	**9** [5, 10, 11, 28]	-	**9** [5, 10, 11, 19, 22]	**6** [5, 10, 11, 20, 22]	**9** [5, 11, 21]	**7** [5, 10, 11]	**7** [5, 10, 11]	**10** [5, 10, 11, 25]
Geothermal	-	-	**6** [5, 10, 11]	-	-	-	**7** [5, 11, 21]	**6** [5, 10, 11]	-	-
Nuclear	**37** [1, 2, 4-9, 16, 29-32]	**9** [5, 10, 11, 27, 33]	**10** [5, 10, 11, 28, 33]	-	**10** [5, 10, 11, 19, 33]	**5** [5, 10, 11, 20]	**8** [5, 11, 21, 27]	**7** [5, 10, 11, 33]	**2** [10, 11]	**9** [5, 10, 11, 25, 33, 34]
Gas	**28** [1, 2, 4-8, 29, 30]	**10** [5, 10, 11, 27]	**9** [5, 10, 11, 28]	-	**8** [5, 10, 11, 19]	**8** [5, 10, 11, 13, 20]	**9** [5, 11, 21, 27]	**6** [5, 10, 11]	**6** [5, 10, 11]	**8** [5, 10, 11, 34]
Gas + CCS	**17** [2, 4, 6-9, 16]	-	-	-	-	-	-	-	-	-
CHP	**5** [2, 6, 29]	-	-	-	-	-	-	-	-	**1** [34]
Coal	**21** [1, 2, 4-8, 29, 30, 32]	-	**8** [5, 10, 11, 28]	-	**5** [5, 11]	**4** [5, 11]	**10** [5, 11]	**6** [5, 10, 11]	**6** [5, 10, 11]	**9** [5, 10, 11, 34]
Coal + CCS	**23** [2, 4, 6-9, 29, 30]	-	-	-	-	-	-	-	-	-
Oil	**11** [1, 4, 6-8, 30]	-	**4** [10, 28]	-	-	**2** [10, 20]	-	**2** [10]	**2** [10]	**3** [10, 25]
Other fossils	-	**2** [10]	-	-	-	-	-	-	-	-

[1] National Grid (2012) [2] Poyry (2010) [3] Esteban et al (2011) [4] UKERC (2009) [5] Energynautics GmbH (2011) [6] Barnacle et al. (2012) [7] Chaudry et al. (2011) [8] Dagoumas and Barker (2010)
[9] Mott MacDonald (2011) [10] Capros et al. (2010) [11] Green peace (2011) [12] IMERC (2011) [13] Argyropoulos and Gardner (2012) [14] Hawkins et al. (2011) [15] National Grid (2011b)
[16] Butler et al. (2012) [17] Decker et al. (2011) [18] EWEA (2011) [19] Green peace (2013) [20] EIRGRID (2013) [21] Lindberg (2013) [22] ECN (2011) [23] Juul and Meibom (2012)
[24] Gunnar Boye Olesen (2010) [25] D'haeseleer et al. (2007) [26] Gill (2013) [27] Wiuff et al. (2007) [28] López-Peña et al. (2011) [29] Grubb et al. (2006) [30] DECC (2011d)
[31] World Nuclear Association (2012) [32] Electricity Networks Strategy Group (2012) [33] World Nuclear Association (2013) [34] Geldhof and Delahaije (2013)

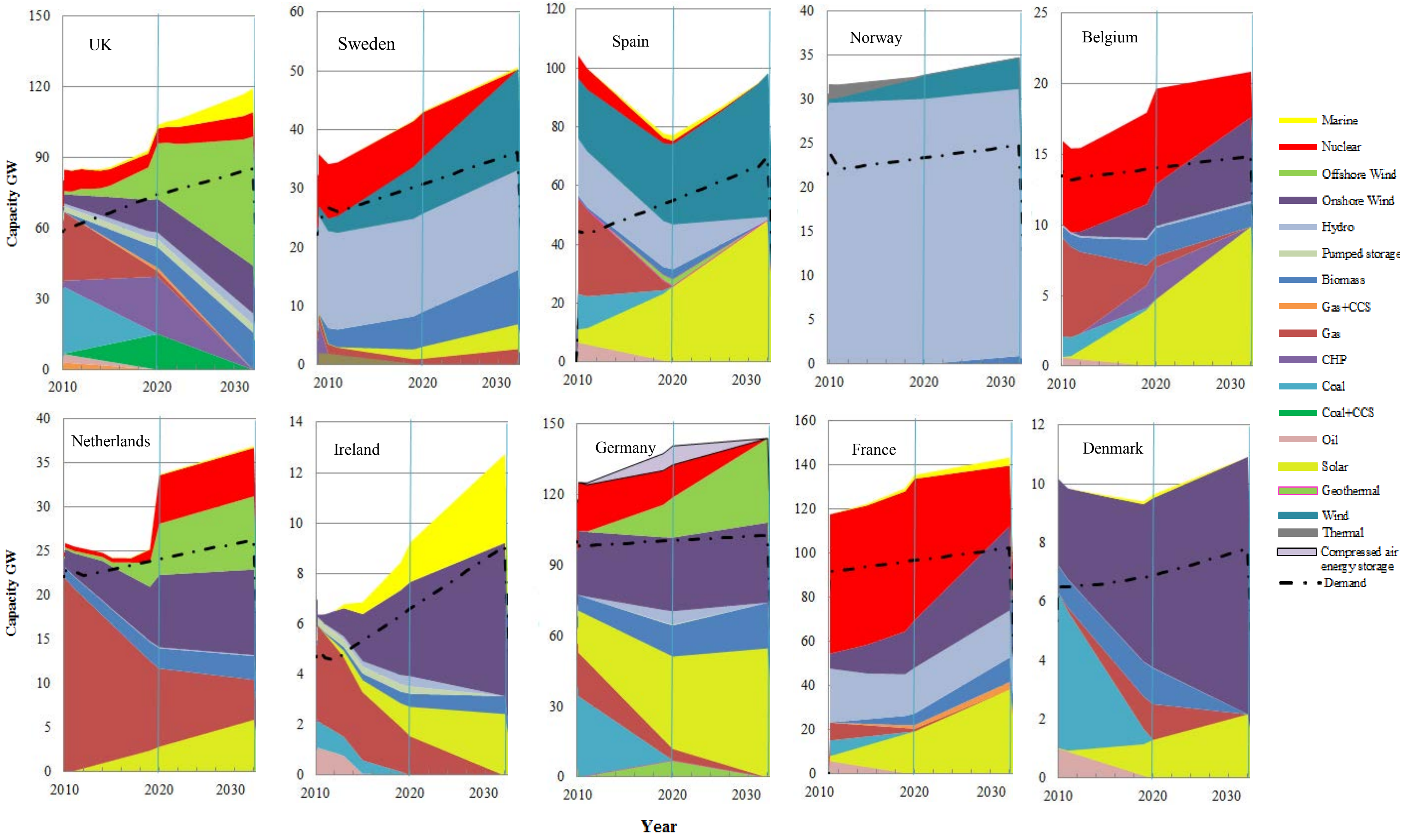


Figure 18: Generated share of technologies in Renewable scenarios for 2030, source Eskandari Torbaghan *et al.* (2014)

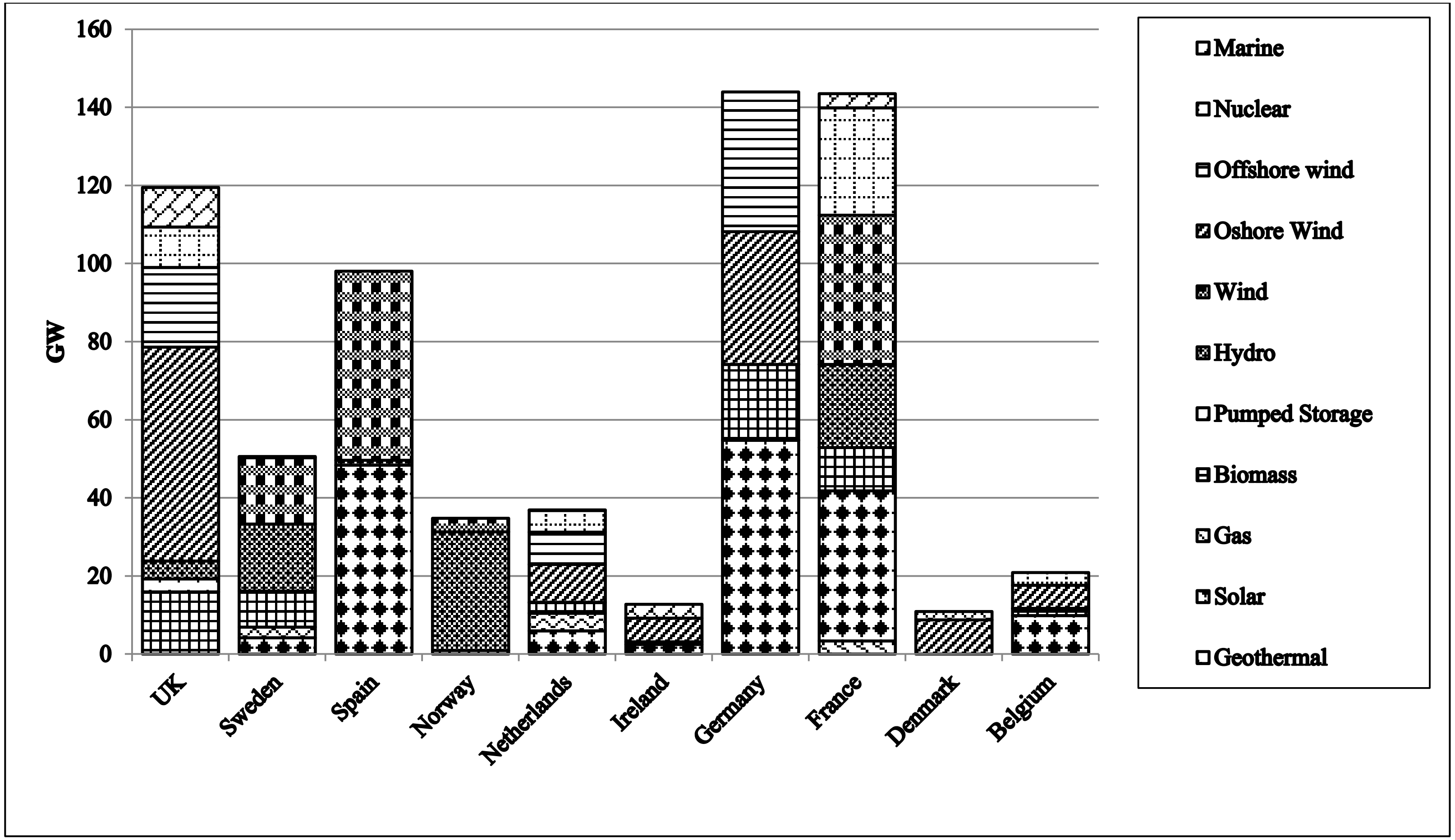


Figure 19: Share of technologies in ‘Renewable’ scenarios in 2030, source Eskandari Torbaghan et al. (2014)

4.2.2.2 Fossil Fuel Scenarios

This scenario set seeks to ‘maximise the share of fossil fuels and minimise renewable sources, increasing reliance on fossil fuels’. Using this ethos, ten individual scenarios were developed (one for the UK and one for each of the candidate countries, Appendix D). These scenarios were developed assuming that energy supplies therein are sourced from the available non-renewable technologies of each country (i.e. those ranked 12 are adopted first, followed by those ranked 11 and so on). The final breakdown of supplies is presented in Figure 20.

Each scenario set will always draw from a narrative and a set of assumptions (Boyko *et al.*, 2012; Hunt *et al.*, 2012). For example, two general common assumptions (factors) for generating the scenarios described in this chapter are economic growth and taxation on CO_2 emissions or meeting associated emissions target (see for instance National Grid (2012), Green Peace (2011), Capros et al. (2010)). Both play vital roles when comparing the economic viability of renewable vs fossil fuel technologies. Taking Germany as an example, the narrative would state that there would be a dramatic drop in total electricity generation capacity due to selection of a lowest demand projection scenario (i.e. from 100 GW (Statistisches Bundesamt, 2013) to around 40 GW (Wiuff *et al.* (2007)) based on an assumption of medium economic growth coupled with a strong focus on improved energy efficiency measures, driven by Germany’s policy to go non-nuclear by 2022.

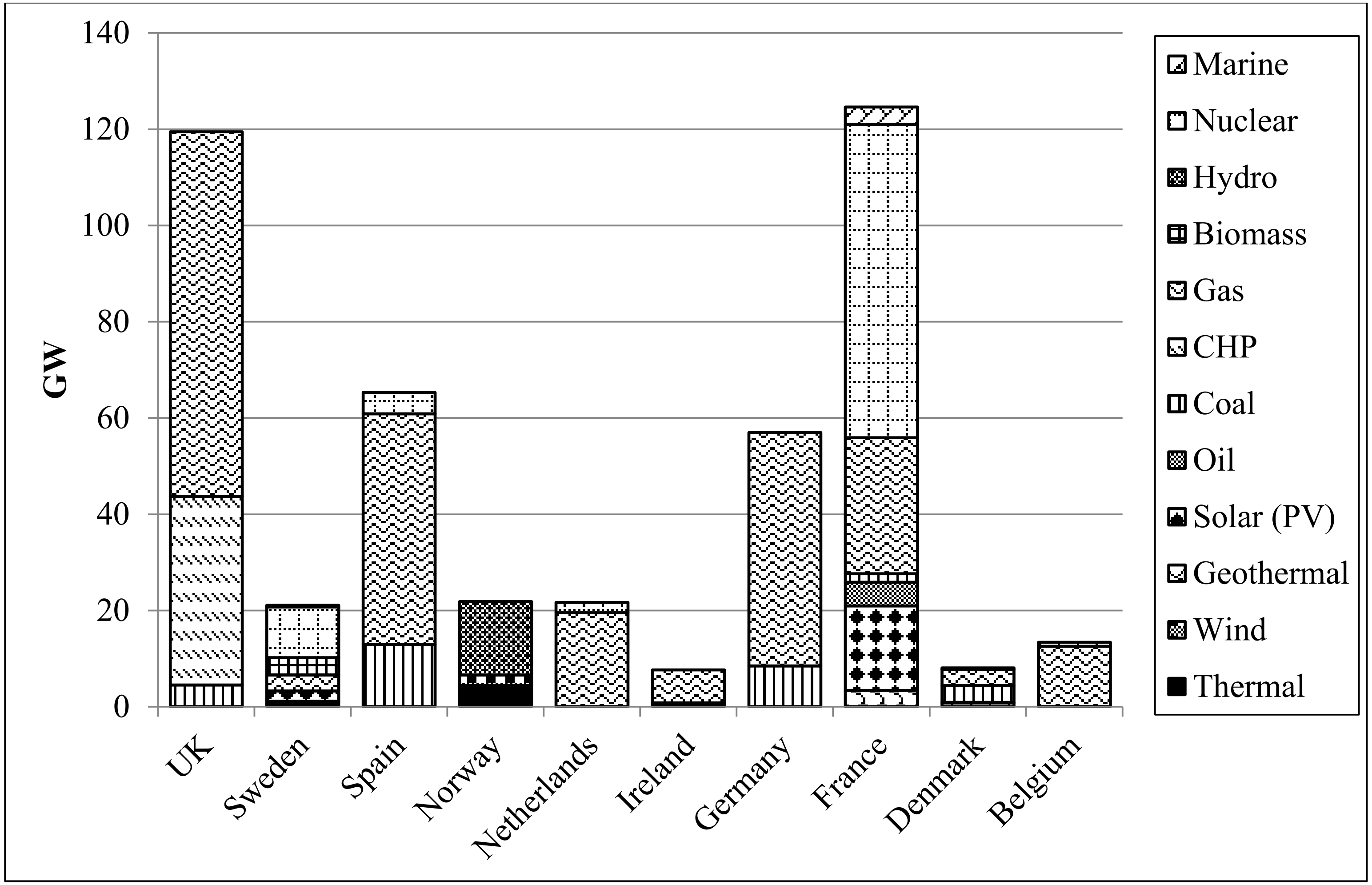


Figure 20: Share of technologies in 'Fossil fuel' scenarios in 2030, source Eskandari Torbaghan et al. (2014)

4.2.2.3 *Other applications of the developed tool*

The format of the developed tool means that additional steps can easily be developed for decision-makers depending on local priorities and local conditions (Hunt *et al.*, 2008) – a key thread of any sustainability policy. For example, it could help decision-maker assess 'risks' and 'uncertainties' associated with various scenario choices and be linked with capital cost(s) and CO_2 emission(s), as possible risk impacts. A comparison between three developed energy/demand scenarios based on the two mentioned parameters was reported in Eskandari Torbaghan et al. (2013). It is hoped that this will identify the key risks associated with each particular technology and provide a framework for assessment of its appropriateness either for direct adoption or interconnection (and the appropriate nation for this to take place). The Excel add-in '@Risk^{TM}' provides a robust platform for such purposes.

Next section describes the method used for assessing interconnection capacities by utilising @Risk^{TM}.

4.2.3 Assessment of interconnection capacities

This section explains the method used for estimating the capacity of surplus energy and exported energy for interconnection across both UK and candidate countries (which is applied for the case study). The process consists of the following three steps.

4.2.3.1 *Step 1: Calculate 'surplus' capacity (Es)*

The surplus capacities for the UK and candidate countries were calculated in this research according to Equation 4.

$$E_S = E_a - D_P \qquad 4$$

Where *(units in italics)*:

E_s = Surplus capacity *(GW)*
E_a = Available capacity *(GW)*
D_P = Peak demand *(GW)*

For the case study it was assumed within the newly developed renewable scenario set and fossil fuel scenario set that in 2030 the UK seeks to connect to the 'Supergrid' to import and export only renewable energy. By making this assumption Equation 4 was used to calculate $E_{S\ (min)}$ and $E_{S\ (max)}$ (i.e. available surplus capacity of renewable electricity (RE) that could be drawn from each of the nine candidate countries or could be exported to those countries). The minimum values were based on the ten fossil fuel scenarios (i.e. for the UK and nine candidate countries) whilst the maximum values were based on the ten renewable scenarios (i.e. for the UK and nine candidate countries). In Table 23 it can be seen that the greatest value of $E_{S\,(max)}$ (i.e. the highest available capacity of RE supplied to the UK through the 'Supergrid') is 41.3 GW from Germany. Likewise the minimum value is 0 GW from 8 countries, excluding Norway.

4.2.3.2 Step 2: Calculate 'export' capacity (Ee)

The surplus capacity E_S calculated in Equation 4 does not provide a true reflection of the energy that could be exported (E_e) through the Supergrid. This should take cognisance of intermittency, through a load factor (F_1) and an export quota (F_2) which accounts for the availability of interconnection (i.e. maintenance of the infrastructure could prevent energy being transferred between the two countries), using the following equation.

$$E_e = E_s \times F_1 \times F_2 \qquad 5$$

Where *(units in italics):*

E_e = Exported capacity *(GW)*

F_1 = Intermittency load factor *(0-1, e.g. 30% capture = 0.3)*

F_2 = Export quota *(0-1, e.g. 100% exported = 1.0)*

F_1 is given by:

$$F_1 = \sum_{x=1}^{n} (A_x \times B_x/100) \qquad 6$$

In which

A_x = Renewables intermittency load factor for a specific technology (x) *(No units)*

B_x = Contribution to $E_{s\,total}$ for a specific technology (x) *(%)*

(e.g. in Table 23 E_s for Sweden = 11.3 × 0.38 × 1 = 4.3 GW or 37,615 GWh/yr)

Table 23: Projected renewable export capacity for a sample set of European countries in 2030 (units GW unless stated otherwise), source Eskandari Torbaghan et al. (2014)

Country	E_s			F_1*	F_2	E_e *(GWh/yr)***		
	$E_{s(min)}$	$E_{s(mean)}$	$E_{s(max)}$			$E_{e(min)}$	$E_{e(mean)}$	$E_{e(max)}$
UK	0	11.9	23.8	0.30	1.0	0.0 *(0.0)*	3.6 *(31,273)*	7.1 *(62,545)*
Sweden	0	5.65	11.3	0.38	1.0	0.0 *(0.0)*	2.1 *(18,807)*	4.3 *(37,615)*
Spain	0	14	28.0	0.37	1.0	0.0 *(0.0)*	3.5 *(30,660)*	7.0*** *(61,320)*
Norway	1.87	5.43	8.99	0.40	1.0	0.7 *(6,552)*	2.2 *(19,027)*	3.6 *(31,501)*
Netherlands	0	0.265	0.53	0.30	1.0	0.0 *(0.0)*	0.1 *(696)*	0.2 *(1,393)*
Ireland	0	1.82	3.64	0.30	1.0	0.0 *(0.0)*	0.5 *(4,783)*	1.1 *(9,566)*
Germany	0	20.65	41.3	0.36	1.0	0.0 *(0.0)*	3.5 *(30,660)*	7.0*** *(61,320)*
France	0	6.77	13.54	0.38	1.0	0.0 *(0.0)*	2.6 *(22,536)*	5.1 *(45,072)*
Denmark	0	1.56	3.12	0.30	1.0	0.0 *(0.0)*	0.5 *(4,100)*	0.9 *(8,199)*
Belgium	0	1.37	2.74	0.37	1.0	0.0 *(0.0)*	0.5 *(4,400)*	1.0 *(8,881)*

* Average load factor of the considered technologies in 2030

** Calculated by multiplying by 8760 (24 hrs/day, 365 days/yr)

*** Value limited to 7 GW due to interconnection capacity being reached

The average load factors and subsequent availability of RE for all ten countries are presented in Table 23*,* from which it can be seen that Norway has the highest average annual load factor reflecting the significant proportion of RE Norway generates from hydro power. In this set of analyses it was assumed that the maximum export capacity was limited to 7GW (i.e. seven interconnecting 1GW cables). This is in line with projected interconnection capacities for the UK in 2030 (Table 23).

For all countries it was assumed that 100% of the surplus renewable energy is exported via the interconnection (i.e. $F_2 = 1$ in Table 23). An 'optimistic' best-case scenario for the UK, as assumed in this example, would be complete access to all of this exported energy. There might be scenarios in which both the UK and the candidate country simultaneously have insufficient or no available renewable energy from a particular source on which both rely. For example, both countries could experience becalmed weather conditions which would prevent them from generating wind energy. An alternative issue could be a situation where scheduled maintenance of the interconnection prevents energy being transferred between the two countries. In the case study, the first case was modelled by considering the minimum capacity and the second case is possible for any interconnection and therefore has the same probability for all the considered countries. Unscheduled maintenance caused by accidents could also be a source of disruption to the trading of RE. In the case study this had been considered through the risk assessment procedure. However, Chatzivasileiadis *et al.*(2013) suggest that the chance of an unscheduled blackout is approximately 1% for the considered interconnections.

4.2.3.3 Step 3: Risk Assessment

In this step a preliminary 'qualitative' risk analysis was implemented to assess the probability (thereby acknowledging uncertainty) of achieving renewable capacities for E_s and E_e, outlined previously in Step 2. This was done through the Excel-based @Risk^{TM} software to represent a range of '*possible'* values that the factors could take instead of limiting them to a singular case (Palisade Corporation, 2012). The process is now described in two stages – input and output.

Input

In this stage, E_s, F_1, F_2 were defined as input variables for @Risk^{TM} and a probability distribution function was chosen to represent them. While it could be argued that the choice of probability distribution is subjective and has a considerable effect on the results (Sweeting, 2011), the major contributing factor is the type of data.

In this research ‘continuous’ distributions (i.e. a simplifying triangular probability density function) for E_s were adopted bounded to minimum and maximum values. While there are various bounded distribution(s) that could have been used (e.g. Pert, Beta and uniform) there was a lack of historical (observed) data against which to compare. Moreover, asymmetrical non-parametric distribution(s) based on three-point estimates (widely used by industry) have been shown to be more closely aligned with triangular rather than Beta or Pert distributions due to the levels of uncertainty achieved (Hulett, 2011).

In this research F_1 was defined as a random variable by allocating a ‘general’ distribution to it for each country, which reflects the uncertainties associated with adopting a mixture of renewable technologies for trading purposes (A_x) and renewable intermittency issues (B_x). For example, in the renewable scenario Norway has available electricity to export from hydro (A_1= 0.4, B_1= 87%), biomass (A_3= 0.53, B_3= 3%) and wind (A_4= 0.3, B_4= 10%), the assigned probability distributions being shown in Figure 21.

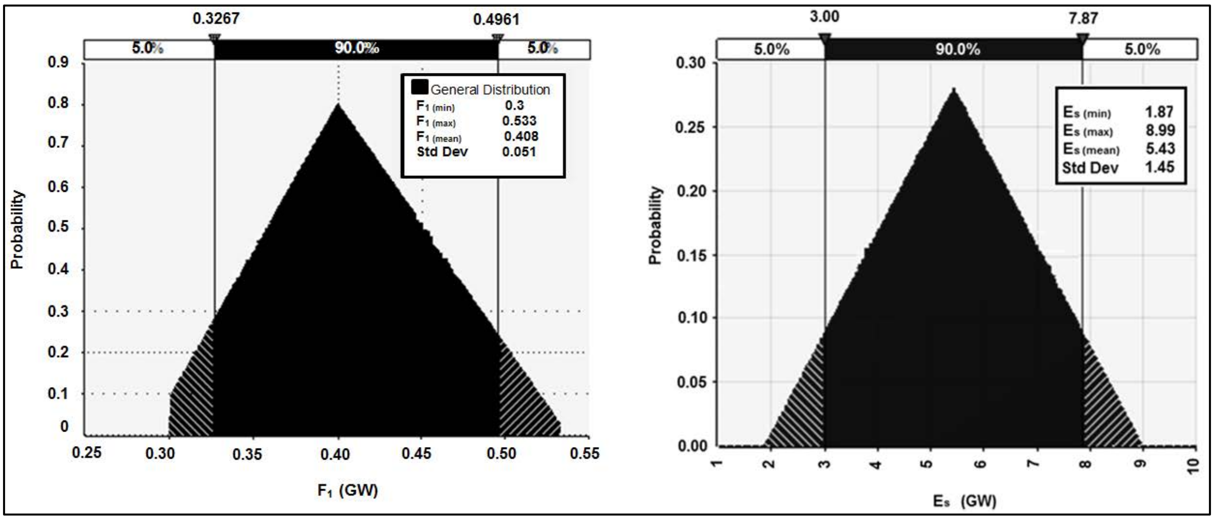


Figure 21: Triangle and General of Es and F1 respectively for Norway in 2030, source Eskandari Torbaghan et al. (2014)

The probability associated with F2, 1% chance of an blackout due to unscheduled maintenance (Chatzivasileiadis *et al.*, 2013), was modelled using a ‘binomial’ distribution (risk-binomial) that specifies the number of trials and probability of success (99% in this case) of each. The number of trials is set as 1, so there are two possible outcomes (0 or 1) where 0 (blackout) has a 1% probability. By setting Equation 5 as the worksheet formula, E_e became the output of the simulation.

Output

@Risk^{TM} was used to recalculate values of E_s, F_1, F_2 and E_e (for each of the ten chosen countries in the case study) many thousands of times (in this case 5000). During this 'Monte Carlo' simulation @Risk^{TM} random values for E_s, F_1 and F_2 were sampled from the assigned distribution function and placed within a statistical model, each time the resulting outcome was recorded ultimately to form a probability distribution for E_e. The distribution was used to read 80th percentile (P80) capacities (i.e. an 80% probability of E_e being less than this value). The respective E_e (P80) values for all candidate countries are summarised in Table 24, from which it can be seen that Germany has the highest capacity (10.97 GW) and the Netherlands has the lowest (0.13 GW). As a result, for the case study it was assumed that no UK-Netherlands interconnection would be feasible due to Netherlands' low E_e (P80).

Table 24: Projected Ee (P80) capacities in 2030, source Eskandari Torbaghan et al. (2014)

	$E_{e\ (P80)}$: GW	Distance from London: km
UK	5.475	-
Germany	10.971	918 (Berlin)
Spain	6.382	1254 (Madrid)
France	3.74	350 (Paris)
Sweden	3.0072	1437 (Stockholm)
Norway	2.7801	1129 (Oslo)
Ireland	0.8978	467 (Dublin)
Belgium	0.662	312 (Brussels)
Denmark	0.6376	941 (Copenhagen)
Netherlands	0.1329	332 (Amsterdam)

The developed tool has significant benefits for decision makers as it allows them to assess interconnection capacities by generating a range of energy supply/demand scenarios. The distinct advantage is that it does not require a team of experts and can be operated on a limited budget or where time restrictions exist.

An additional benefit of the tool is its capability to embed risk assessment add-ons such as @Risk^{TM} to facilitate consideration of energy uncertainties and risks. However, while step 3 provided a highly important risk assessment for 'surplus' exportable capacities, it is not the only risk. Further risk analysis was required to do this, considering factors such as construction and operation. Therefore this research supplement the risk assessment initiated in this section through a series of risk-based stakeholder interviews that identified other risks that were used within the proposed methodological approach.

Assessing the risk cost of the candidate countries was done through utilisation of the net present value method (NPV) within a whole life appraisal (WLA) technique. The methodology used in the case study to conduct WLA is described in the next section.

4.3 Whole Life Appraisal (WLA)

WLA is a useful technique for making an effective choice between various competing options as it discussed in Section 2.3. Therefore, as part of the overarching framework, WLA was suggested as a suitable technique for comparing the viability of making interconnections with candidate countries. The overall concept and its components were described in tions 3.2.2 and 3.3.2. The method used for utilising WLA for the case study is described in the following sections.

The following elements associated with WLA, were undertaken as part of the case study:

1. Establishment of the design life of an interconnection (assumed to be 40 years for each interconnection / candidate country (Chatzivasileiadis *et al.*, 2013))
2. Determine all costs and revenues associated with an interconnection (sections 6.2.2 and 6.2.3)
3. Discount all costs and benefits to today's value using the NPV technique tion 6.2.1)

The costs were determined from a literature review as described further in section 6.2.2. In order to determine the revenues, the model, described in Section 4.2, was used to forecast the availability of RE and the demand in both countries involved from which the interconnection's revenue was estimated (see Section 6.2.3).

The NPV decision rule was used as a means of interconnection investment appraisal where the NPV is given by (Flanagan and Jewell, 2008):

$$NPV = C_I + \sum_{i=1}^{T} \frac{C_{Oi}-R_{Ai}}{(1+r)^i} \tag{7}$$

Where *(units in italics)*:

C_I = Investment cost *(£)*

T = time *(40 years)*

C_O = Annual operational cost *(£)*

R_A = Annual revenue *(£)*

r = Discount rate (unit-less)

The costs in Equation 7 were those associated with the construction and operation of an interconnection. Investment (construction) costs (Section 6.2.2) included the cost of the cables, the convertor station (i.e. High Voltage DC (HVDC) cables and DC-AC convertor stations; an HVDC connection within an AC system requires two converter stations) and saving equal cost of generating electricity. The operational costs (Section 6.2.2) were to do with:

1. Maintenance costs
2. Annual cost of losing power due to heating of the line
3. Cost of imported RE

In order to determine revenue streams the likely supply capacity of the interconnections (E_e) (i.e. the energy available) was determined as described in Section 4.2. The revenue stream (Section 6.2.3) consists of i) the ability of the UK to sell spare renewable energy to the candidate country (after meeting its domestic demand); ii) CO_2 related cost savings (e.g. reduced carbon credit payments).

In this study when calculating the NPV using Equation **7**, the cost and revenue streams and the discount rate were considered as uncertain variables. These uncertainties are mainly caused by one or both of the following factors:

1. Uncertainties associated with future estimation
2. Construction and operational risks (which have impacts on future revenue and cost steams)

Two uncertain factors mentioned earlier were accommodated in the risk assessment framework.

1. Uncertain estimation were addressed by considering a range of values with associated probability instead of a single value estimation
2. Construction and operational risks were quantified to consider their impact and probability

4.4 Summary

The process for identifying the candidate countries through an initial screening exercise was described in this chapter. The method for assessing the interconnections’ capacity using generated scenarios was also discussed. The risks and uncertainties associated with generating and utilising energy scenarios were deliberated and a risk based approach was utilised to address them.

However, there are further uncertainties associated with interconnections, which also need to be addressed through the described cost risk model. These are associated with construction and operational risks and were identified via a literature review and from consultation with a panel of experts through the risk identification stage described in Chapter 5.

5 CASE STUDY: RISK IDENTIFICATION

A case study was used to demonstrate the practical application of the theoretical framework described in Chapter 3. Chapter 4 described the process utilised for calculating NPV, to be used for assessing the candidate countries, wherein the risks and uncertainties associated with interconnections were highlighted. Selecting the best option from the countries considered relies heavily on the risks associated with each country, and the manageability of these risks. This chapter investigates the risks related to construction and operation (including maintenance costs) of establishing and maintaining interconnections.

The risk identification process, described in Section 3.2.3.1, was conducted by using two sources

1. Literature review
2. Expert opinion

This chapter is divided into two main sections associated with the risk identified by literature review and those identified by experts respectively.

5.1 Risk identification; by literature review

The literature review was utilised to identify the major categories of risks associated with seabed interconnections and some further qualitative assessment was conducted on the identified risks to select the most suitable ones for the task in hand. Risks which were found at this stage to have the same low probability and/ or low impact for all candidate countries were not selected for further analysis by the expert panel. The identified risks are summarised in Table 25 and described in detail below.

Table 25: list of identified risks by literature review

Risk category	Risk ID	Identified risk
Social	H1	Public acceptability
Technical	H2	a. Loss of Dynamic Positioning (DP)
	H16C	b. Earthquake
	H3	c. Seabed topography
	H4	d. Seabed contamination
	H5	e. Unforeseen ship wrecks and other submarine debris
	H6C	g. Fishing activities and ship anchoring

Economic	H7	a. Uncertainty in cost estimation (quantity and rates)
	H8	b. Supply chain; contractor
	H9	c. Solvency of contractor
	H10	d. Inflated bid price
	H11	e. Cost of material
Environmental	H12C	a. Disturbing habitats and ecosystems
	H17C	b. Climate change
Political	H13	Changes in energy policy of candidate country
Social	H14	Demonstrations caused by raised price
Technical	H15	a. Availability of electricity from renewable resources
	H16(O)	b. Earthquake
	H6(O)	c. Fishing activities and ship anchoring
Economic	H18	Increase in prices of imported electricity
Environmental	H12(O)	a. Disturbing habitats and ecosystems
	H17(O)	b. Climate Change

5.1.1 Construction risks

In this section the major risks associated with the construction of interconnections are discussed with a view to selecting those risks which are appropriate for the countries in the case study. The risks have been divided into Social, Technical, Economic, Environmental and Political categories.

5.1.1.1 Social

Public acceptability regarding the investment of making an interconnection and also its environmental impacts were considered as sources of uncertainty for the project. The possible impact could be the cost of running a public enquiry, negative publicity and media coverage and could result in a potential cable route change. For example, public demonstrations occurred in protest of the environmental impacts of Westernlink (an interconnection being built between Western Scotland and the North Wales) and resulted in a 4km cable relocation.

5.1.1.2 Technical

i. Loss of Dynamic Positioning (DP)

DP systems which are used to keep a cable laying vessel at a determined position can be disturbed by severe storms, waves or currents preventing the vessel from keeping its position. This in turn could lead to excessive deformation (strain) on the cable (Worzyk, 2009). The associated delays can increase the construction cost, leading to less productivity of cable laying (Worzyk, 2009).

By selecting appropriate seasons for cable installation the risk of DP loss can be minimised, however, the risk cannot be mitigated completely. However, by studying wind and waves patterns the country with the minimum risk of loss of DP can be identified. To this end, Figure 22, which shows the annual mean wind speed at 100 metres above sea level, and Figure 23, which shows the annual mean wind significant wave height, were used in the case study. Both figures are provided by Department for Business Enterprise and Regulatory Reform (BERR) (2008a). From these it can be seen that wind speed and wave height are at their greatest in the northern part of the North Sea and that accordingly the risk exposure for Norway is high.

Figure 22: Annual mean wind speed at 100m, source BERR (2008a)

Figure 23: Annual mean wind significant wave height, source BERR (2008a)

ii. Earthquake

Some common types of earthquake damage to seabed cables include seabed displacement induced by fault movement, submarine landslides and seabed soil liquefaction (Aiwen, 2009). The risk of earthquakes can be mitigated by adopting a number of measures for improving the earthquake resistance of seabed cables (Aiwen, 2009). As for overhead cables, in general, they have been found to perform well in past earthquakes according to Oliveira et al. (2006).

One of the measures for reducing the consequences of an earthquake is avoiding areas with a high probability of earthquake occurrence which may require longer routes. The threat of the occurrence of earthquakes may also require increases in costs associated with the adoption of earthquake resistant construction methods and cables.

Figure 24, which shows potential earthquake sources in the vicinity of the UK, suggests that the possible occurrence earthquake is very low.

Figure 24: UK map of earthquakes, source Simkin *et al.* (2006)

iii. Damages caused by anchors, kinks and loading/re-loading

These three risks are related to accidents which may occur during a cable laying procedure damaging the cable as a result of:

1. The anchors used for mooring of cable laying vessels
2. Insufficient coordination of a cable laying vessel's forward motion and cable pay-out mechanism which may cause kinking of the cable
3. Accidents during the loading of a cable onto a vessel or during cable transfer between its land transport and a cable laying vessel.

However, these three risks were not considered further for assessing the proposed countries, since their possible cause is associated with human or mechanical error and are difficult therefore to differentiate between the candidate countries.

iv. The Seabed topography

The existence of boulder fields and / or an excessively stiff seabed or one of irregular stiffness can raise the cost of constructing trenches. An appropriate marine survey is vital to identify such occurrences and minimise the associated risk. In some cases however, it is not always possible to identify unusual conditions using such conventional techniques. For example, the presence of a hard rock under a layer of soft sand is often problematic to detect.

Figure 25 shows the seabed topography in the surrounds of the UK. From which it may be seen that the majority of the North Sea seabed is sandy in nature and therefore is considered relatively easy to lay cables on, and that some stiff (rocky) seabed exists in some parts of the UK, Ireland, Norway and Sweden coastlines.

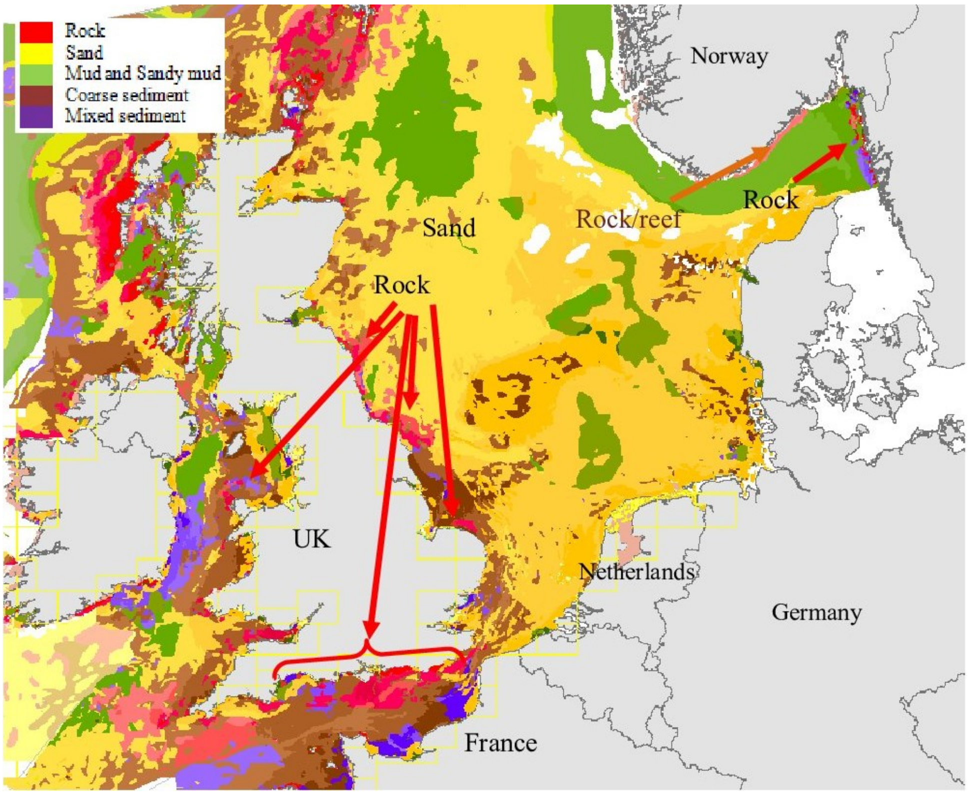


Figure 25: Seabed topography around the UK, source MESH (2014)

v. Seabed contamination

Oil and gas fields are sources of contamination in the sea (Liang *et al.*, 2009). The locations of oil and gas fields and the other offshore infrastructure in seas surrounding the UK are given in Figure 26 from which it can be seen that during construction of an interconnection from the UK to all of the countries considered in the study, except for France, Ireland and Spain there is a high likelihood of encountering an oil or gas field.

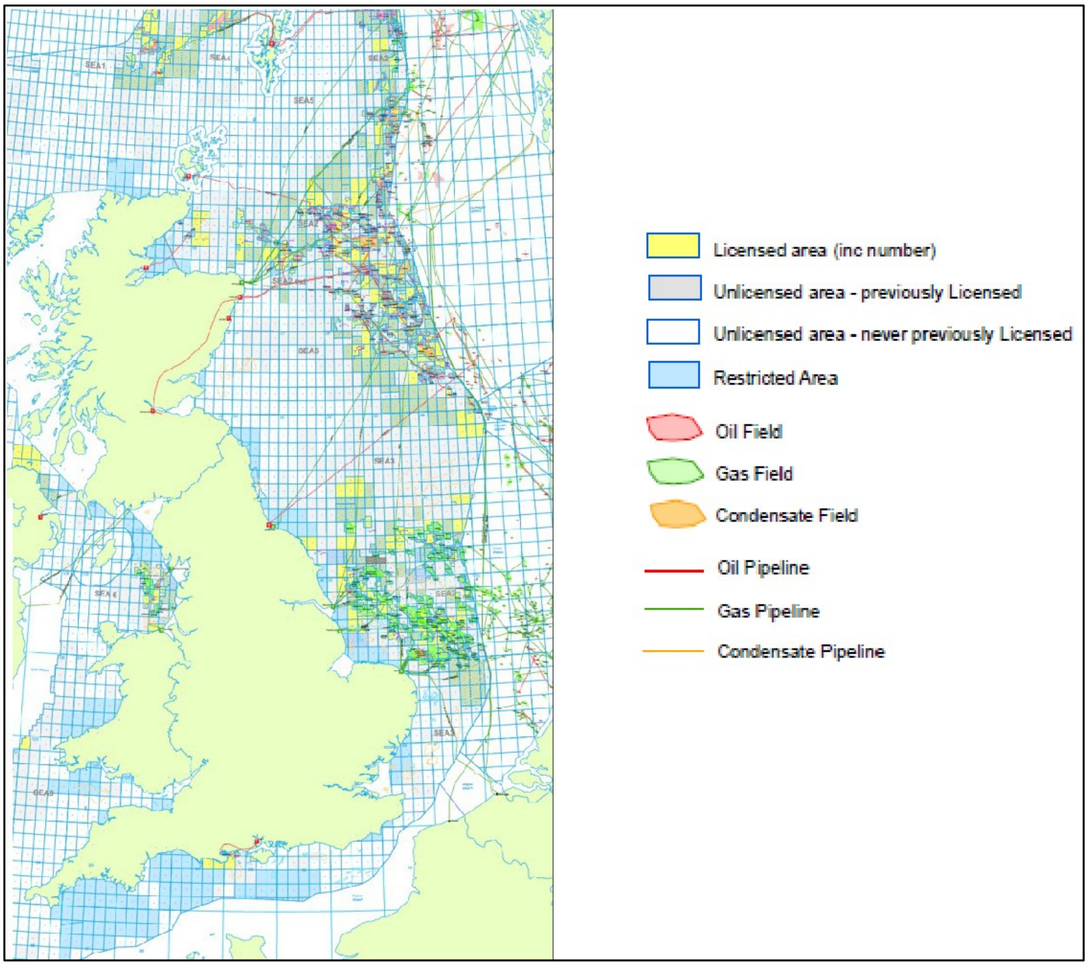


Figure 26: Map of UK offshore infrastructures, source DECC (2014c)

The impacts of encountering contamination during the installation procedure are associated with difficulties in cable laying, possible corrosion of cables and the cost of cleaning or avoiding the contaminated land. In addition the possibility of encountering other cables and pipelines as well as abandoned cables increases in the vicinity of the oil and gas fields. Existing cables and pipelines can be identified by conducting marine surveys as well as when obtaining associated permissions and coordination for construction of a new interconnection.

vi. Ship wrecks and other submarine debris

Suitable marine surveys can be used to identify ship wrecks and other submarine junk which can require changing the route of the cable and / or a cost associated with removing the debris during construction. The data provided by European Marine Observation and Data Network (2011) (Figure 27) shows the positions of wrecks in the North Sea and was used herein to identify the risks of encountering debris for the nine candidate countries.

From Figure 27, it may be seen that the ship wrecks risk exposure for countries located in the south of the North Sea and English Channel is high.

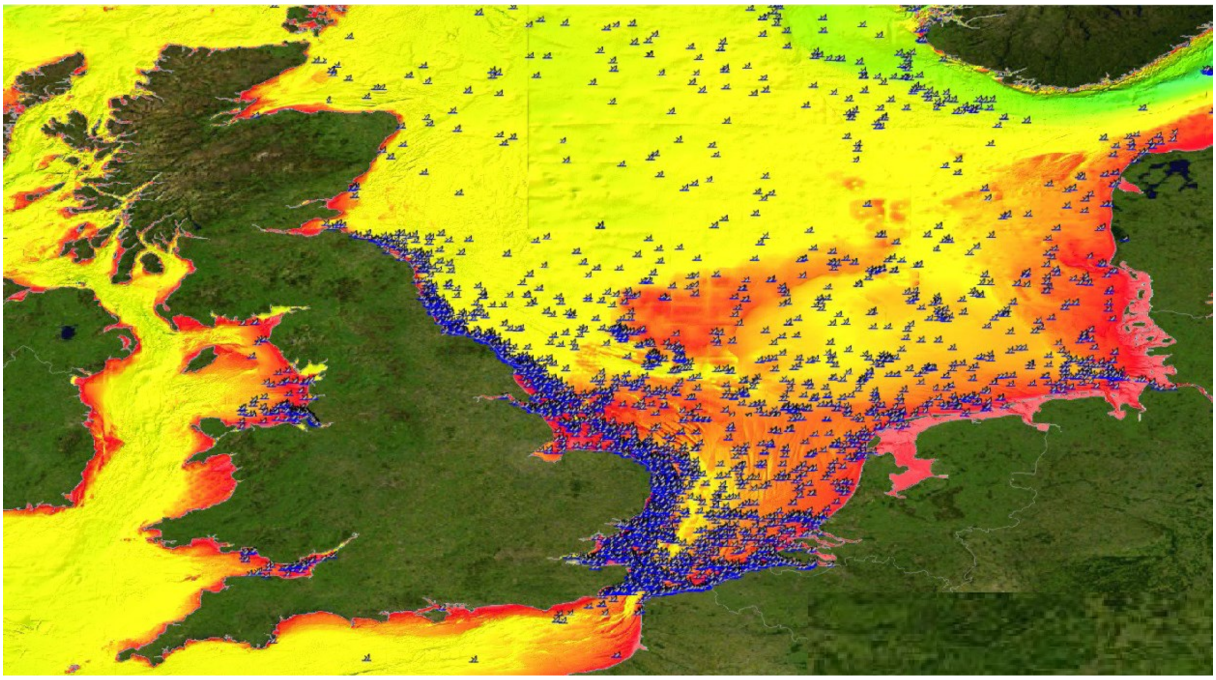


Figure 27: Wrecks positions in North Sea source European Marine Observation and Data Network (2011)

vii. Fishing activities and ship anchoring

Fishing activities and/ or anchors are a major cause of seabed cable failures (CIGRÉ, 2009; Karlsdóttir, 2013). These risks can be reduced significantly by avoiding the areas with high vessel and fishing traffic or by using protective measures such as burying cables. Nevertheless, such measures and the associated studies required to identify areas of high shipping and fishing density evidently add to the cost of construction. These costs can be reduced by limiting fishing and shipping activities during the cable laying procedure.

Finding appropriate data regarding sea vessel traffic, is now relatively straightforward, as the International Maritime Organization (IMO) requires all vessels to transmit their position (International Maritime Organization, 2013). In Europe, data provided by the European Commission (2011a) showing maritime traffic was utilised for the case study (see figures 28 and 29). As far as the UK is concerned, heavy shipping occurs in the South of the UK and the English Channel. It is lighter in the North and almost no fishing activity occurs in the North-East of the UK (figures 28 and 29).

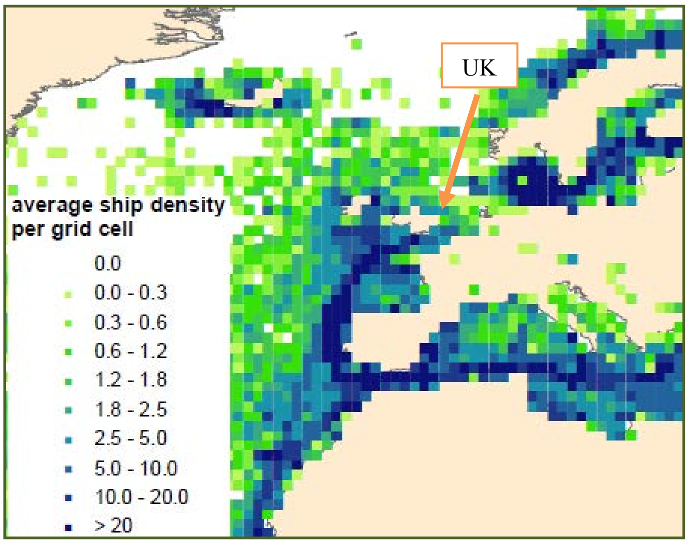


Figure 28: Maritime traffic density (all ships) around the UK, source European Commission (2011a)

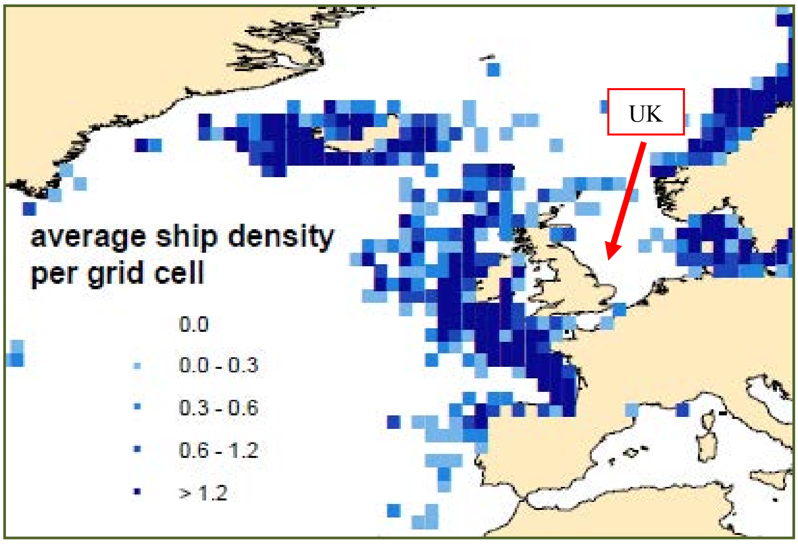


Figure 29: Density map of fishing vessels around the UK, source European Commission (2011b)

5.1.1.3 Economic

i. Uncertainty in cost estimation

A major source of risk in a project is the inaccurate forecasts of project costs and duration and therefore predictions of benefit and costs ratio (Flyvbjerg, 2006). Additional explanations on inaccuracy in forecasts, the reason behind it and the proposed measure for dealing with are provided in Appendix E. Generally, those countries with a high number of existing interconnections have the least cost estimation risk since they are likely to be able to provide an appropriate amount of historical data for the estimation. Table 26 shows the number of seabed interconnections for the nine countries considered in this study (see ENTSO-E, 2014), from which it can be seen that those with the least cost estimation risk are likely to be Sweden and Denmark each with seven existing interconnections and three under construction. However, adequate data about seabed interconnections should be available in the UK, since it is the offshore wind world leader (Kern *et al.*, 2014) and it also has four seabed interconnections with other countries (DECC, 2015).

Table 26: Number of seabed interconnections for nine candidate countries

Country	Number of seabed interconnection	Comments
Norway	4	Including 1 under construction
Sweden	10	Including 3 under construction
Netherlands	2	-
Germany	3	Including 1 under construction
France	3	-
Denmark	10	Including 3 under construction
Spain	7	Including 5 under construction
Belgium	0	-
Ireland	1	Under construction

ii. Supply chain; contractor

Building an interconnection with a country with little or no competition between contractors, (i.e. where any development is restricted to a single organisation such as grid operator e.g. France where only Réseau de Transport d’Electricité (RTE) is eligible for any grid development) can increase the cost of a project.

iii. Solvency of the contractor

Contractors involved in the construction of an interconnection which then become insolvent can delay a project. Additionally, the cost of the project can also increase as a result of the additional cost required to purchase insurance policies to protect the contractors from insolvency. This can be exacerbated during times of economic recession when insurance costs are higher and the risk of insolvency greater. To account for these risks in the case study, the changes in Gross Domestic Product (GDP) over time for the nine candidate countries were used as an indicator of local contractor solvency (Figure 30).

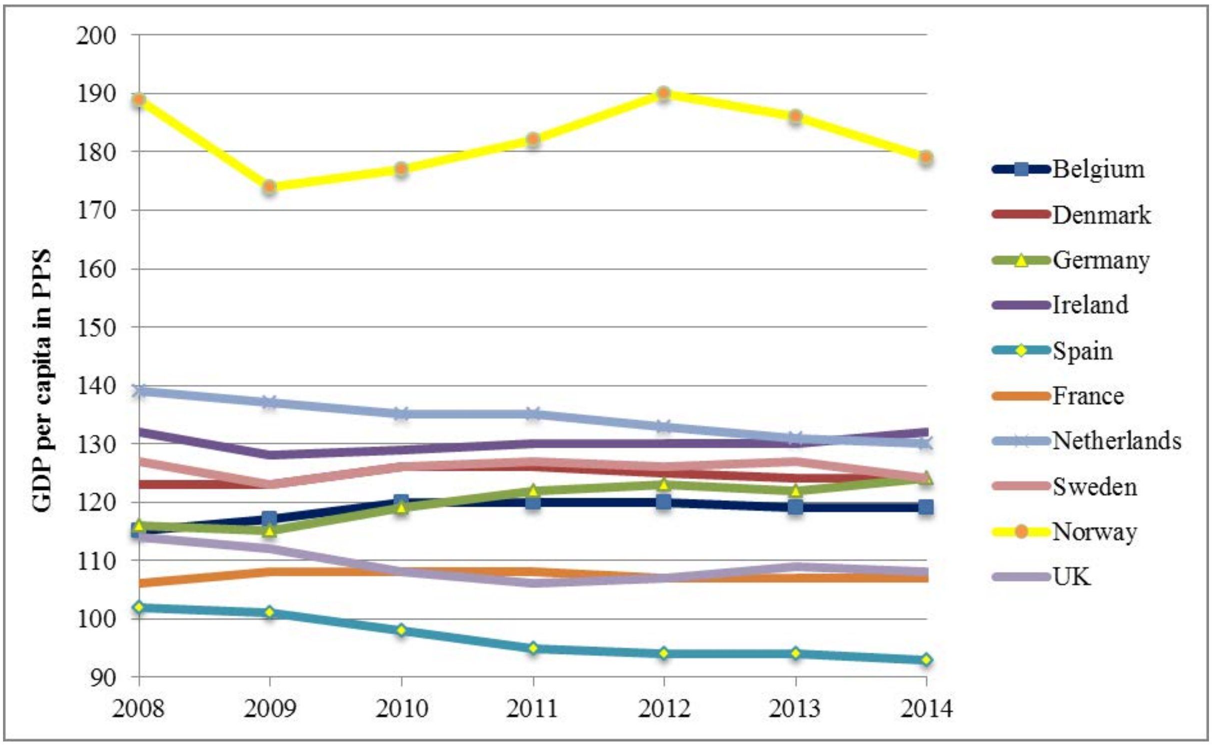


Figure 30: Nine countries and the UK's GDP history, source (Eurostat, 2015b)

iv. Inflated bid price

Laying interconnections is a specialist task and consequently there are relatively few contractors operating in the business. The resulting lack of competition can cause an inflated bid price for the work, thereby increasing the cost of the project. This risk may be lower for those countries with greater experience of undertaking similar projects (Narayanan, 1999).

v. Cost of material

The overall cost of a seabed interconnection is largely driven by the cost of the key raw materials used in cables. This is primarily copper or aluminium (Decker *et al.*, 2011). The superior conductivity of copper compared to aluminium, means that cables made of copper require a smaller cross sectional area to achieve the same capacity (Decker et al., 2011). This can make transport and installation of a copper cable easier. However, the surge in global demand for copper has not only driven the price of copper to historically peak levels, but has also introduced significant volatility in its price (see Figure 31 below). For example, in the last 5 years the global price of copper reached a peak of £6/ kg in compared to around £1.6/ kg for aluminium in the same period (Figure 31). It is likely that a manufacturer of cables made from copper as a raw material would account for this price risk in its quotation, therefore pushing up the price of a seabed interconnection. This is exacerbated by the fact that globally there are a limited number of suppliers of cables used for interconnections, i.e. Prysmian in Europe (formerly called Pirelli). However this risk exists equally for all the candidate countries and thus was not used in the case study for assessing the candidate countries.

Figure 31: Copper and Aluminium price history, source InfoMine.com (2015)

5.1.1.4 Environmental

i. Disturbing habitats and ecosystems

Marine habitats and ecosystems may be disturbed by the cable laying and associated actions. Changing the route during the construction, to mitigate disruptions to natural habitats, leads to increased construction cost. Interfering with marine habitats should be avoided in the design phase by identifying them properly. In addition, an appropriate marine survey can identify the existing habitats to be avoided, albeit at a possible risk of increasing the cost of construction.

The approach adopted herein was to identify the major existing habitats between the UK and the nine proposed countries. According to data provided by MESH (2014) significant numbers of faunal communities are predicted to exist on rock surfaces, whilst there is a relatively low diversity of communities on sandy seabed. This suggests that according to the geological map of the North Sea seabed (see Figure 25) the risk of disturbing marine habitats and ecosystems is likely to be most significant along the coastlines of Sweden and Norway.

Adopting technical measures such as burying a cable or anchoring a cable can address many environmental risks without any significant cost. It was revealed during one of the interviews that in the Westernlink project this issue was addressed near to and on the shore by laying the two polar cables 20 cm apart so they neutralize their magnetic fields.

The stringency of various environmental regulations in the candidate countries can also be considered to add to the impact of this risk.

ii. Climate change

Risks associated with climate change include the costs of studies to identify potential impacts and possible mitigation measures of climate change on the changes in strengths and direction of water currents and waves. Severe winds and waves can affect crew productivity. It is reported by Worzyk (2009) that in extreme weather 10 to 30 per cent of the crew might be sick and unable to work at any one time.

5.1.1.5 Political

A change in energy policy of the exporting country impacts the availability of renewable energy and can threaten the feasibility of a project. This can be caused through the pressure of public opinion, such as has happened recently in Germany after the Fukushima nuclear disaster which caused Germany to reduce its nuclear energy capability. The knock-on effect of Germany's new energy policy is that it has less available renewable energy to export because of the necessity to replace nuclear energy sources. Further, new energy policies might also lead to imposing higher tax or charges and therefore increase the cost of importing electricity from that country.

5.1.2 Operational and maintenance risks

Operational risks considered in this research, include the threats to operating interconnections, such as any changes in the candidate country which may lead to a scarcity in exportable renewable electricity, increases in maintenance costs and/ or blackouts.

Maintenance risks include those associated with accidents (e.g. caused by fishing activity) during the operation of an interconnection which may lead to unscheduled maintenances and/ or blackouts.

5.1.2.1 Social

Possible demonstrations in both involved countries caused by the energy price rises associated with the higher cost of renewable energy may threaten the operation of an interconnection (see Parail, 2010a on impacts of interconnections on electricity prices). This might cause the government to impose restrictions on lending money for the operation and/or maintenance of interconnections.

5.1.2.2 Technical

i. Availability of electricity from renewable resources

The risk depends on the energy generating characteristic of the candidate country considering the intermittency of renewables. For example importing electricity from a country which relies on the wind for generating electricity is risky as there is no guarantee of the availability of wind power. A potential effect of this risk can be a loss of profit caused by a power blackout.

ii. Earthquake

As discussed earlier in this section there is no earthquake hot spot in the vicinity of East, South and West of the UK, where the cables are likely to come into the UK. The impact of this risk however, is associated with the cost of maintenance of minor earthquake induced damage.

iii. Fishing activities and ship anchoring

Fishing activity or anchors are the major causes of seabed cables' failures (see Figure 32). The possible impact of the risk is the cost associated with maintenance of minor or major damages. Fishing equipment and anchors can snag on a seabed cable, unearth it or damage it to the extent an electrical failure occurs (Svoma *et al.*, 2009). Risks associated with fishing activities can impact both the construction and operations phases of a project (see tion 5.1.1.2).

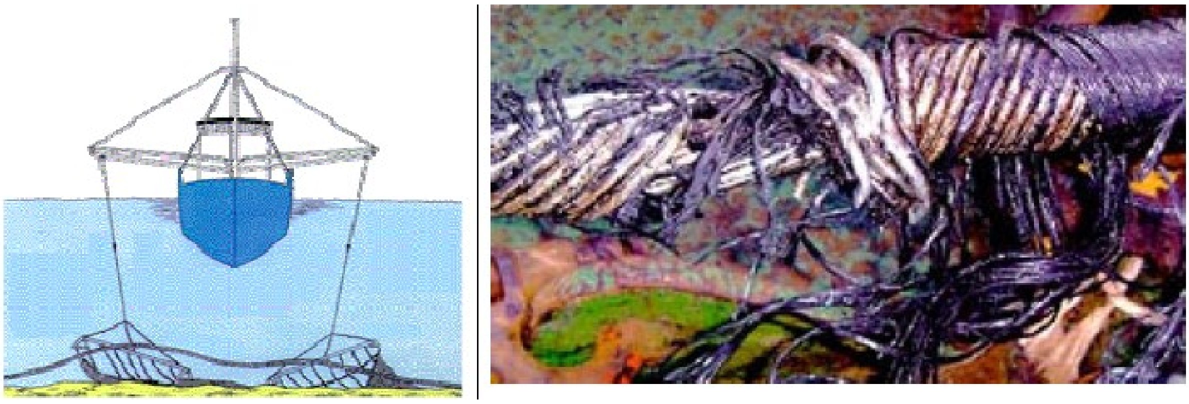


Figure 32: Schematic of fishing accident and damage to a snagged cable, source ISLES (2012)

5.1.2.3 Economic

The impacts of any increase in prices of the exported electricity can be significant, especially on tax payers and electricity consumers in the importing country.

To this end, the history of the price of electricity of the candidate countries was used as an indicator of the future price of its electricity. The electricity prices for household consumers of the nine considered countries over a 14 year period are shown in Figure 33, from which it may be seen that Ireland has experienced the greatest change (around 150%), whilst Norway has had the greatest fluctuation in price over this period. Although the prices shown in Figure 33 concern the domestic market, and in some countries may be subsidised by the tax payer, they still may be regarded as a useful metric associated with pricing energy.

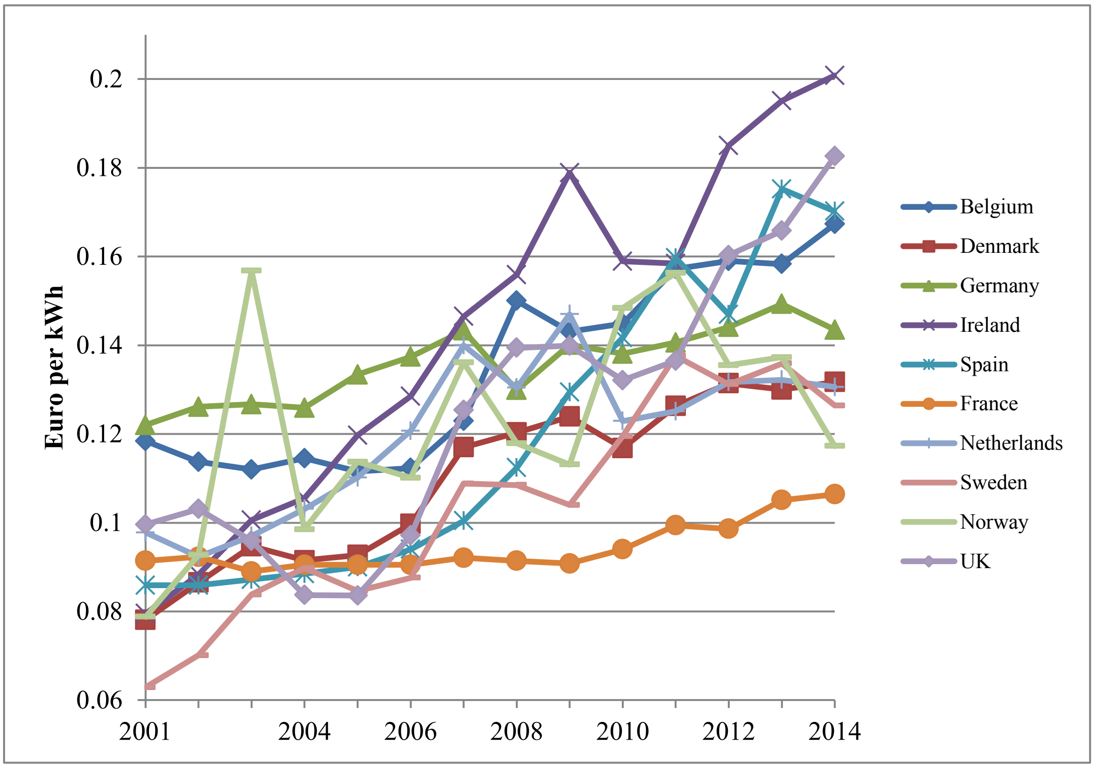


Figure 33: Electricity price history for 9 candidate countries and the UK (€ / kWh), source Eurostat (2015a)

5.1.2.4 Environmental

i. Disturbing habitats and ecosystems

The cost of avoiding disturbing new habitats formed on and around cables during maintenance can increase the maintenance cost (Kogan *et al.*, 2003). Besides, electromagnetic fields made by seabed cables might influence the migration of fishes such as salmon and eels (May, 2005; Boehlert and Gill, 2010). The electromagnetic fields caused by overhead cables may also have an impact on human health (Huss *et al.*, 2009) and animals (Drewitt and Langston, 2006).

Also severe weather events, which are predicted to increase in many areas due to climate change, can impact oceans currents and tides (Nelson *et al.*, 2009; Greenberg *et al.*, 2012) which can have a significant impact on seabed cables causing major movements and possibly as a result blackout.

5.1.2.5 Political

ii. Changes in energy policy

Changes in energy policy can threaten the trading of electricity in two ways; first the changes can lead to an agreement being revoked. Although, long term contracts between the two countries can reduce this risk. When both countries have invested in the construction of the interconnection, the probability of the occurrence of such a risk will be almost zero. Second the availability of renewables might also be threatened as a result of changes in energy policy for example by generating electricity from nonrenewable technologies. Nevertheless the probability of this risk is currently low, as there is a trend amongst European countries towards increasing the proportion of renewable energy used. All of the countries considered also have a target of renewable energy to achieve.

iii. Security of renewable energy supply

Some threats to energy security include (Wesley, 2007):

- The political instability of energy producing countries,
- The manipulation of energy supplies,
- Terrorist attacks on infrastructure

These threats are very unlikely to occur however when the interconnections are between democratic countries, such as those in the European Union. The risk related to the manipulation of RE supply also has a low probability of occurrence (unlike fossil fuel). This is due to technical issues and costs related to storing electricity, such as using batteries. Furthermore, and in general, Battaglini et al. (2010) argues that an equitable and well thought-out deal between two countries can set the fundaments for a reliable electricity supply.

5.2 Risk identification; expert opinion

As it is mentioned above experts opinion was used during the risk identification process. To address the possible bias of interviewees, experts with different backgrounds were selected.

The risks chosen by the experts to be used for assessing the candidate countries are presented in Table 27 (see Appendix F for the experts' responses). As shown in Table 27 all the identified risks uncovered in Section 5.1 were confirmed by at least two experts. The risks identified by experts are presented in Table 28 and the selected risks for further analysis described in detail below.

Table 27: Expert judgment on the identified risks

Risk category	Risk ID	Identified risk	Number of experts agreeing / total number of questioned experts
Social	H1	Public acceptability	13/20
Technical	H2	a. Loss of Dynamic Positioning (DP)	5/20
	H16C	b. Earthquake	2/20
	H3	c. Seabed topography	9/20
	H4	d. Seabed contamination	8/20
	H5	e. Unforeseen ship wrecks and other submarine debris	5/20
	H20	f. Unforeseen sea depth	1/4
	H21C	g. Weak onshore grids	2/4
	H19	f. Regulatory framework	7/10
	H6C	g. Fishing activities and ship anchoring	11/20
Economic	H7	a. Uncertainty in cost estimation (quantity and rates)	11/20
	H8	b. Supply chain; contractor	9/20
	H9	c. Solvency of contractor	8/20
	H10	d. Inflated bid price	9/20
	H11	e. Cost of material	6/20
Environmental	H12C	a. Disturbing habitats and ecosystems	11/20
	H17C	b. Climate change	7/20
Political	H13	Changes in energy policy of candidate country	15/20
Social	H14	Demonstrations caused by raised price	6/20
Technical	H15	a. Availability of electricity from renewable resources	12/20
	H16(O)	b. Earthquake	3/20
	H6(O)	c. Fishing activities and ship anchoring	7/20
	H21(O)	e. Weak onshore grids	2/4
Economic	H18	Increase in prices of imported electricity	13/20
Environmental	H12(O)	a. Disturbing habitats and ecosystems	9/20
	H17(O)	b. Climate Change	5/20

Table 28: Newly identified risks by experts

	Risk category	Identified risk	Risk description	Risk impact	Comments
Construction risks	Technical	New transmission technologies	New developed transmission technologies can bring opportunities to the interconnections	Increase or decrease in costs Decrease the transmission loss	This risk was not added to the questionnaire as despite being a risk it has same impact and probability for all candidate countries as there are few companies which are leading the transmission industry
		Electrification of the transportation system	Increasing use of electric cars and their usage for storing electricity	Impacts on demand profile and peak hours and therefore less spare electricity to be traded	This risk was not used for comparing the countries as it is in its early stages of development and its implication in future relays on its technological developments rather than countries choose
		Cost of material			Politics was identified as additional cause of the risk (initially only inflation) which is added to the risk description
		Regulatory framework	Different regulatory framework between the UK and candidate country	High impact on the selection of the country as well as adding cost to introduce new joint organisation for operating the new interconnection. Also risk of not cooperating regulatory in a country and cost allocation issues. e.g. Rates of return allowed, Ramp rate and other market rules	This risk was added to the questionnaire. This risk was also mentioned by De Decker and Woyte (2012) under "Regulatory challenges"
		Competition	Competition between interconnections	Risk from competition for interconnections so there can be a business case for building one to a country but an interconnection to another country can win the competition and then there is no more case for the interconnection to be built	It has almost same impact and probability for all candidates and it is more a general risk and therefore not useful for comparing the candidates
		Storage technologies	Development of new electricity storage technologies threating the feasibility of new interconnections	The development of storage technologies can threaten the interconnections however, they are in early stage and the possibility of the economic feasibility is low	Furthermore this risk is generally threatening the interconnections so it was not added for comparing candidates.
		Unforeseen sea depth	Unpredicted sea depth during the installation or need for conducting measurements due to existence of non-studied zone during design phase	Added cost during installation and/or design of the cables	This risk was added to the questionnaire
		Weak onshore grids	Weak infrastructure at the connection points to the grids might lead to further cost to upgrade the systems	Added cost to the project	The risk was added to the questionnaire
	Economic	Governmental support	Financial support from the governments as well as consistency regarding willing for making the interconnections	Long period for designing and building the interconnections leading to overrunning the budget or even stopping the project	This risk and its impacts is very similar to the changes in energy policy so this risk was not added
		Discount factor for investment	The discount factor has high impact on the NPV and therefore on the decision making by considering cost benefit analysis	Different return on investment from the initial estimation on which the decision had been made to build the interconnection	This is a common risk for any investment and its probability might be very high for the interconnections as the uncertainty is high regarding the profit and loss of the system. However this risk was not added to the questionnaire as its probability and impact are very similar for all candidate countries however, a sensibility analysis in the WLA model was conducted to assess its impact on decision making
	Political	Climate change	The opportunity brought forward by climate change mitigation policy to push forward the interconnections	Opportunity; its impacts on policy makers to push forward the interconnections	As the model was not considering the opportunities this risk was not considered but it can be modelled in future work

		Capacity Market	Capacity market legislations are being conducted individually in each European country which can lead to less willingness for developing interconnections for having more stable prices and lower fluctuations	Long duration for getting permission or cancelation of the project	As the cause and impact are very similar to the changes in energy policy this risk was categorised under same risk but just the new caused was added to the questionnaire [for more information on Capacity Market see (DECC, 2013a)]
		Banking	Financial risk regarding borrowing money which can be raised in countries with less stability	Cancelation or delay of the project	This risk depends on the owner and or investor of the interconnection. Assuming public sector to be responsible for the project (which is more likely by considering the history and responses from experts during interviews) then this risk is not relevant or can be translated and categorised as changes in energy policy but it is an important risk for privet sector and therefore in that case it was considered as the solvency of contractor
		Carbon Tax and price	New carbon price can has impact on the future of interconnection	Opportunity; by introducing high carbon price enhancing the feasibility of interconnection or threat by decreasing the carbon price	As the opportunity was not modelled the risk was merged with the political risk and added to the risk description
Operational risks	Technical	New storage technologies	The developed storage technologies in future, such as batteries and even the new technologies such as power to gas (using gas pipe line to store the electrolysed Hydrogen produced from surplus wind energy), might threaten the usage of interconnections in future	Limited usage of interconnections and/or spare electricity	This risk relays on the developments of storage technologies and therefore was identified as unsuitable for comparing candidate in this stage
		Weak onshore grids	Weak infrastructure at the connection points to the grids can lead to loss of electricity	Losing profit due to electricity loss	The risk was added to the questionnaire
	Economic	Price of electricity (opportunity)	A more interconnected Europe will cause the price to decrease all around the continent by introducing new compatible renewable resources and more flexibility (less use of expensive plant margins)	Opportunity; decreasing the price of electricity	It is a general risk and cannot be used to compare the countries
		Future additional interconnections	Newly built interconnections can pose a threat to those already existing due to competition for supply of electricity.	This can have an impact on the future availability of RE as well as the current price of electricity leading to a decrease in the return on investment of the existing interconnection and an associated loss of profit.	Assessing this risk requires knowledge of the future plans for developing interconnections in each candidate country. This risk was not added to the questionnaire. For more information see Parail (2010b) and Decker et al. (2011).
		Customer duty	Changes in associated taxation for importing electricity	Higher price for imported electricity	As the impact is on the price of the RE this risk was added as the new cause of increase in prices
	Political	Availability of RE	Pressure from national government not to export at times of high demand and low supply	Increase the price of importing electricity and the availability of RE	As the impact is on the availability of interconnection it was added as a new cause to the risk of availability of RE (link between political and technical risks

5.2.1 Regulatory framework (Construction risk)

Different existing regulatory frameworks between countries forming an interconnection require the introduction of a joint organisation to build the new interconnection which might cause delay and additional costs for obtaining the required approvals. In the pan-European transmission system this is being addressed by the development of an unified regulatory framework of national and regional grid codes, which takes into account grid connection charging methods (Hendriks *et al.*, 2010). However, due to dissimilarities in the existing regulatory frameworks in the countries concerned and the interdependency between technical, e.g. voltage, and regulatory aspects in Europe a complete accomplishment of a unified framework has yet to be achieved (Hendriks *et al.*, 2010).

5.2.2 Sea depth (Construction risk)

Construction costs increase as a function of sea depth and are exacerbated when the sea depths are unknown. Whilst the seas surrounding the UK are well mapped and their depths are well known in remote areas around the world this is not necessarily the case.

5.2.3 Weak onshore grids (Construction and operation risk)

Connection points of interconnections are usually located away from the main areas of population where access to a strong grid with the required properties to connect with the interconnection is limited. Weaker infrastructure at the connection points can lead to additional cost requirements in order to upgrade the grid to avoid the risk of losing the entire capacity which might threaten the network stability (Ibrahim *et al.*, 2012). Improving the grid at a connection point including construction of a new grid is capital intensive but may often be unavoidable.

Voltage fluctuation due to load fluctuation in a weak grid can be magnified which can aggravate the power quality problem (Ayodele *et al.*, 2012). Weak onshore grids at the connection points can lead to loss of electricity and therefore loss of income as well as the possibility of the failure of the entire system resulting in a possible blackout.

ENTSO-E (2014) provides a map for the European countries showing the existing, under construction and planning electricity infrastructure. It was assumed that the number of existing grid connection points in the candidate countries located in the shores facing the UK (Table 29) was an indicator of having a higher possibility of strong connecting points for the new interconnection. Based on this assumption, Sweden and Belgium were considered to be the greatest risk, and Spain and Norway are the least risky.

Whilst the ENTSO-E map does not provide complete details of all of the grids it was considered a satisfactory source of information for the case study. For future work a more detailed map against defined criteria (such as required voltage) of the considered countries should be considered for a more accurate assessment.

Table 29: Number of interconnections and grid branches facing the UK for nine candidate countries, source ENTSO-E (2014)

Country	Number of connection points
France	>10
Spain	>10
Norway	6
Netherlands	4
Germany	4
Ireland	4
Denmark	3
Sweden	2
Belgium	1

5.3 Risks identified after the literature review and expert consultation process

For the purpose of this study only risks which were found to be different in terms of either their impact or probability between the countries considered were analysed further. These are shown in tables 30.a and 30.b. For example, “Security of renewable energy supply” was not considered further as its impact and probability can be considered to be very similar for the countries considered. However, an exception was the impacts associated with earthquakes because it was confirmed by three the experts as being a possible risk.

The risks identified in this section were further analysed in a semi-quantification process described in the next chapter.

Table 30.a: Identified risk associated with the construction of an interconnection

	Risk category	Identified risk	Primary sources	Suggested sources of information
Construction risks	Social	Public acceptability	Expert's opinion	
	Technical	a. Loss of Dynamic Positioning (DP)	Worzyk (2009)	
		b. Earthquake	Aiwen (2009)	Simkin et al. (2006) for Hot spots
		d. Seabed topography; Unforeseen excessively stiff seabed	Expert's opinion	MESH (2014) for seabed map
		e. Seabed contamination	Liang et al.(2009)	DECC (2014c) for UK offshore infrastructures
		f. Unforeseen ship wrecks and other submarine debris	Expert's opinion	European Marine Observation and Data Network (2011) for map
		g. Unforeseen sea depths	Expert's opinion	
		h. Weak onshore grids	Expert's opinion, (Ayodele *et al.*, 2012; Ibrahim *et al.*, 2012)	
		i. Regulatory framework	Expert's opinion	Hendriks et al.(2010) for literature review
		j. Marine activities; fishing activities and ship anchoring	(CIGRÉ, 2009; Karlsdóttir, 2013)	International Maritime Organization (2013) for regulations, European Commission (2011a) for map of activities
	Economic	a. Uncertainty in cost estimation (quantity and rates)	Flyvbjerg (2006)	ENTSO-E (2014) for list of existing interconnections
		b. Supply chain; contractor	Expert's opinion	
		c. Solvency of contractor	Expert's opinion	Eurostat (2015b) for European countries financial data
		d. Inflated bid price	Narayanan (1999)	
		e. Cost of material	Decker et al. (2011)	
	Environmental	a. Disturbing habitats and ecosystems	Van den Hove et al (2007)	
		b. Climate change	Expert's opinion	
	Political	Changes in energy policy of candidate country	Expert's opinion	

Table 30.b: Identified risk associated with the operation of an interconnection

	Risk category	Identified risk	Primary sources	Suggested sources for data collection
Operational risks	Social	Demonstrations caused by an increase in the price energy	Expert's opinion	Parail (2010a) on impacts of interconnections on electricity prices
	Technical	a. Availability of electricity from renewable resources	Expert's opinion	
		b. Earthquake	Expert's opinion	
		c. Marine activities; Fishing activities and ship anchoring	(CIGRÉ, 2009; Karlsdóttir, 2013)	International Maritime Organization (2013) for regulations, European Commission (2011a) for map of activities
		e. Weak onshore grids	Expert's opinion and also (Ayodele *et al.*, 2012; Ibrahim *et al.*, 2012)	
	Economic	Increase in prices of imported electricity	Expert's opinion	Eurostat (2015a) on electricity price history
	Environmental	a. Disturbing habitats and ecosystems	Expert's opinion	
		b. Climate Change	Expert's opinion	(Nelson *et al.*, 2009; Greenberg *et al.*, 2012) about impacts on oceans currents and tides

6 CASE STUDY: RISK ANALYSIS

The process utilised for calculating NPV to assess the candidate countries and the risks associated with those countries were described in chapters 4 and 5 respectively. This chapter describes the process utilised to analyse the risks related to construction and operation of the considered interconnections through two stages, risk semi-quantification and risk quantification.

Section 6.1 describes the process utilised for obtaining risk scores through the semi-quantification stage where Section 6.2 presents the risk quantification stage which models the impact and probability of identified risks within the NPV technique. The results of the case study are presented and discussed in Section 6.3.

6.1 Risk semi-quantification

As described in Section 3.3.4, the method for semi-quantifying the identified risks is based on BS EN 31010: 2010 and was adopted from the UK's Highways Agency standard risk assessment and the best practices guidelines (BSI, 2010; IRG, 2013). The analysis utilised semi-qualitative method including mapping identified risks to the activities of building and maintaining the interconnections.

To semi-quantify the risks, interviews were conducted with the panel of experts (see Section 3.3.5). An integer scale of 1 to 5 was used to rate the probability and impact of each risk, where 1 represents a very unlikely event, or very low impact, and 5 the maximum possible probability of occurrence or impact (see Section 3.3.4). The risk scores were calculated by using Equation 1.

Within this process, experts were asked to rate the probability and impact of each of the identified risks (Table 27). Using their responses, the range of probabilities and impacts associated with each integer was subsequently determined (e.g. low probability = 10 to 30%, see Figure 11) [Details of the analysis for the countries considered are presented in Appendix D]. By taking the average of the responses, in accordance with current risk analysis practice, data were combined according to Equation 8 to give a single risk score for a particular country (BSI, 2010).

$$R = \sum_{i=1}^{n} R_i = \sum_{j=1}^{n} P_j I_j$$

8

In which probabilities and impacts are allocated integer scale of 1 to 5, and n is the number of identified risks

Risk scores were portrayed in the form of a risk matrix as shown in Figure 11 tion 3.3.4) to better aid their visualisation. In accordance with BS EN 31010:2010 (BSI, 2010), scores of 15 or greater were considered to be ‘high risk’, and those equal or greater than 5 but less than 14 were considered to be ‘medium risk’, whilst scores less than 5 were categorised as having ‘low risk’.

6.1.1 Results

The scores obtained for the nine countries considered are presented in Table 31 according to ‘construction risks’ (i to xvii) and ‘operational risks’ (xviii to xxvi). It can be observed that of the 234 possibly identified risk–country combinations, around 68% have low risk scores, 32% have medium risk scores whilst none of them obtained high risk score. The highest individual risk scores in Table 31 are associated with the regulatory framework (ix in list, with Ireland and Belgium each scoring 10) and changes in energy policy risk (xviii in list, with France scoring 10). In the case study it was assumed that risks had an equal weighting, by making this assumption, they were summed down columns to give a total risk for each country (Section 6.1.1.1) and averaged across rows to find a measure for risk type tion 6.1.1.2).

6.1.1.1 Risk by country

Figure 34 presents the total risks obtained for each country ranked in order from highest to lowest. From Figure 34 it may be seen that Spain has the highest total risk score (i.e. sum for column = 104), whilst Ireland has the lowest total risk score of 80. The low risk score for Ireland is mainly related to its proximity to the UK and the relatively well-mapped ocean (the Irish Sea) between the two countries (resulting in low risk scores associated with the sea or seabed (i.e. iv to vii in Table 31)). In addition to the relatively short distance between Ireland and the UK (Table 18), its energy and distributing system are similar to the UK, and therefore, it achieved a low risk scores associated with ‘increased electricity prices’ (xxvi in Table IV) and ‘changes in energy policy’ (xviii in Table 31).

As for the Spain, conversely, the comparatively large distance (Table 18) and expanse of ocean between it and the UK are the major factors in highest-risk ranking (Figure 34). The distance between Sweden and the UK, which is the largest of the countries considered, is also a major factor for the country being assigned the second highest total risk score of 100 (Table 31 and Figure 34).

Despite the relative proximity of France to the UK, an interconnection between the two countries achieved the fourth highest risk score. This is due to the experts considering the socio-political environment in France to be more volatile than in any of the other eight countries considered. Consequently, risks associated with public acceptability, the regulatory framework and changes in energy policy (6, 9 and 10, respectively) were given the highest scores, or amongst the highest, of all countries considered (Table 31).

Nonetheless, whilst most of the identified risks were scored either low or medium, the fact that the UK currently does not have any under-construction interconnection with any other country, despite an identified need, and the ongoing protracted negotiations (Section 1.2.1) suggest that regulatory and changes in energy policy risks are perhaps the most influential risks as far as decision makers are concerned.

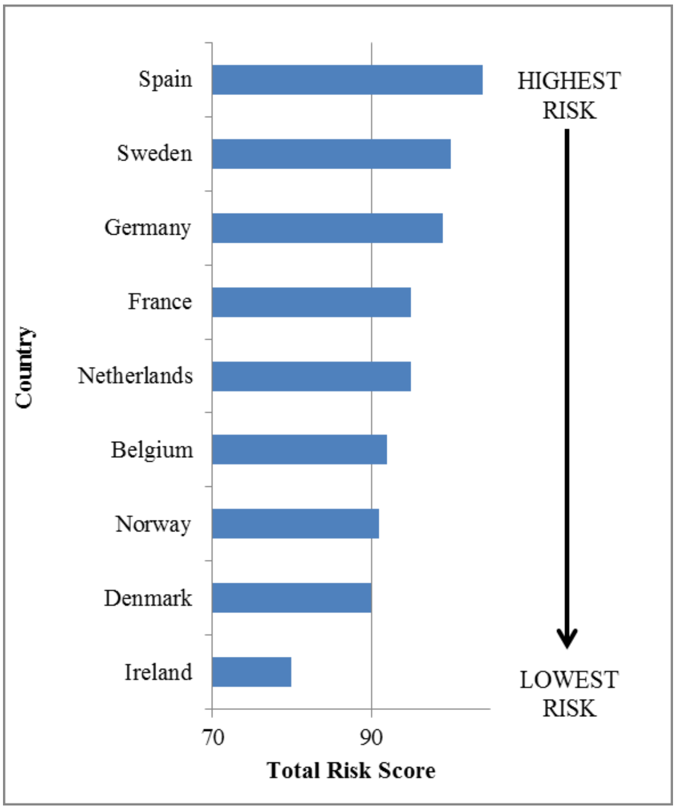


Figure 34: Risk by Country (Ranked in order), source Eskandari Torbaghan et al. (2014)

Table 31: Results of semi-quantification stage for the candidate countries, source Eskandari Torbaghan et al. (2014)

Identified risk	Norway	Sweden	Spain	Denmark	Germany	Netherlands	Belgium	Ireland	France	Average score
i. Public acceptability	5	5	4	5	6	5	3	5	6	5
ii. DP	2	2	2	1	2	1	1	1	1	1
iii. Earthquake	0	0	0	0	0	0	0	0	0	0
iv. Rocky seabed	1	2	3	2	2	3	2	1	2	2
v. Seabed contamination	3	4	2	3	3	4	3	1	2	3
vi. Ship wrecks	2	2	2	2	2	1	1	1	1	2
vii. Unforeseen sea depth	1	0	0	0	3	0	0	2	0	1
viii. Weak onshore grids	5	8	5	7	7	8	8	5	7	7
ix. Regulatory framework	6	9	8	8	8	8	10	10	9	8
x. Fishing activities	3	5	4	3	3	3	4	4	6	4
xi. Cost estimation	7	8	9	6	6	6	5	6	7	7
xii. Supply chain	4	4	4	4	3	2	3	2	2	3
xiii. Solvency of contractor	1	2	5	2	1	2	3	3	3	2
xiv. Inflated bid price	5	5	6	4	4	3	5	4	4	4
xv. Cost of material	3	4	3	3	3	3	3	3	4	3
xvi. Disturbing habitats	6	5	3	4	4	4	3	2	4	4
xvii. Climate change	5	5	4	4	4	4	4	2	4	4
xviii. Changes in energy policy	8	8	9	7	9	9	8	7	10	8
xix. Demonstrations	1	1	1	1	1	2	2	1	2	1
xx. Availability of electricity	4	4	8	4	6	7	5	2	6	5
xxi. Earthquake	0	0	1	0	0	0	0	0	0	0
xxii. Fishing activities	3	3	3	3	2	2	3	3	3	3
xxiii. Weak onshore grids	4	5	5	4	8	5	5	7	3	5
xxiv. Disturbing habitats	4	5	4	5	3	3	3	2	3	4
xxv. Climate Change	2	2	2	2	2	3	2	1	1	2
xxvi. Increased electricity prices	6	2	7	6	7	7	6	5	5	6
Sum	91	100	104	90	99	95	92	80	95	

🟩: Low Risk 🟨: Medium Risk 🟥: High Risk

6.1.1.2 Risk by type

Average risks (by type) ranked in order from highest to lowest are presented in Figure 35. The highest average risk scores in the construction category (i.e. 8 - medium risk) were assessed to be those associated with 'changes in energy policy' and 'regulatory framework'. In terms of the operational risk category, 'increased electricity prices' obtained the highest average score (i.e. 6 - medium risk), and was as a result of a number of external influences such as daily and hourly auctioning. This is not surprising as the existing electricity trading system causes uncertainties related to the pricing of electricity and these are exacerbated where interconnections exist. This risk can be controlled, to some extent, through adoption of fixed-pricing strategies (i.e. via long-term contracts).

Key risks are those that may require mitigation measures to reduce their probability of occurrence and or impact. There is no commonly recognised process to identify such key risks. Therefore, by using the risk ranking process described (and given that no risk was ranked as high), it was decided that, for the purpose of the case study, 'key risks' were those with an average score of 5 or greater (indicated by those located above the dashed line in Figure 35).

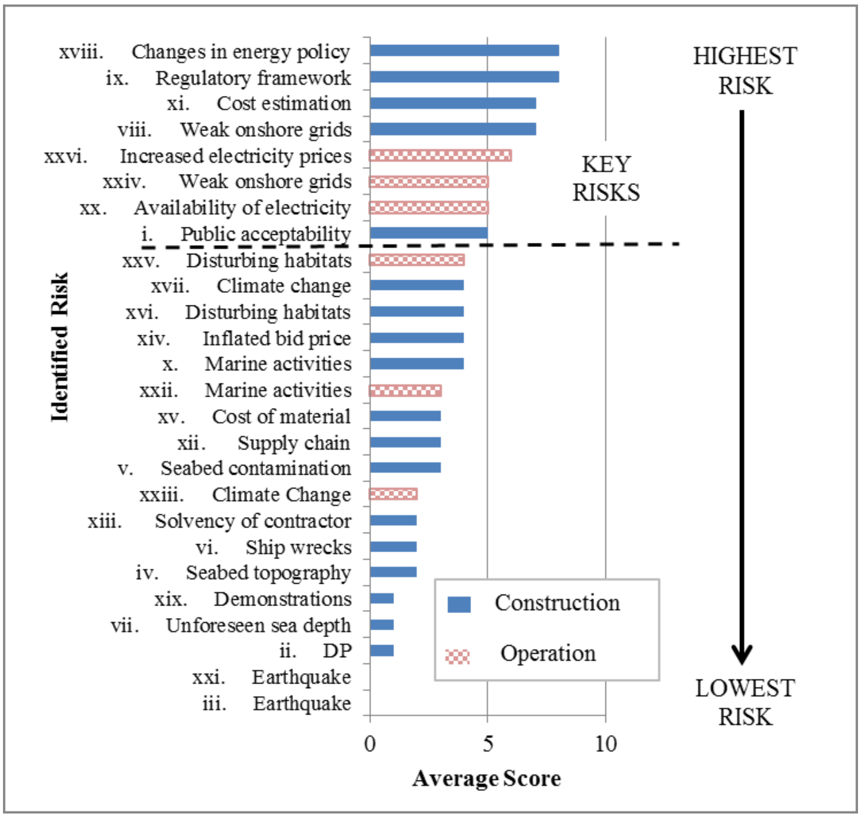


Figure 35: Risk by type (Ranked in order), source Eskandari Torbaghan et al. (2014)

These top seven risks in Figure 35 are discussed further by comparing the experts' opinion with the finding from the literature (Section 5.1).

1. Changes in energy policy (construction risk)

'Changes in energy policy' was the top-ranked risk and confirms the findings from the literature (Section 5.1.1). Potential changes in energy policy are considered to be of significant risk due to the fact that any change in energy policy of the exporting country may directly impact the availability of renewable energy and can threaten the feasibility of a project during inception. The example discussed in Section 5.1.2.5 was Germany's recent policy to reduce its nuclear energy capability and rely more on renewable energy sources. Therefore it has less available renewable energy to export because of the necessity to use it to replace nuclear energy sources. Consequently, we see that Germany, in terms of energy policy risk, was assessed as having one of the highest risk scores (Figure 35 and Table 31).

The risk was identified as relatively high for all the countries considered (with risk scores between 7 and 10) with France ranked as the most risky and Ireland and Denmark the least. The interviews with the experts revealed a feeling that there is a history of France not completing interconnection projects and was the key reason for it being assessed as the most risky. Conversely, the similarity in energy policies between Ireland and the UK was the reason why experts considered it to have the lowest risk associated with regard to energy policy (Table 31).

2. Regulatory framework (construction risk)

The complexity associated with introducing a collaboration between two countries involved in building the new interconnection, might cause delays and additional costs when trying to obtain the required approvals (Section 5.2.1). The regulatory framework as a risk was scored similarly for all of the candidate countries, with risk scores of between 8 to10 with the exception of Norway which was assessed as 6 under this category. Norway was ranked as the least risky because of its previous successful collaborations with its neighbouring countries in building number of interconnections.

3. Cost estimation (construction risk)

Inaccurate forecasting of projected costs and construction duration was found in the literature as a major source of risk in any project (Section 5.1.1.3). By using the data provided in the literature (Table 26) Sweden and Denmark were identified to have the least cost estimation risk as they each have seven existing interconnections and three under construction (and so have more experience and the cost estimations are likely to be more accurate), whilst Belgium with no current interconnections was considered to be the most risky country when assessed according to cost estimation risk. However, nearly all experts when interviewed advised that Belgium and Spain were the countries with the least and highest risks, respectively. This is unexpected given that Belgium currently has no interconnections. The experts suggested that the Belgium's ranking reflected the country's good reputation in the energy sector. As for Spain, the distance between it and the UK (it is the second longest as mentioned earlier) and the perceived financial instability of Spain's economy were the reasons why the experts scored it as the highest cost risk.

4. Weak onshore grids (construction and operational risk)

The literature described in Section 5.2.3 suggested that weaker infrastructure at the connection points could lead to additional cost requirements in order to upgrade the grid of the receiving country. Therefore, the fact that this was found to be the fourth highest risk is not surprising. The expert suggested that Sweden, Netherlands and Belgium were perceived to be the most risky in terms of proving access to a strong grid. The previous analysis tion 5.2.3), by considering the number of existing grid connection points in each candidate country located on a coastline facing the UK (Table 29), confirms the findings of the experts that Sweden and Belgium could be considered to be the most risky countries when assessed according to weak onshore grids. Ireland, Norway and Spain were suggested as being the least risky by the experts. For the Ireland, this finding is confirmed by the information given in Table 29.

5. Increase in imported electricity prices (operational risk)

The impacts of any increase in exported electricity pricing were explained in Section 5.1.2.3. When considering the electricity prices for household consumers of the nine countries over a 14 year period (Figure 33), it can be seen that Ireland has experienced the greatest increase (approximately 150%), whilst Norway has had the greatest fluctuation in price over this period. However, the experts' opinion provided evidence to the contrary, proposing that Sweden (Table 31) was the least risky in terms of future increases in electricity cost, whilst France was regarded as the second least risky with a relatively high score of 5. Spain, Germany and Netherlands were considered to be the riskiest countries with an average risk score of 7. This demonstrates the importance of compiling both historical information and using expert opinion to establish appropriate and accurate risks.

6. Availability of electricity from renewable resources (operation risk)

The risk associated with the availability of electricity from renewable resources was described in Section 5.1.2.2. The risk exposure is greatly dependent on the energy-generating characteristic(s) of the target country and considers the intermittency of renewable supplies. On that basis, Table 31 shows Spain and Ireland as the highest and lowest ranked countries in terms of this risk, with risk scores of 8 and 2, respectively. This is not surprising because Spain obtains a large proportion (around 40%) (MINETUR, 2011) of its energy from both hydroelectric and wind power and is likely to replace (or at the very least supplement) much of its hydroelectricity capacity with solar energy in the future (Energynautics GmbH, 2011), thereby providing a measure of diversity. Notwithstanding this, the risk associated with Spain's energy policy of developing renewables in the future was the main reason why Spain was chosen as the riskiest country by the expert group (see *'Changes in energy policy'* above).

7. Public acceptability (construction risk)

The risk concerning public acceptability was described in Section 5.1.1.1 but no measure of the risk was identified from the literature, rather expert opinion was used to assess this risk. According to the experts, the risk was the lowest for Belgium with a score of 3, whilst Germany, which has a strong public energy lobby, and France, which to some of experts canvassed appears to be reticent to develop interconnections, were found to have the highest risk score of 6 in this category.

Questionnaires (described in Section 3.3.5) were utilised in the risk identification and semi-quantification stages to identify the risks and to estimate the impact and probability of the risks. The reliability of the questionnaire results is described in the next section.

6.1.1.3 Reliability of the questionnaire results

Testing the reliability of the questionnaire results was considered before conducting any further analysis. The standard deviation of the responses for each risk ranking (for each country) was calculated to test the responses reliability and as an indication of the degree to which the experts were agreed or disagreed on a risk level.

The analysis showed that the ‘uncertainty in cost estimation’ had the highest standard deviation and therefore the most disagreement between the experts for all the considered countries. For instance, the risk was scored in a range of 0–25 for Norway as shown in Figure 36(a).

The reason for the relatively large disparity in agreement between the experts was that several experts considered that the scarcity of available suppliers and contractors in the high-voltage cable industry, and therefore fewer competitors, could potentially cause unforeseen increases in actual costs for cables and/or installation procedure. However, several other experts considered that the European countries involved in the project have relatively stable economic environments, and therefore, the cost estimate of any project was not likely to be uncertain, and therefore, they identified this as a low score risk. The risk of an earthquake in the UK was the risk that had the highest consensus of agreement amongst experts, the majority of whom considered that an earthquake posed zero risk (Figure 36 (b)). This is a reflection that the UK is stable geologically and therefore not likely to be subject to earthquakes of any great magnitude.

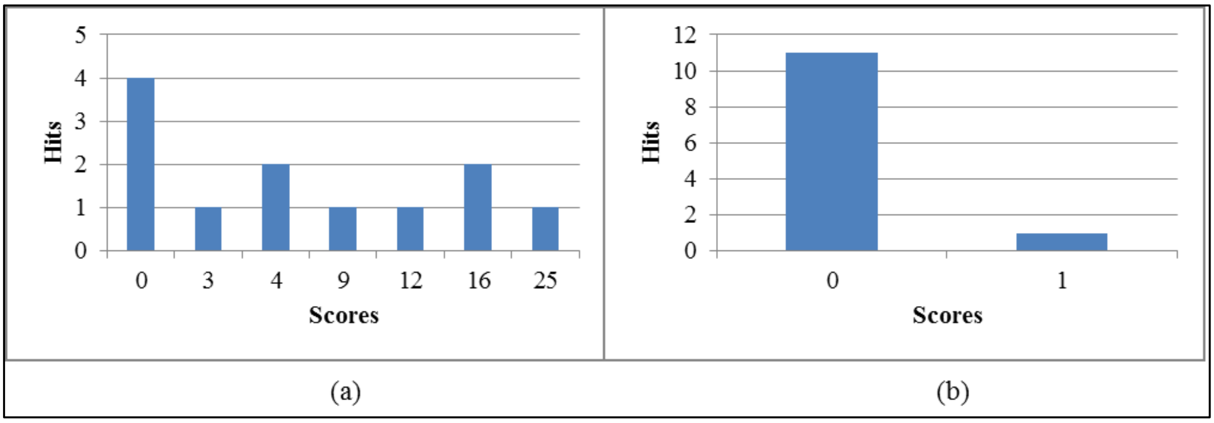


Figure 36: Distribution of the scores for (a) “Uncertainty in cost estimation” and (b) Earthquake for Norway, source Eskandari Torbaghan et al. (2014)

The following section describes the risk quantification process used to associate the identified risks with the NPV technique in order to assess the candidate countries.

6.2 Risk quantification

Quantitative analysis estimates practical values for consequences and their probabilities (rather than numerical scores as in the semi-quantification stage), and produces values of the level of risk in units which are defined when developing the context (BSI, 2010). For the case study the probabilities and impacts of the identified risks on the costs and benefits of an interconnection to the UK were evaluated using a cost risk model incorporating a NPV analysis as described below.

6.2.1 Cost risk Model

The cost risk model, Equation 9, was used to consider the mentioned uncertainties and to determine the risk-cost in terms of the NPV of an interconnection. The equation was developed based on the Equation **7** described earlier in Section 4.3.

$$\widehat{NPV} = \widehat{C_I} + \widehat{R_O} + \sum_{i=1}^{T} \frac{\widehat{C_{Oi}} - \widehat{R_{Ai}}}{(1+\hat{r})^i} \tag{9}$$

Where: (^) signifies uncertainty (risks)

$\hat{C}_I$ (Investment cost) in Equation 9 defined by

$$\hat{C}_I = \hat{C}_C + \hat{C}_{CT} - S + \sum_{j=1}^{N} \left(I_j \times P_j\right) \tag{10}$$

In which $\hat{C}_C$ is the Cable cost, $\hat{C}_{CT}$ is the Converter station cost [the uncertainties associated with their estimations are modelled using three-point estimation (triangular distribution)]

S is the saving equal cost of generating electricity (the money which can be saved by supplying electricity from other countries compared to the capital cost of building electricity power plants with the same capacity).

I and P in Equation 10 are the impact and probability of N identified construction risks

[For calculating S the average cost of various electricity generation technologies is considered as the cost of generating electricity, Section 6.2.2.]

In Equation 9 $\widehat{R_O}$ (Cumulative operational risk cost) is calculated using Equation 11

$$\widehat{R_O} = \sum_{n=1}^{K} \mathrm{R}_n = \sum_{n=1}^{K} (I_n \times P_n) \tag{11}$$

Where I is impact and P is the probability of the number (k) of identified operational risks (R)

$\hat{C}_O$ the annual operational cost in Equation 9 is calculated using the following equation

$$\hat{C}_O = \hat{C}_M + \hat{C}_L + \hat{C}_{RE} \qquad 12$$

In which $\hat{C}_M$ is the annual maintenance cost, $\hat{C}_L$ is the annual cost of losing power due to heating of the line and $\hat{C}_{RE}$ is the cost of imported RE

$\widehat{R_A}$ (Annual revenue) in equation 9 is defined by

$$\widehat{R_A} = \widehat{R_{A1}} \times \widehat{r_{RG}} \qquad 13$$

In which $\hat{R}_{A1}$ is the first year (2030) revenue and $\hat{r}_{RG}$ is annual revenue growth rate (see Section 6.2.3)

Within Equation 9, the cost uncertainties were represented as a range of possible cost values (i.e. impacts) with an associated likelihood of occurrence. The costs and their probabilities were determined from the literature and via consultation with the pool of experts (Section 3.3.5) and were modelled using statistical distributions, to accommodate the range of expert estimated values. Triangular and binomial distributions were used to model costs and their likelihood (probability) respectively.

Monte Carlo Simulation (MCS) was used to generate, using Equation 9, a distribution of plausible NPVs with their associated probabilities. Before describing the MCS process and its results, the assumptions behind developing the cost risk model and cost and revenue streams are discussed in the following sections.

6.2.1.1 Assumptions

A fixed discount rate of, nine per cent, was used for this study for all countries concerned based on work by Nooij (2011) for the NorNed interconnection. However, it is recognised that the discount rate can vary temporally and spatially and that therefore a more thorough treatment of discount rates may be appropriate for more in depth studies than that which has been possible for this case study.

6.2.2 Cost streams

Costs have been broken down into investment and operational costs.

6.2.2.1 Investment (construction) costs

A study by Georgiou et al. (2011) was used to identifying the cost components as:

1. Cable

Generally there are two types of cable namely:

a. Direct Current (DC)
b. Alternative Current (AC)

The cost of various types of cables provided by Georgiou et al. (2011) is presented in Table 32:

Table 32: Installed cost of various cables types, source Georgiou *et al.* (2011)

Equipment/ services	Cable Capacity (MW)	Cost per km per MW (€/km-MW × 10^3)
Seabed DC cable	250	1.77
	350	1.59
	500	1.46
Seabed AC cable	140	5.00
	280	2.85

Consideration of the costs of cable connections from Table 32 and a variety of other sources (Van Eeckhout *et al.*, 2010; Van Hertem and Ghandhari, 2010) suggest that transmission at high voltage DC is the most cost effective means of transmitting electricity (also see 2.2.3). Accordingly, it was decided for the case study to consider only high voltage DC cables. Table 33 shows the cost estimates adopted and the sources on which they are based.

Table 33: Cable costs

DC cable capacity (MW)	Unit Costs (10^3 £ /km) [1]		
	Minimum	Most likely [2]	Maximum
250	361 [3]	369	377 [4]
300 - 350	475 [4]	612.5	750 [5]
500	622 [4]	723	880 [5]
1000	850 [6]	1105	1500 [5]
1400	980 [7]	1590	2200 [7]
3000	670 [8]	2050	3430 [8]
5000	1480 [9]	1770	2060 [9]
Over 5000 [10]	1480 [9]	2455	3430 [8]

[1] Euro figures converted to £ by assuming 0.85 exchange rate, [2] The most likely is the average of the gathered figures for each row, [3] Aguado Cornago (2011), [4] Georgiou et al. (2011), [5] ISLES (2012), [6] SAPEI project Chatzivasileiadis et al. (2013), [7] NorGer project Chatzivasileiadis et al. (2013), [8] Delucchi and Jacobson (2011), [9] Trieb et al.(2006) [10] As no data is found for this category the gathered data for other categories is used to form the range

2. Convertor station

Since it was assumed that the energy transmission via the interconnections would be via high voltage DC (HVDC), for the both countries involved it is necessary to first convert the DC supply to AC. Therefore a high voltage DC connection within an AC system requires two converter stations (Bahrman and Johnson, 2007; Weigt *et al.*, 2010). The cost of the convertor station depends on the location and local conditions (Cavallo, 2007). Various studies and researchs have been reviewed and the cost estimations are presented in Table 34. The precise locations of the convertor stations were not considered for the cost estimation. This was due to the fact that the developed framework considers the overall cost of the interconnections, whilst in order to include the precise locations, detailed analysis is required to identify the precise cable routes (see Section 7.2.3.2 for further discussion on the associated assumptions).

Table 34: Convertor station costs

DC cable capacity (MW)	Unit Costs £m [1] Minimum	 Most likely [2]	 Maximum
300	35.2 [3]	81.6	128 [4]
500	50.34 [3]	89.17	128 [4]
1000	94.62 [5]	102.31	110 [3]
1200 – 2000	151 [6]	184.72	247.65 [7]
3000	199.11 [5]	279.762	331 [8]
4000	196 [6]	334.375	442 [8]
5000	205.69 [9]	246.83	287.97 [9]
Over 5000 [10]	205.69 [9]	323.845	442 [8]

[1] Euro and $ figures converted to £ by assuming 0.85 and 0.65 exchange rate respectively, [2] The most likely is the average of the gathered figures for each row, [3] ISLES (2012), [4] Minimum of Weigt et al.(2010) is assumed as maximum, [5] Hauth et al.(1997), [6] Black &Veatch (2009), [7] Hammons et al.(1993), [8] Bahrman and Johnson (2007), [9] Trieb et al.(2006), [10] As no data is found for this category the gathered data for other categories is used to form the range

3. Saving equal cost of generating electricity

This is the money which can be saved by supplying electricity from other countries compared to the capital cost of building power plants with the same capacity. In order to estimate the equal cost of electricity generation a number of studies were used to obtain the installed capital cost of generating electricity various for the energy technologies considered, as shown in Table 35. These costs were then used to determine an average cost of generating electricity (i.e. £1400/kW).

Half the capacity of an interconnection was assumed to be available for importing RE and the other half was assumed available for exporting RE and therefore to reflect this a factor of 0.5 was applied to the projected saving costs of electricity generation. For example the S in Equation 9 for the Norway was calculated as:

S = UK-Norway interconnection capacity (kW) [Table 24] × average cost of generating electricity (£/kW) × 0.5

$= 2800 \times 10^3 \times 1400 \times 0.5 =$ £196 billion

Table 35: Installed capital cost of generating electricity

Technologies	Installed capital costs in 2030 (£000'£/kW)	Source
Marine	2.2	(Mott MacDonald, 2011)
Nuclear	2.4	
Offshore Wind	1.8	
Onshore Wind	1.1	
Hydro	1.7	
CCS (Gas)	0.83	
CCS (Coal)	2.10	
Biomass	2.91	
Gas	0.08	
CHP	0.10	
Coal	0.21	
Oil	0.74	(Kannan, 2009)
Pumped Storage	1.9	(Parsons Brinckerhoff, 2011)
Average installed capital costs of electricity in 2030 (£000'£/kW)	1.4	

6.2.2.2 Operational Costs

The operational costs were to do with:

1. Maintenance costs
2. Annual cost of losing power due to heating of the line
3. Cost of imported RE

1. The maintenance costs were categorised as:
   i. Annual scheduled maintenance
   ii. Annual unscheduled maintenance

The costs in both categories include power blackout as well as engineering related costs.

Annual scheduled maintenance

The major maintenance cost of HVDC interconnections are associated with (Berdal Stromme, 1998):

- Maintenance of converter station equipment including monitoring, inspections and technical surveillance
- Maintenance of land cable sections including inspection
- Maintenance of seabed cable including periodic landfall inspection

Unscheduled maintenance

Those concerning unscheduled maintenance in HVDC systems typically result from manual inspection or error signals (Berdal Stromme, 1998). These typically can result in up to 42 days per year of loss of operation of the interconnection during which it is not possible to transmit energy.

The literature found tends to give a single figure for overall annual operational and maintenance cost and therefore operational and maintenance costs were included as one item for the purposes of the case study. DKM (2003) gives yearly fixed operations and maintenance costs of approximately £24096/MW whilst Nooij (2011) suggests an annual costs of £4057/MW for the NorNed interconnection. Sousa et al. (2012) assumed an annual maintenance cost equal to two per cent of the cost for the HVAC system.

The information provided by DKM (2003) and Nooii (2011) were used to determine the annual operational costs for the purposes of the case study. There are shown in Table 36.

Table 36: Annual operational cost distribution

	Minimum	Most likely [1]	Maximum
Annual operational cost (£/MW)	4057 [2]	14077	24096 [3]

[1]Most likely is the average, [2]Nooii (2011), [3]DKM (2003)

2. Annual cost of losing power due to heating of the line

The power or transmission loss of a number of cables (Table 37) was calculated using the data provided by Weimers (2011).

Table 37: Energy losses as percentage for various cable lengths, source (Weimers, 2011)

Length (km)	Loss (%)		
	500 kV	600 kV	750 kV
0	0	0	0
100	1	1	1
200	1.5	1.17	1.3
400	2.8	2.3	2
600	4.2	3.5	2.9
800	5.6	4.7	3.8
1000	7.0	5.89	4.75
1200	8.4	7.08	5.67
1400	9.81	8.27	6.58
1600	11.21	9.46	7.5
1800	12.60	10.64	8.42
2000	14	11.83	9.3

The data presented by Weimers (2011) may be considered to be on the high side. Trieb (2006) for example suggests 2.5% per 1000 km, and Siemens (2014) suggests that it is less than 3% for a similar cables. Chatzivasileiadis et al.(2013) used the 3 % for every 1000 km in their study of a '*globally interconnected network'* with an additional 6% loss for each station.

3. Cost of imported RE

The method used for calculating the cost of imported RE was similar to that for exporting RE which is described in Section 6.2.3.1.

6.2.2.3 Assumptions

Three components of capital costs were considered for this case study, the cable (including installation costs), convertor stations and saving an amount equal to the cost of generating electricity. A number of other costs exist including land costs (for building convertor stations) and possible permissions costs however these were not considered for the following reasons:

1. Simplification; which is an important parameter for risk assessment part (risk mapping)
2. Lack of data due to confidentiality associated with the size of the project

The cost of identified operational risks is considered as cumulative operation risks ($\widehat{R_O}$ in Equation 9) and applied for calculating NPVs.

For the purposes of the risk analysis the triangular probability distributions were determined by using within the MCS the minimum, maximum and mean values obtained from the literature (Section 6.2.4).

6.2.3 Revenue streams

In order to calculate the interconnections first year revenue for the UK (R_{A1} in Equation 13) the following were considered:

1. The revenue generated from selling the UK's spare RE to the candidate country
2. Value of savings CO_2 (£) (i.e. reduced carbon credit payments, CO_2 permits, are estimated to be worth €28.30 million annually for the East–West interconnection from Ireland to the UK (Nooij, 2011).

6.2.3.1 Selling the UK's spare RE

The following assumptions were made in considering the revenues from trading RE.

Historical prices, obtained from Eurostat (2015a), were used to determine the price of buying and selling energy. Prices obtained from 2008 to 2012 were projected forward to 2030. A 0.85 exchange rate of 1 Euro equals 0.85 GBP was assumed.

The modelling of an energy market in order to project the future prices of energy is complicated and there are many items which are influential and should be taken into the account. This is further complicated when trying to project two interconnected markets, and requires expertise and knowledge in finance (see Parail, 2010a for an example). Therefore, for simplification in the case study it was assumed that the energy markets in both the UK and the candidate country would have no influence over the electricity price.

6.2.3.2 Value of savings CO$_2$

This factor reflects the money which can be saved from reduced carbon credit payments, CO$_2$ permits, by importing RE rather than generating electricity.

The level of CO$_2$ emissions was estimated using an average of current various technologies' emissions as shown in Table 38.

The CO$_2$ cost of generating equal electricity was considered using the DECC (2011a) study which provided three scenarios for the price of carbon credit in 2030 (£37, 74, 111/KW).

The annual revenue growth rate in Equation 13 is assumed two per cent for all the candidate countries (Section 6.3.2.1).

Table 38: CO$_2$ emissions of various technologies

Technologies	Life-cycle emissions (tCO$_2$-eq/GWh)	Studies
Coal	1180	(Kharecha *et al.*, 2010)
Heavy fuel oil	771	
Natural gas	1100	
Hydro	86	
Geothermal	114	
Biomass	48	
Onshore Wind	9.5	
Offshore Wind	9.5	
Solar PV	57	
Solar CSP	200	
Nuclear	57	
CHP	474	(Matthes *et al.*, 2005)
Pumped Storage	36	(Weisser, 2007)
Marine	20	(Douglas *et al.*, 2008)
CCS (Gas)	110	(Kharecha *et al.*, 2010; CCS system is assumed 90% effective for reduction of CO$_2$ emissions)
CCS (Coal)	118	
Average Life-cycle emissions (tCO$_2$-eq/GWh)	274	

The data gathered and the revenue stream for Norway in 2030 are presented, as an example, in Table 39.

Table 39: UK revenue stream for an interconnection to Norway in 2030

		Min (fossil fuel scenario)	Mean	Max (renewable scenario)
UK	Available Renewable capacity (GW in 2030)	0	11.90	23.81
	Renewable available (GWh in 2030)	0	31282.68	62565.36
	Available RE for trade (MW in 2030)	0	3571	7142
Norway	Available Renewable capacity (GW 2030)	3.01	6.38	9.75
	Renewable available (GWh in 2030)	10553.22	22353.00	34152.77
	Available RE for trade (MW in 2030)	1205	2552	3899
Capacity of the Interconnection (MW)		0	2000	4000
UK	Availability of the Interconnection (MWh)	0	17520000.00	35,040,000
Norway	Availability of the Interconnection (MWh)	10553226	22352998.82	34,152,772

	Min	Most Likely	Max	Comment
Selling the spare RE (£) in 2030 year	0	1,219,878,180	2,439,756,360	50% unavailability is applied which is the time used for importing.
Value of savings CO_2 (£)	26,018,733	146,105,193	360,259,380	The CO_2 cost for 2030 is assumed 37, 74, 111(£/t 2011) (DECC, 2011a)
2030 Revenue (£)	26,018,733	1,365,983,373	2,800,015,740	

6.2.4 Monte Carlo Simulation

The WLA process (Equation 9) has uncertainties associated with the estimates of the risk costs and their likelihoods. It was therefore necessary to determine optimistic (or lowest) and pessimistic (or highest) values and the most likely value of these probabilities and costs.

To this end, the probabilities and costs scores obtained in the semi-quantification stage from the range of estimates given by the experts were used for the three point estimates for each risk (Appendix D). These were then modelled as triangular probability distribution in the cost risk process (see Section 6.2.1). Consider the following example. If an interviewee selects a medium range for a risk (see Figure 11) with an impact range of £30 to £60 million and a probability range of 10% to 30% the following costs and probabilities would be chosen;

- The lowest value (£30 m) as minimum cost
- The highest value (£60 m) as the maximum cost
- And the average value (£45 m) as the most likely cost

- The lowest value (10%) as minimum probability
- The highest value (30%) as the maximum probability
- And the average value (20%) as the most likely probability

Three point estimates (minimum, most likely and maximum values from sections 6.2.2 and 6.2.3) were obtained for the following risks for inclusion within the risk cost model:

1. Cable installation
2. Converter station
3. Annual operational costs
4. First year revenue
5. Value of savings CO_2

In addition the uncertainty in annual revenue growth rate, $\hat{r}_{RG}$ (Equation 13), was also modelled using a normal distribution, based on a 2% mean value and 1% standard deviation (see section 6.3.2.1).

6.3 Results

In this section the results of applying WLA technique are presented followed by the outcome of the risk analysis process.

6.3.1 WLA results

The NPV (prior to considering the uncertainties), the investment cost and the length of the cable are provided in Table 40 for each candidate country.

Table 40: WLA results before modelling uncertainties

Countries	Cable Length (Km)	Projected capacity (MW)	Investment cost (b£)	NPV (b£)
France	40	4000	0.590	-10.68
Germany	380	5500	1,717	-6.37
Belgium	98	650	0.331	-0.387
Denmark	600	600	0.944	-0.282
Ireland	85	1000	0.290	-0.26
Sweden	800	3000	2,508	3.98
Norway	460	3000	1,726	5.57
Spain	700	5500	2,557	12.66
Netherlands	170	0	NA	NA

From Table 40 it can be seen that of the 9 candidate countries, only 5 of them have negative NPVs (i.e. the benefits are greater than the costs) and it was not possible to calculate a NPV score for the Netherlands as the projected spare RE was not enough to consider an interconnection with the country (see Section 4.2.3). France was found to have the highest, whilst Spain had the lowest. This suggests that France is the preferential country, from those considered, for the UK to make an interconnection with, whilst Spain is the least preferred. Some of the reasoning for this is related to the proximity of France to the UK resulting in low construction costs (Table 18). In addition the interconnection capacity between the two countries is projected to be high (i.e. 4000 MW), because of France's high projected spare RE, and the price of exported electricity is low. Conversely the comparatively large distance (Table 18) and expanse of ocean between Spain and the UK is a major factor in a connection between the two having the highest investment costs (£2.6b) and a resulting relatively low NPV.

The probabilities of achieving at least these initial NPV and also results of modelling the risk and uncertainties are provided in the next section.

6.3.2 Risk assessment results

The @Risk^{TM} software (Palisade Corporation, 2012) was utilised to carry out the MCA and thereby model the probability and cost uncertainties associated with the identified risks.

6.3.2.1 Uncertainties in cost and revenue estimations

In order to model the uncertainties in cost and revenue estimations the three point estimates from literature discussed in Section 6.2.4 are applied on the cost risk model using a Triangular Distribution. Figure 37 illustrates the distribution for the first year revenue of the interconnection to Norway.

As it is shown in the Figure 37, the first revenue for the Norway interconnection has three estimation, minimum £301b, most likely £429b and maximum £529b and there is 90 per cent chance according to the distribution to get e revenue between £343b to around £501b.

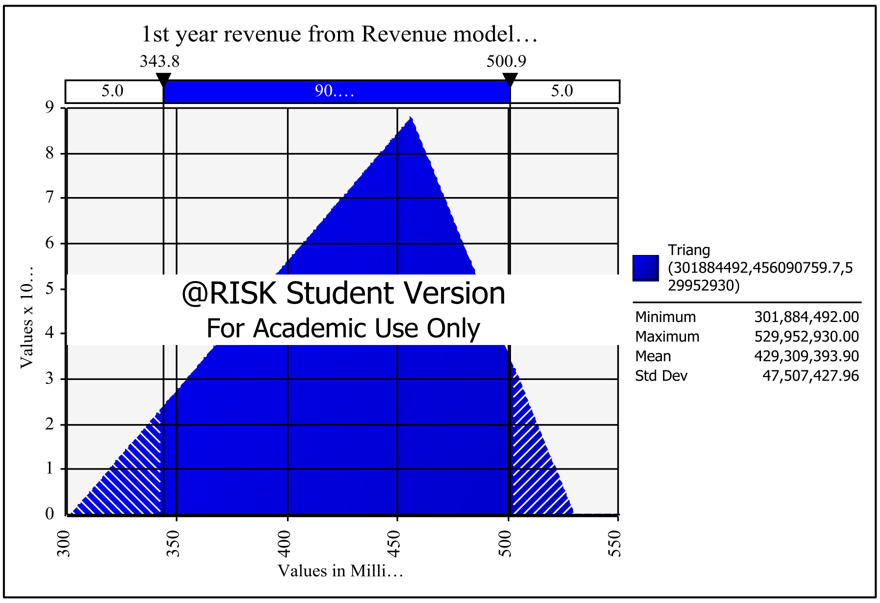


Figure 37: Triangle distribution for the first year revenue of interconnection to Norway

The uncertainty in revenue growth is also modelled using a normal distribution. The model considers growth for revenue in each year. The reason for this growth can be the raise in electricity price as well as the cost of CO_2 by taxation. For each year of operation of interconnection two per cent growth is assumed with a standard deviation of one per cent. This assumption is in line with the economic model developed by Nooij (2012), who assumed 1.7 percent as the annual economic growth rate for the NorNed.

The distribution of Norway revenue growth rate is shown as an example in Figure 38, which shows 80 per cent chance of achieving a growth rate between 0.718 and 3.282 per cent in the simulation.

Before presenting the result of MCS on uncertainties of costs it should be noted that these uncertainties are almost the same for all the candidate countries and the only parameter which is different for countries is the revenue which takes in to account the availability of renewables in future for countries and therefore the range is unique for each countries.

After running the MSC the chance of achieving the initial estimation of NPV, from the previous section is presented in Table 41. A column shows comments for each country which discussed the trend for each country regarding NPV.

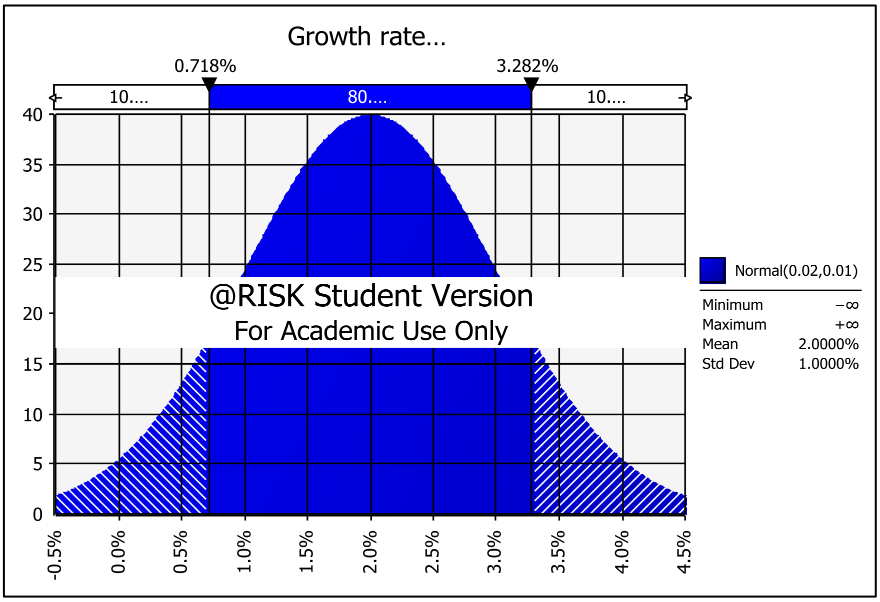


Figure 38: Normal distribution for revenue growth rate for the fourth year of operation of interconnection to Norway

Table 41: Results of modelling the revenue and costs estimation

Countries	NPV (b£)	Chance of achieving (%)	Comments
France	-10.68	56	44% chance of getting more negative value
Germany	-6.37	58	42% chance of getting more negative value
Belgium	-0.387	65	35% chance of getting a more negative value
Denmark	-0.282	54	46% chance of getting a more negative value
Ireland	-0.26	70	30% chance of getting a more negative value
Sweden	3.98	61	39% chance of getting a more positive value
Norway	5.57	65	35 % chance of getting a more positive value
Spain	12.66	53	47% chance of getting a more positive value
Netherlands	NA		

As it is illustrated in Table 41 the probabilities of achieving at least these initial NPV estimates are relatively low, for example the highest probability is 70% (for France) whilst the probability for the other countries is between 53% and 65%. This demonstrates the uncertainties inherent in using a single-point cost estimation to appraise an interconnection project.

In the next section after providing the result of the risk quantification stage, all the candidate countries are compared regarding the achievable P80 NPVs.

6.3.2.2 Risk assessment - results of quantification stage

The first step for conducting the quantification stage was extracting the three point estimates from the average risk ranking from the semi-quantification stage (see Table 31) using risk matrixes for each country. The three point estimates were then modelled in @Risk^{TM} software by adopting the following procedure:

1. Allocating a triangular distribution to the three point estimations of the cost and revenue streams
2. Allocating a binomial distribution (the RiskBinomial function @Risk^{TM}) to model the probability of the risk occurring, the function specifies a binomial distribution with n draws and p probability of success on each draw. For modelling the probability n=1 is selected so that there are two possible outcomes (0 or 1), where the 1 has a specified probability p, and the 0 has probability 1- p. and as a result by multiplying the output of the function by the impact, to obtain the actual impact, there would be a (p) per cent (the probability) that the impact occurring (see Table 42 for an example)

Table 42: Example of applying RiskBinomial function

Risk ID	Probability	Occurs (output of Risk-Binomial function)	Impact if occurs (£m)	Actual impact
H1	0.30	1	16,164	16164.83793
H2	0.80	0 (1)	22,594	0

[1] The probability of Risk H2 does not occur is only 20% (1-0.8)

3. Inclusion of the actual impacts with the associated costs, operational or construction, in the cost risk model

The NPV distributions after modelling the impacts of the identified risks and the uncertainties associated with cost and revenue estimations for the eight candidate countries (the Netherlands was excluded as explained before) are presented in Figure 39, whilst Table 43 shows the associated P80 NPVs.

Comparing tables 41 and 43 it can be seen that the hierarchy has remained unchanged with the exception that Ireland has been placed above Denmark in Table 43. The P80 NPVs after applying risks impacts have however worsened (i.e. the NPV values are higher), those for an interconnection between the UK and France and Germany increasing by 30% and 25% respectively. Those were caused as a result of considering the cost impact of the identified risks on NPV.

The higher position of Ireland with respect to Denmark is because of the lower risks impacts associated with an interconnection between Ireland and the UK, than between the UK and Denmark. The risk semi-quantification results of the same candidate countries confirms the later finding as Ireland was found to pose the lowest overall risk among the same nine candidate countries (Section 6.1.1.1). In addition to the comparatively short distance between Ireland and the UK, its energy and distributing system is similar to the UK and therefore an interconnection between Ireland and the UK was found to have low risk scores associated with identified electricity price and energy policy related risks.

The numbers on the vertical axis of histogram in Figure 39 are indicating the probability density. This is an adjusted scale so that the areas (height × width) of all the bars add up to 1 (Oracle, 2009).

Table 43: NPV values of the candidate countries with 80% chance of achievement

Countries	NPV (b£)	Chance of achieving (%)	NPV (b£) with 80% chance
France	-10.68	56	-7.62
Germany	-6.37	58	-4.78
Belgium	-0.387	65	-0.266
Ireland	-0.26	70	-0.19
Denmark	-0.282	54	-0.149
Sweden	3.98	61	4.79
Norway	5.57	65	5.91
Spain	12.66	53	16.6
Netherlands	NA	NA	NA

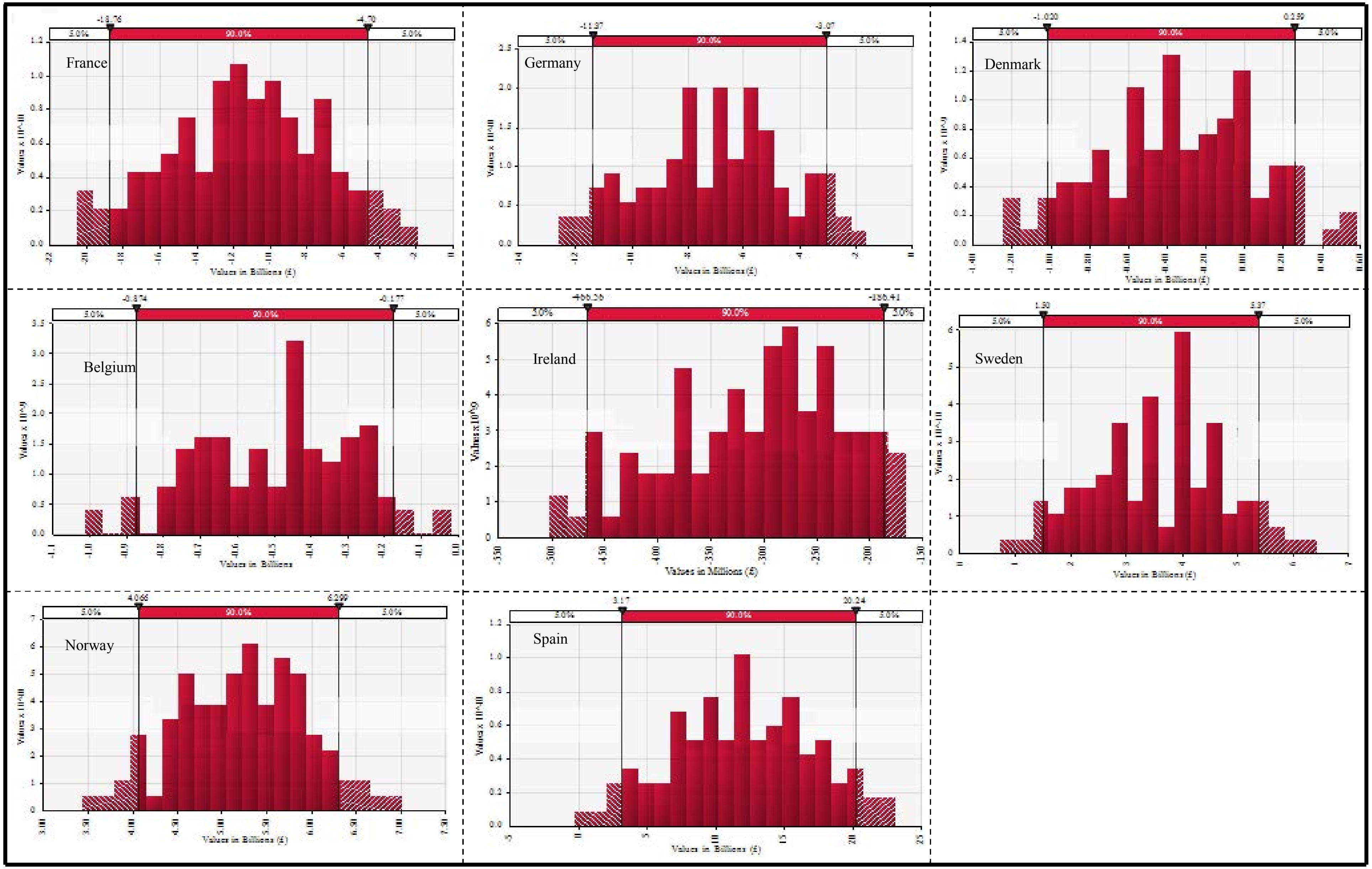


Figure 39: Risk contribution for candidate countries

6.3.3 Profitability Index (PI)

PIs were calculated to take into account the possible capital limitation for developing a new interconnection. PI was used to identify the interconnection with the highest NPV per invested pound (Section 2.3.1).

The profitability index was calculated using following equation

$$\mathrm{PI} = \frac{\mathrm{P80\ NPV}}{\mathrm{Investment\ cost}} \qquad 14$$

Where *(units in italics)*:

P80 NPV = 80 percentile NPV *(£)*

Investment cost *(£)*

The calculated PIs are presented in Table 44.

Table 44: PI results

Countries	Investment cost (b£)	NPV (b£) with 80% chance	PI
France	0.59	-7.62	-12.915
Belgium	0.33	-0.27	-0.804
Ireland	0.29	-0.19	-0.655
Denmark	0.94	-0.15	-0.158
Germany	1,717	-4.78	-0.003
Sweden	2,508	4.79	0.002
Norway	1,726	5.91	0.003
Spain	2,557	16.60	0.006
Netherlands	NA	NA	NA

Comparing tables 43 and 44 it can be seen that the hierarchy has remained unchanged with the exception that Germany has been placed fifth (from second in Table 43). This was due to the consideration of the high investment cost (£1,717 billion) associated with the interconnection to the Germany caused by the comparatively large distance between Germany and the UK (Table 18).

The PI index for the France shows that the interconnection will generate £12 for each pound invested.

6.3.4 Sensitivity analysis

In order to identify parameters that most influenced calculated NPVs, and therefore those which may require additional focus to enhance the accuracy of the risk analysis, a sensitivity analysis was conducted. Tornado graphs from within the @Risk$^{\mathrm{TM}}$ software were used for the analysis which displays a ranking of the input variables that impact NPV as the output. Each bar in the tornado graph represents the relationship between the calculated NPV and the input variables.

The result of the sensitivity analysis for all the candidate countries shows that the first year revenue has the highest impact on the NPV. This is due to the fact that the revenue of each year depends on this input, as they are changing with the growth rate. However the second place is varying country to country, for Norway it is the “Cable installation cost” (Figure 40).

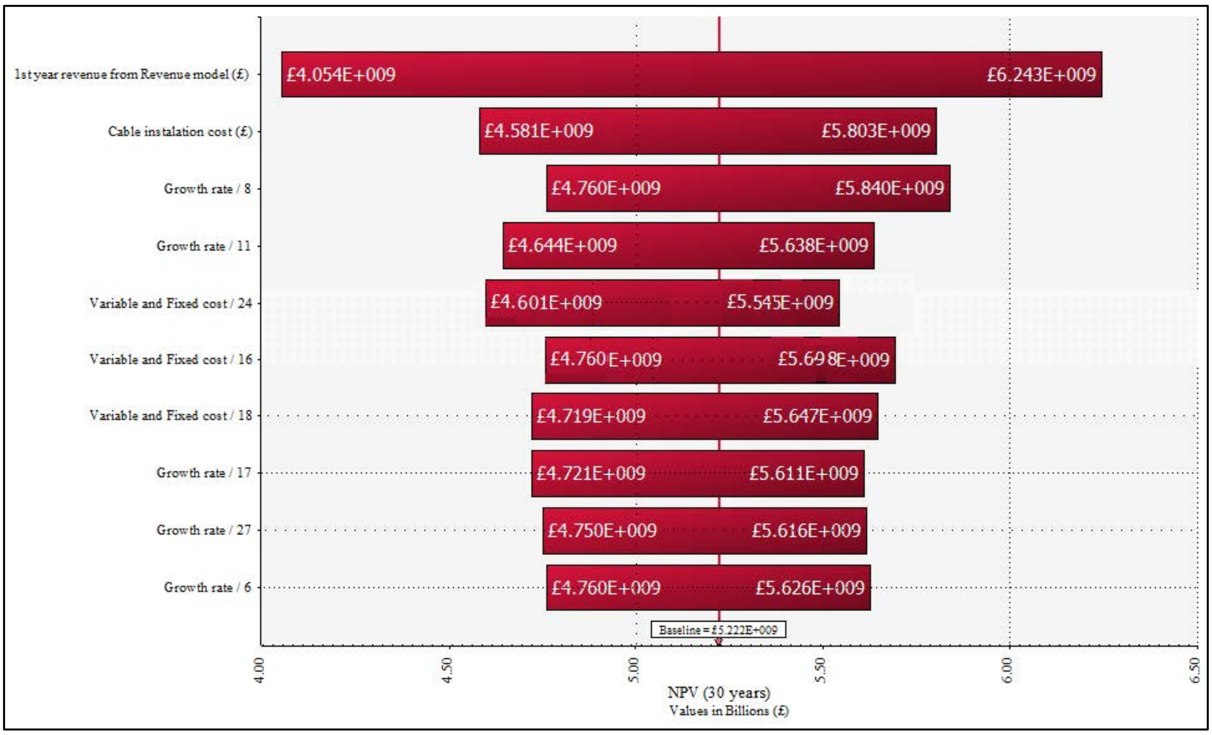


Figure 40: Tornado graph for Norway; inputs ranked by effect on Output (NPV) Mean

6.4 Summary

Chapters 4 - 6 have described how the UK with nine candidate energy supply countries, was utilised as a case study to demonstrate the risk based methodology. The case study demonstrated the inherent need for such an approach and highlighted the benefits that can be reaped in terms of informed decision-making.

As far as the risk quantification process is concerned, the whole life appraisal approach was utilised along with a MCS technique. A barrier for adopting the proposed methodology is the availability of appropriate data for risk identification and for estimating the associated risk impacts and probabilities. A well tried method of tackling this issue, as used in the method reported here, is to make use of expert opinion. To this end, in the case study a pool of 20 experts drawn from across Europe were drawn from the industry and academia, and their opinions were sought and recorded via targeted questionnaires and in depth interviews. This produced a balance of expert opinion, by making use of knowledge obtained from experts who are well versed in terms of experience and knowledge in electricity generation and distribution (see Section 7.2.4 for further discussion on expert opinion).

In terms of the case study, France was identified as the least risky country for the UK to make interconnections with, when considering PI and NPV with its associated probability. France was shown to be the least risky option as it requires a relatively low capital cost, has a low risk in general and a relatively large availability of RE. The findings for France are consistent with the past and current UK policy as the UK's first interconnection to be built was with France and there are on-going discussions about building a second interconnection one. An interconnection with Germany has also been recognised in this research as potentially attractive if not to consider any capital restriction. Indeed Germany has been recognised as a potential option by the UK government [albeit without any apparent numerical evidence] (see Great Britain Parliament, 2012). Whilst the cost risks associated with the large distance between Germany and the UK are relatively high, these are offset by Germany's very large projected supply of RE, albeit this may change as Germany switches from nuclear energy to RE sources. Spain is ranked as the most risky mainly because of the large distance to the UK causing relatively high capital costs and associated risks.

The results of the sensitivity analysis emphasises the importance of interconnection revenue estimation, and in particular the component of the benefit associated with selling spare RE, as it was found to have the highest impact on the distribution of NPVs.

The next chapter will discuss the findings of this research in more details by critically reviewing the research and the performance of the proposed framework.

7 DISCUSSION

This thesis has described the development of a risk-based framework that can be used to assess the risks and uncertainties associated with energy grid interconnections so that the process of identifying suitable countries with which to make an interconnection can be greatly facilitated.

The framework also addresses a major challenge of carrying out a risk analysis, with regards to constructing and operating interconnections, namely obtaining reliable information. Such information is required to identify risks, and thereafter assessing their likelihood of occurrence and impact. Knowledge obtained from a diverse range of experts in the field, who are well versed in terms of experience, judgment and application including rules-of-thumb was proposed and demonstrated in a case study which considered assessing the risk of the UK making interconnections with a number of its neighbours.

This chapter provides a critical review of the methodology followed in this research to develop the risk based framework.

7.1 Summary of the Research

The research carried out in this project may be summarised as follows:

1. **The development and testing of a theoretical framework for selecting the most appropriate country (ies) with which to make electricity interconnections for trading renewable electricity.**

Based on the findings of the literature review (Chapter 2), a methodology was proposed to develop a Whole Life Risk Cost Appraisal model which could be used to quantify the construction and operational risks.

The Whole Life Risk Cost Appraisal model consisted of 1) risk identification to identify the construction and operational risks. 2) Risk semi-quantification which ranks and compares identified risks. 3) Risk quantification to quantify the impact and probability of identified risks on interconnection's NPV.

The applicability and usefulness of the framework was applied via a case study which considered the risks of the UK forming an interconnection with a number of neighbouring countries. This involved:

1. Identifying a number of neighbouring candidate countries with which if may be suitable for the UK to develop an interconnection
2. Projecting interconnection capacities between the UK and candidate countries using an energy-based scenario tool
3. Developing the Whole Life Cost Appraisal model for the UK and the candidate countries
4. Soliciting expert judgement through questionnaires and interviews to assist with the risk identification and risk semi-quantification processes
5. Quantifying the identified risks by including their impacts and probability of occurrence in the Whole Life Risk Cost Appraisal model
6. Ranking, in terms of interconnection risk cost, the candidate countries.

2. Developing a tool to project interconnection capacities between the UK and candidate countries.

A procedure, described in Section 4.2, was developed by which information from the literature was used to obtain supply/demand scenarios which can be utilised to project the interconnections capacities of countries. The usefulness of the tool was demonstrated in the case study described in Section 4.2.3.

3. A Whole Life Risk Cost Appraisal model

The WLRCA model utilized the Net Present Value technique to assess the risk costs and benefits of forming an interconnection between particular countries over the design life of the interconnection.

MCA was utilised within the developed WLRCA model to rank the countries considered on a risk cost basis. This was done by modelling identified risks impact and probability as statistical distributions using @Risk software. The software was used to generate the sets of random numbers for use in testing various costs and revenue options (scenarios). The random values for each uncertain parameter were then generated within the allocated distributions.

4. The use of expert opinion elicited via questionnaires and interviews to inform risk identification and risk semi-quantification

Initially, an extensive literature review was undertaken to identify the most prominent risks and thereafter this was augmented by canvassing the opinion of a group of experts, through a series of structured interviews. In total 20 experts (out of 100 contacted) from continental Europe, who have specialist skills and knowledge in electricity generation and distribution participated in the research. These included those working in electricity generating and distribution companies, design engineering consultants, academic researchers of note in their field (including energy policy specialists, electrical power engineers and economists), policy makers and government advisors.

7.2 Critical Review of the Research

The methodology adopted for the development of a risk-based framework, which quantifies the probability and impact of the identified risks for development of an interconnection, is discussed under the following headings:

Risk Identification
Risk semi-quantification
Risk quantification

7.2.1 Risk Identification

The method adopted for risk identification, described in section 3.2.3.1, comprises of a literature review and canvassing expert opinion. The literature review was utilised to identify the major categories of risks associated with seabed interconnections thereafter this was augmented by canvassing the opinion of a group of experts. The use of experts opinion on the risk identification is suggested as it is a valuable technique to:

1. Use the experts knowledge and experiences where prototype techniques will be used in the construction and/or operation of the interconnection
2. Avoid any bias that might be happen when just one firm is engaged in the process
3. Engage the various stakeholders in the early stages of the project

Historical data (evidence based methods (BSI, 2010)) could have been used for identifying risks and estimating their associated impact and probability where they are available, (were not available for this research). The records on the faults, minor and major accidents and blackouts of the existing interconnections could be used to generate a list of potential risks associated with a new interconnection after analysing the similarities and dissimilarities of the existing and new interconnection. Instead of using historical data, literature review is used in this research for similar reason. The list of identified list could be consulted with a team of experts follow a systematic process to check the identified risks or to identify new risks by means of a structured set of prompts or questions.

The experts' engagement during the risk identification process could be enhanced by adopting more interactive techniques such as the Delphi method or Structured "what-if"

Technique (SWIFT) through a set of facilitated workshops rather than individual consultation techniques such as interviews. A facilitated workshop allows experts to discuss their opinion and to share their expertise and as a result can achieve a higher possibility for identifying complex potential faults, accidents and risks by triggering imagination. The workshops could also help avoiding bias, which could be tolerated during individual consultations, and also building consensus among experts through group discussion. These types of involvement in the risk identification process by those who are accountable for an interconnection project and for further risk treatment actions reinforce their responsibility and collaboration.

A facilitated workshop was not utilised herein due to resource and scheduling limitations, namely 1) costs associated with recruiting experts for a day-long workshop and 2) time required to coordinate the large number of experts, n=20, for attending the event, and 3) difficulties associated with bringing a sufficient number of experts together (in one location) at the same time.

7.2.2 Risk semi-quantification

Where the ranking of the identified risk or prioritising the risk mitigation strategy is not important and only the quantification of actual risks impact is required, the risk semi-quantification stage can be disregarded and the quantification stage can be carried out directly after risk identification. However when adopting a risk management strategy for an interconnection. As it is suggested by number of asset management standards (e.g. ISO, 2014), the semi-quantification stage is recommended as it will help to assess the risks level against preset criteria, help to identify the key risks and prioritise associated mitigation measures.

The semi-quantification stage in this research assumed that all of the risks were equally important. However, a relative weighting system could be used in the semi-quantification stage as the risks had different associated probabilities and impacts. For example, a risk which had a greater potential impact than another risk but both with a similar probability was therefore more important and the risk had been weighted by its potential impact. Moreover, a system could have been used to weight the risks which have some special prominence for the project and/or for the stakeholders (e.g. regulatory framework which was selected as the major risk for the case study by the experts).

7.2.3 Risk quantification

The risk quantification process introduced in this study has various components which are reviewed separately below.

7.2.3.1 Economic evaluation method

NPV technique was used as a method to appraise the risk costs and benefits of an interconnection.

There are a number of alternative techniques to NPV available for assessing the economic performance of an interconnection such as Payback and Internal rate of return. The selection of the most appropriate technique depends on the factors and parameters required for decision making. NPV was chosen because it ranks candidate countries in terms of least risk cost by considering the whole life costs and benefit of the interconnections. However, there may be other occasions (such as limited capital for construction of an interconnection) when other economic techniques could be more appropriate.

The NPV technique requires a discount rate to be used. Herein a single discount rate (of nine per cent) was used for the purposes of the case study. However, it is acknowledged that different results may have been obtained had different discount rates been used reflecting the economic conditions in each of the candidate countries.

7.2.3.2 Cost stream

For the purposes of the case study, the costs of the UK forming an interconnection with the identified countries were quantified in terms of construction and operational costs and were chosen from the sources described in sections 6.2.2, and 6.2.3 respectively. The construction costs were broken down in to cable and convertor station costs and saving equal cost of generating electricity. The operational costs were represented by maintenance costs, annual cost of losing power due to heating of the line and cost of imported RE. Where historical data was available both construction and operational costs could be broken down further as follows:

For construction costs:

1. Cost of getting required permission (e.g. environmental permission)
2. Cost of buying cable
3. Cable installation costs
4. Cost of land to be used for the convertor stations
5. Construction cost of convertor stations
6. Cost of upgrading the existing onshore grid or developing onshore grid

For our case study 2, 3 and 4, 5 are combined together separately where 1 and 6 were not considered due to lack of data which could cause unrealistic cost estimations. To avoid this in the case study, experts were consulted to check the accuracy of the overall cost estimation.

As for the operational costs annual scheduled and unscheduled maintenance could be considered separately as discussed in 6.2.2.2.

7.2.3.3 Revenues (benefits) stream

Revenues were included under the following categories:

1. The revenue generated from selling the UK's spare RE to the candidate country
2. Value of savings CO_2 (i.e. from reduced carbon credit payments)

Among these components the trading mechanism (for both selling and buying RE) is complex. Herein it was represented by prices obtained from historical data (i.e. 2008 to 2012). However it recognised that considering impacts of the emerging markets could improve the accuracy of the analysis by developing more complicated models to estimate the future prices for RE [for example see Parail (2010b)].

The calculation for the CO_2 saving should be updated with the most recent approved rates for CO_2 taxation whilst the cost of losing power due to heating of cables needs to be reviewed according to the type of the cable selected for developing the new interconnection.

7.2.4 Expert judgments

7.2.4.1 Interviewees

The opinions of a group of experts were consulted via the questionnaire and interview process for the risk identification process. As adopted within this risk assessment methodology, risk identification should be considered as a precursor within any risk analysis work and should occur in the initial stages of any interconnection project. The results obtained however will ultimately depend upon the number, range and experience of the experts considered. For this work the range of experts should be diverse and their experience high.

In terms of the number of experts, selecting a sample from the population is a crucial parameter in any study based on obtaining information from people to avoid the bias and to accurately reflect the population as a whole (Ott and Longnecker, 2008). The literature describes a variety of different methods of selecting samples based on the requirements. However, when representing a larger population (similar to the UK case study) the sample (number of interviewees in this case) desirably should form a normal distribution (bell-shape curve) for the responses (Urdan, 2005; Ott and Longnecker, 2008). Please see Appendix G for more discussion on normal distribution. Having said that, a number of related studies suggest a minimum of 20 samples may be satisfactory (Babuscia and Cheung, 2014; Tversky and

Kahneman, 2014). The resource limitations of this study meant that 100 experts were consulted, with 20 of these taking part in the research.

The main issues associated with having too few responses are:

1. The lack of responses in some categories such as contractors was due to the associated risk categories such as technical risks not being identified by some respondents who felt that they did not have require subject knowledge. The result could cause an underestimation of some risks e.g. technical risk impacts on the WLA model.
2. As mentioned earlier some risks which were identified later during the interview processes, e.g. one risk was identified in the 17th interview (out of 20), which evidently could not be assessed and quantified by previously interviewed experts, leading to a paucity of respondents. To address this, an alternative approach could have been used to data gatherings such as running workshops to gather all the experts in one place for brainstorming sessions or by applying the Delphi technique which is suggested by BSI (2010) by which a loop is defined to re-circulate the experts' idea.
3. Having equal responses from all the candidate countries can assure avoidance of bias for the theoretical framework especially in the presence of any historical and/or current political conflicts between countries. Not having equal responses however can cause risks being quantified with unrealistically high impacts for some countries. Nevertheless, for the case study as there are no current conflicts in the region and, as the similar number of experts from other countries rather than the UK participated in this study, the impact of possible bias could be considered to be negligible.

However, as the case study was used to test the proposed theoretical framework, not having a large and diverse number of respondents may be considered not to be important for the purposes of demonstrating the framework. Nevertheless, it is recognised that careful consideration of the number and diversity of experts would be very important for the real application of the framework so as to obtain a balanced response to better ensure the accuracy of the result and to avoid bias.

7.2.5 The developed tool

The procedure presented in Section 4.2.1 shows how an energy-based scenario tool can be used by decision-makers to contrast and compare scenario choices depending on the factors they consider to be most important. It also highlights the trade-offs that may have to be made. The examples could just have easily considered other scenarios including:

1) A scenario which strongly incentivizes only new markets;

2) A scenario which provides maximum storage capacity;

3) A scenario which addresses renewable intermittency issues.

The developed tool shows great potential as a research tool, firstly because it provides a database for selecting projections of future electricity demand and electricity supply mix within the UK. Secondly, as shown in Section 4.2.1.3, it can be used to generate new electricity supply mix scenarios (by cherry picking previously developed scenarios) whilst considering the implications on (i) CO_2 emission and (ii) Capital cost. These attributes, in particular the technology ranking system, are extremely valuable for decision-makers within the energy sector who wish to compare / contrast the plethora of energy related scenarios that are in existence and select a viable supply demand mix.

In order to adopt and use the tool in a new research to generate energy related scenarios for the UK, more recent studies (energy supply/demand projections) if available should be added to the database to reflect the recent progresses after the development of the tool in 2013. This function was foreseen during the development of the tool and can be completed straightforwardly.

The tool can also be further developed to reflect a more complicated procedure of risk assessment by allowing the probability associated with each generated scenario to be considered (Section 4.2.2.3). This will allow the tool's outputs, i.e. share of a particular electricity generation technology, CO_2 emissions and capital cost, to be assigned a probability of achievement in the considered timespan, a feature which will assist a more reliable decision to be made when comparing various generated energy scenarios and parameters. The most challenging part of such a development would be assigning the probability to each technology. This can be facilitated by considering available historical data for the developments and implications of that technology in the past and by using appropriate models and simulations for calculating the probability of future developments and also the impacts of possible threat and /or opportunities such as CO_2 related taxation.

7.3 Value of the Research

The value of the research was achieved by developing a risk-based framework which can facilitate decision makers to selecting the most appropriate country (ies) with which to make electricity interconnections. As there are perceived risk-associated barriers to the development of interconnections such a framework should therefore help to encourage the development of interconnections and thereby help to maximise the utilisation of renewable energy resources.

A risk based framework for finding the most appropriate country to make interconnection with was not evident in the literature, despite the needs for such a framework is identified in the literature (Great Britain Parliament, 2011b; Great Britain Parliament, 2011a). The literature identified one study (Parail, 2010b) that had used a probabilistic approach to add economic uncertainty to the electricity trading via interconnections with a focus on electricity prices after putting interconnection in operation.

The application of using expert opinion where appropriate data is unavailable was demonstrated in this study. Lack of sufficient data can be one of the main reasons for not adopting a relatively complicated risk based approach widely in construction industry. This study shows how the expert opinion can be used to fulfil such a shortfall. Further, the canvassing of expert opinion together with the review of the literature has enabled a number of risks related to building and operating interconnections to be identified.

7.4 Summary of the Discussion

This chapter has critically reviewed the research methodology adopted in the development of a risk-based framework for selecting the most appropriate country for making interconnection with and trading renewable electricity. In particular, the effectiveness of the framework and assumptions made throughout the research were discussed and, where appropriate, suggestions have been offered to facilitate future developmental work and improvements to the framework for using it for a new interconnection development.

The canvas of expert opinion for the risk identification and estimating risks impact and probabilities in the absence of adequate data were achieved through the use of structured interviews. Although the required data were obtained from the experts, the impact of the number of experts participated in the study (n=20) was discussed.

Furthermore, suggestions were provided for further development of the framework to be utilised as an interconnection appraisal tool including using historical data for risk identification processes and incorporating a weighting system within the semi-quantification stage. Using different discount rates for various potential countries or regions was also suggested. Adding more components to the cost stream and projecting future electricity prices after implication of interconnections were also discussed. The later was suggested to consider the impacts of emerging markets on revenues by developing new models rather than just using historical data.

Conclusions from the research together with recommendations for future research are presented in the following chapter.

8 CONCLUSIONS AND RECOMMENDATIONS

The development of Supergrids through interconnections is recognised as a means by which spare renewable energy can be exchanged between countries to help to meet growing energy demand and thereby reduce reliance on fossil fuels, thus reducing harmful GHG emissions.

The need for a rational risk-based framework which can help decision makers find the most appropriate country (ies) with which to make an interconnection is vital for developing the Supergrid. The current procedure associated with the development of interconnections is protracted and this is due in part to the high level of uncertainties associated with selecting the most appropriate country with which to make an interconnection. The proposed risk-based framework reduces the protracted procedures by identifying and quantifying associated risks and uncertainties. The framework consists of three components namely;

1. Initial screening to identify candidate countries
2. Whole life appraisal which considers all relevant costs and revenues associated with the interconnection over the service or design life of the interconnection
3. Risk assessment to take into account the risks and uncertainties associated with construction and operation of the interconnections and to model their impacts and probability of occurrence

The use of the framework was illustrated using the UK as a case study.

8.1 Accomplished Work and Main Findings

The research has demonstrated the objectives outlined in Chapter 1 by:

1 Developing a framework which can be used to identify candidate countries with which to make an interconnection

2 Investigating the viability of risk based technique for the project framework

3 Developing a risk based framework which incorporate an economic model to assess the viability of the candidate countries

4 Verifying the developed framework using the UK as a case study through which the impact of risks, identified in the literature and from expert opinion, were analysed on the economic viability of making interconnections with the screened candidate countries.

It is possible to draw the following conclusions from the research:

- There are different renewable technologies available to meet global energy demand and to reduce the level of CO_2 emission. However **Chapter 2** reported that there are various barriers, limitations and uncertainties associated with the development and implication of these technologies. Trading RE between different countries by developing interconnections is a feasible measure for addressing the barriers and uncertainties associated with renewables, such as intermittency and security of supply, and hence facilitating the development of RE technologies.
- HVDC cables were found to be more efficient than HVAC for long distance transmission of energy. Their use may therefore help to overcome excessive energy loss from interconnections, which has been a barrier to the widespread use of interconnections.
- The 'future scenarios' tool developed to calculate the interconnection capacities has been used to address successfully the complex issues of projecting the most appropriate electricity supply mix and electricity demand by using a range of existing energy studies.
    - The 'future scenarios' developed tool showed that Germany, based on an assessment of P80 interconnection capacities for 2030, can provide the greatest (10.97GW) surplus capacity of RE from the nine candidate countries considered.
- Canvassing expert opinion was shown to be a viable means of estimating the probability and impact of identified risk in the absence of required data.
    - Structured interviews and questionnaires were found to be a useful means of eliciting expert opinion (see Section 3.3.5).
    - As discussed in Chapter 7 the results obtained when using expert opinion will ultimately depend upon the range and quality of the experts considered; (and should be both diverse and high respectively).
- Chapters 5 and 6 demonstrated that the proposed methodology could be successfully used for the UK as the case study.
    - For the UK it was found that the Regulatory framework, Changes in energy policy and Weak onshore grids were the major risks.
    - Of those countries considered, France was deemed to be the most desirable option for the UK to build an interconnection with, as it has the lowest risk cost in terms of PI and NPV.

    - Monte Carlo simulation was found to be an appropriate technique for risk quantification within the proposed framework as it can model complex economic relationships such as NPV in order to estimate the risk contingency and define dominant contributors.
- With further stakeholder engagement the developed framework will provide a deeper understanding of the key fundamental risks associated with interconnections as well as mitigation measures.

8.2 Recommendations for Further Research

While the results presented in Chapter 6 have demonstrated the promise of the framework, to further develop and improve the convenience of the prototype framework to practitioners, the following further research is recommended:

- The research presented herein has relied on the use of information from the literature and the elicitation of expert knowledge. Further research is recommended to supplement these sources of information with where possible, historical data to identify risks and estimate their associated impact and probability. Research should be carried out to identify methods, such as Fault Tree Analysis, facilitate this process. The outputs from such methods could then be utilized by experts and other stakeholders, thus by engaging stakeholders in the project at an early stage providing an opportunity to identify new risks.
- The use of a weighting system which could be incorporated into the semi-quantification stage for scoring and ranking the identified risks should be explored. This process could be used to weight the opinion from experts with different backgrounds and / or to weight the risks which score higher in the semi-quantification stage.
- When calculating the NPV for an interconnection individual discount rates for the potential countries should be used to reflect the different economic condition and or expectations that might exist in each country considered. Historical data, where available, for the existing interconnections to a country should also be used for validating the calculations.
- Actual quotations and cost estimations from engaged contractors in the construction of the project should be used in the cost model where possible. As for the mainte-

nance models historical data of the existing interconnection should be utilised in the cost stream

- Further research should also explore the development of a risk model which is able to :
    - Project the future electricity prices to be used in the revenue stream.
    - Include the impact on cost of interconnecting the two electricity markets as well the potential impact of the changes in CO_2 taxation in future.
    - Consider plausible scenarios in future electricity pricing by developing a probabilistic model which can generate ranges of future scenarios for electricity prices with associated probabilities.

8.3 Additional applications for the framework

The proposed risk-based framework has been offered and validated for selecting the best countries with which to make interconnection, but it is not its only application. The proposed framework can be also used for other aspects of project appraisal including identifying a suitable route between the chosen countries and for the construction phase.

The selection of the most appropriate route between two countries, or regions, is normally based on economic considerations and therefore the shortest route is most often selected. However, the shortest route may not necessarily be the most appropriate as other uncertain factors may need to be considered. A risk based framework could facilitate such decision making. For example:

1. The shortest route may have a higher cost when considering potential future maintenance. For example when the shortest route has the busiest shipping traffic and marine activities which can cause accidents and therefore more routine and unscheduled maintenances might be required.
2. There might be more than one route available with very similar lengths and therefore an appraisal would be required.
3. There might be some other parameters rather than the monetary which are needed to be considered such as environmental and or social aspects. The Westernlink, which is discussed in Chapter 5, is such an example.

When addressing these issues the proposed framework can be used to:

1. Identify risk to be considered. Include uncertain whole life cost of the potential interconnections, by using the risk based method developed herein which incorporates

WLA, and therefore to be able to compare their whole life cost rather than only the capital cost.

2. Include various construction and operational risks

The risk assessment stage could also help during construction of interconnections to:

- Identifying the associated hazards
- Identify appropriate methods to control or mitigate the identified hazards (risk treatment stage).
    - During the risk treatment stage engagement and communication with all stakeholders including the contractors and subcontractors is vital to ensure that the risk treatment measure will be identified and implemented appropriately.
- The proposed risk based framework would need to be modified for the construction of an interconnection as follows:

a. WLA stage is included in the first stage of the framework “Establishing the context” as a less complicated step just covering the construction cost estimation.

b. Establishing the context includes the selection of the most viable route and also setting the criteria for further risk evaluation part.

c. The inclusion of Risk evaluation within the framework. Risk evaluation involves comparing estimated levels of risk with risk criteria, in order to determine the significance of the level and type of risk (BSI, 2010).

d. The inclusion of Risk treatment to select and agree on one or more relevant options for altering the probability of occurrence, the effect of risks, or both, and implementing these options (BSI, 2010). Accordingly the proposed framework would require an additional module as shown in Figure 41.

e. Monitoring and reviewing is the process of checking, on a regular bases, to verify that the assumptions about risks remain valid, expected results are being achieved and risk treatment measures are effective

f. Communication and consultation with stakeholders is the key for successful risk assessment and it should be carried out during all stages of the process.

After the construction of the interconnection a risk-based framework similar the proposed framework can be utilised for its operation and managing the asset. The risk-based framework for the operational stage can be used for the maintenance of an interconnection, by being used for the appraisal of different maintenance strategies and formulating a maintenance plan. Such a framework is recommended by asset management standards such as ISO (2014) which provides more details on the required framework.

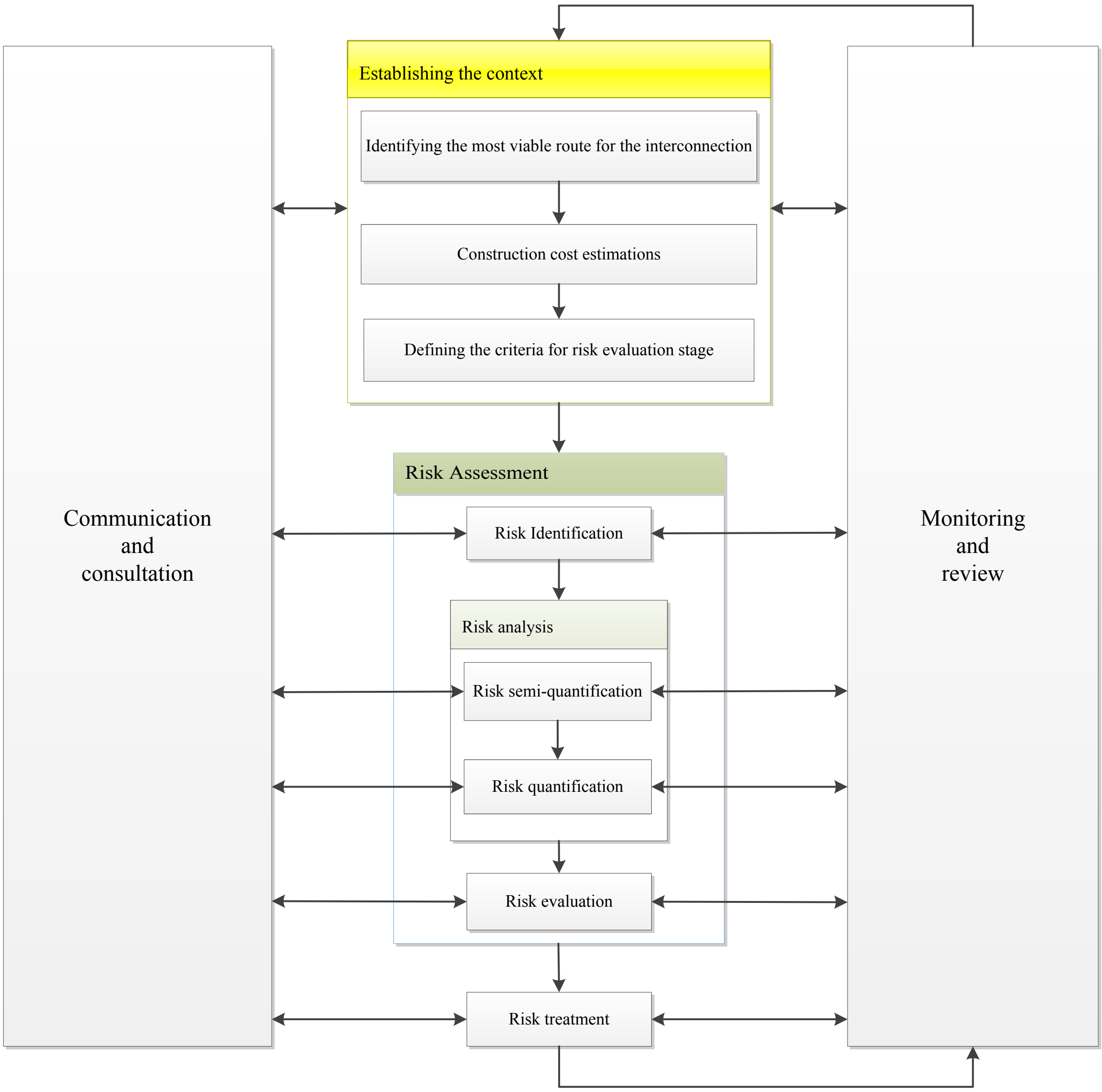


Figure 41: Revised framework for the construction of an interconnection

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Appendix A

Appendix A. Published Papers

1. Eskandari Torbaghan, M., M. P. N. Burrow and D. V. L. Hunt (2015) Risk assessment for a UK Pan-European Supergrid. **International Journal of Energy Research** 39 (11): 1564–1578
2. Eskandari Torbaghan, M., D. V. L. Hunt and M. Burrow (2014) Supergrid: projecting interconnection capacities for the UK. **Proceedings of the ICE - Engineering Sustainability** 167 (6): 249-263.
3. Eskandari Torbaghan, M., M. Burrow, D. V. L. Hunt, et al. (2015) A Risk based framework for grid interconnections: UK Pan-European Supergrid. **International Journal of Energy Research** Under Review. (not included)
4. Eskandari Torbaghan, M., D. Hunt and M. Burrow (2013) "Projecting the UK's Future Electricity Supply Mix: A Tool for Generating Sustainable Future Energy Scenarios" In *3rd World Sustainability Forum*. Electronic Conference: Sciforum.

Appendix B

Appendix B. Economic opportunities for the UK

One of the key benefits of developing interconnection would be the economic opportunities associated with exporting technology and electricity. It is due to the fact that the offshore renewables resource such as wind and tidal energies around the British Isles is potentially vast.

Public Interest Research Centre (2010) reveals that in harnessing 29 per cent of the practical offshore renewable resource by 2050 around 145,000 jobs and £62bn of annual revenues could be generated for the UK. The report estimated the UK's full practical renewable energy offshore resource at 2,131 TWh/year, which is six times the current UK electricity demand. Developing interconnection could help UK to maximise access to its potential offshore by offering a route to market when UK demand is low or even to meet the EU demand.

Moreover, the developments in the seabed cable interconnection technology has the potential to make the UK key player in the offshore transmission sector. The well-developed offshore oil and gas technology and experts in the UK could be transferred to other offshore industries, particularly as output from the oil and gas sector continues to fall (Great Britain Parliament, 2011a).

UK Parliament (2011a) suggests that investment in offshore transmission could create 775,000 jobs in Europe and add €19bn to European GDP and could create 50,000 new jobs in the UK alone by 2020.

Appendix C

Appendix C. Advantages and disadvantages of economic evaluation methods developed by Levander *et al.*(2009)

[redacted]

[redacted]

Appendix D

Appendix D. Excel files [CD]

Part.1: Developed Scenarios, Excel-based tool (for the UK and nine candidate countries)

Part.2: @Risk^{TM} includes:

1 Risk ranking (responses and analysis for probability and impact estimation)
2 Interconnections' capacity (@Risk^{TM} is required)
3 Cost and revenue streams
4 WLA models (@Risk^{TM} is required)

Appendix E

Appendix E. Inaccuracy in forecasts

The Channel tunnel, opened in 1994 at a construction cost of £4.7 billion, is a case in point, with construction cost overruns of 80 per cent, financing costs that are 140 per cent higher than those forecast and revenues less than half of those projected (Flyvbjerg *et al.*, 2003). Inaccuracy in cost forecasts on average for rail, bridges and tunnels, and for roads projects demonstrated by Flyvbjerg (2006) are presented in Table E.1.

Table E.1. Inaccuracy in cost forecasts (Flyvbjerg, 2006)

Type of Project	Average Inaccuracy (%)	Standard Deviation	Level of Significance P
Rail	44.7	38.4	<0.001
Bridges and tunnels	33.8	62.4	0.004
Road	20.4	29.9	<0.001

There are different explanations for inaccuracy in forecasting such as: technical, psychological, and political-economic (Flyvbjerg, 2006). For instance, strategic misrepresentation from political aspect can be one of the reasons of inaccuracy; "*When forecasting the outcomes of projects, forecasters and managers deliberately and strategically overestimate benefits and underestimate costs in order to increase the likelihood that it is their projects, and not the competition's, that gain approval and funding*" (Flyvbjerg, 2006).

Strategic misrepresentation can be traced to political and organisational pressures, for instance, competition for scarce funds or jockeying for position (Flyvbjerg, 2006). However, Flyvbjerg (2006) proposed Reference Class Forecasting method for dealing with this problem, in the following three steps for a particular project:

a. Identification of a relevant reference class of past and similar projects.
b. Establishing a probability distribution for the selected reference class. This requires access to credible data for a sufficient number of projects.
c. Comparing the specific project with the reference class distribution, in order to establish the most likely outcome for the particular project.

The result of the reference class forecasting method is providing empirically based optimism bias uplifts for selected reference classes of projects, to produce more realistic forecasts of construction cost in projects. As an example, overview of applicable optimism bias uplifts for the 50 per cent and 80 per cent percentiles for some road projects are presented in Table E.2 (Flyvbjerg, 2006).

Table E.2. Applicable capital expenditure optimism bias uplifts for road projects (Flyvbjerg, 2006)

Category	Type of Projects	Applicable Optimism Bias Uplifts	
		50% percentile	80% percentile
Road	Motorway	15%	32%
	Trunk roads		
	Local roads		
	Bicycle facilities		
	Pedestrian facilities		
	Park and ride		
	Bus lane schemes		
	Guided buses on wheels		

However, there is a guidance table provided by Her Majesty's Treasury (HM Treasury) (2011) regarding the adjustment percentages for generic project categories that should be used in the absence of more robust evidence. The guidance is presented in Table E.3. According to the definitions of the project types provided by HM Treasury (2011), the seabed interconnections are categorised as Non-standard civil engineering projects.

Table E.3 Recommended adjustment ranges (Her Majesty's Treasury, 2011)

Project Type	Optimism Bias (%)			
	Works Duration		Capital Expenditure	
	Upper	Lower	Upper	Lower
Standard Buildings	4	1	24	2
Non-standard Buildings	39	2	51	4
Standard Civil Engineering	20	1	44	3
Non-standard Civil Engineering	25	3	66	6
Equipment/Development	54	10	200	10
Outsourcing	N/A	N/A	41	0

Appendix F

Appendix F. Experts responses

a. Identified risk

			List of experts identified by number																			
		Identified risk	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Number of hits
Construction	Social	Public acceptability		√	√		√	√	√	√	√			√	√		√	√	√		√	13
	Technical	a. Loss of Dynamic Positioning (DP)		√			√	√		√	√											5
		b. Earthquake					√										√					2
		c. Seabed topography	√	√			√	√	√	√			√			√		√				9
		d. Seabed contamination		√			√	√		√	√					√	√	√				8
		e. Unforeseen ship wrecks and other submarine junk					√	√		√	√							√				5
		f. Unforeseen sea depth	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	√				1
		g. Weak onshore grids	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	√		√	√	3
		h. Regulatory framework	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	√	√	√		√	√	√	√	√		8
		i. Marine activities		√			√	√	√	√	√		√			√	√	√	√	√		12
	Economic	a. Uncertainty in cost estimation		√	√		√	√	√		√		√	√			√	√	√	√		12
		b. Supply chain; contractor	√				√	√	√		√		√				√	√	√			9
		c. Solvency of contractor		√	√		√	√	√							√	√	√				8
		d. Inflated bid price		√	√		√	√	√		√		√	√			√			√		10
		e. Cost of material			√		√	√	√				√					√				6
	Environmental	a. Disturbing habitats and ecosystems		√	√		√	√	√		√				√	√	√	√	√			11
		b. Climate change			√		√	√		√			√					√	√			7
	Political	Changes in energy policy of candidate coun-		√	√		√	√	√	√	√	√	√	√		√	√	√	√	√	√	16

		try																			
Operational	Social	Demonstrations caused by raised price			√		√	√		√			√					√				6
	Technical	a. Availability of electricity from renewable resources	√		√		√		√	√	√	√	√	√	√		√	√		√		13
		b. Earthquake			√		√										√					3
		c. Marine activities		√			√	√	√		√		√					√				7
		d. Weak onshore grids	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	√		√	√	3
	Environmental	a. Disturbing habitats and ecosystems		√	√		√	√	√		√		√			√		√				9
		d. Climate Change					√	√			√		√					√				5
	Economic	Increase in prices of imported electricity		√	√	√	√		√	√	√		√	√	√		√	√		√	√	14

The cells highlighted in black shows that the risk is identified by experts and therefore added later to the list

b. Risk ranking

Norway

			List of experts identified by number											
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**19**	**18**
Construction risks	Social	Public acceptability	9	4	16	9	16	0	1	0	0	6	0	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	9	0	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0	0
		c. Seabed topography	0	12		0	0	0	0	2	2	0	0	0
		d. Seabed contamination	0	12	0	0	12	0	12	0	2	0	0	0
		e. Unforeseen ship wrecks and other submarine junk	0	12	0	0	6	0	0	0	0	0	0	0
		f. Unforeseen sea depth										0	4	0
		g. Weak onshore grids										0	0	16
		h. Regulatory framework						4	3	16	12	2	0	6
		i. Marine activities	0	6	0	0	16	0	3	6	1	4	0	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	4	4	25	0	16	0	3	9	0	12	0	16
		b. Supply chain; contractor	0	4	5	0	12	0	4	16	0	1	0	0
		c. Solvency of contractor	2	6	4	0	0	0	1	0	4	0	0	0
		d. Inflated bid price	1	3	10	0	15	0	2	9	0	0	0	16
		e. Cost of material	4	16	12	0	0	0	0	9	0	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	16	12		0	9	0	3	0	16	9	0	0

		b. Climate change	9	9	0	16	0	0	0	16	0	4	0	0
	Political	Changes in energy policy of candidate country	3	5	6	12	16	4	4	16	6	5	3	12
Operational risks	Social	Demonstrations caused by raised price	4	1	0	9	0	0	0	2	0	0	0	0
	Technical	a. Availability of electricity from renewable resources	9	0	2	2	16	4	1	6	0	0	0	4
		b. Earthquake	1	0	0	0	0	0	1	0	0	0	0	0
		c. Marine activities	0	12	3	0	6	0	0	9	0	0	0	0
		d. Weak onshore grids	0	4	0	0	4	0	0	16	0	0	0	0
		a. Disturbing habitats and ecosystems										0	4	9
	Environmental	d. Climate Change	12	8	0	0	12	0	0	9	9	0	0	0
	Economic	Increase in prices of imported electricity	9	0	12	16	6	0	8	6	0	0	0	16

Sweden

			List of experts identified by number										
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**18**
Construction risks	Social	Public acceptability	9	4	16	6	12	0	1	0	0	6	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	9	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0
		c. Seabed topography	0	12		0	0	0	0	2	9	0	0
		d. Seabed contamination	0	12	0	0	12	0	12	0	12	0	0
		e. Unforeseen ship wrecks and other submarine junk	0	12	0	0	6	0	0	0	0	0	0
		f. Unforeseen sea depth										0	0
		g. Weak onshore grids										0	16
		h. Regulatory framework						4	3	16	20	2	6
		i. Marine activities	0	6		0	16	0	3	6	9	2	4

	Economic	a. Uncertainty in cost estimation (quantity and rates)	4	4	25	0	16	0	3	9	0	12	16
		b. Supply chain; contractor	0	4	5	0	12	0	4	16	0	1	0
		c. Solvency of contractor	2	6	4	0	0	0	1	0	6	0	0
		d. Inflated bid price	1	3	10	0	15	0	2	9	0	0	16
		e. Cost of material	4	16	12	0	0	0	0	9	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	16	12	0	0	9	0	3	0	9	6	0
		b. Climate change	9	9	0	20	0	0	0	16	0	4	0
	Political	Changes in energy policy of candidate country	2	5	6	12	16	4	2	16	12	5	12
Operational risks	Social	Demonstrations caused by raised price	4	1	0	9	0	0	0	2	0	0	0
	Technical	a. Availability of electricity from renewable resources	4	0	2	9	9	4	1	6	0	0	6
		b. Earthquake	1	0	0	0	0	0	1	0	0	0	0
		c. Marine activities	0	12	3	0	6	0	0	9	0	0	0
		d. Weak onshore grids	0	4	0	0	4	0	0	16	0	0	0
		a. Disturbing habitats and ecosystems	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0	9
	Environmental	d. Climate Change	6	8		0	12	0	0	9	9	0	0
	Economic	Increase in prices of imported electricity	4	0	12	16	9	0	8	6	0	0	16

Spain

			List of experts identified by number											
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**19**	**18**
Construction risks	Social	Public acceptability	4	4	16	9	9	0	1	0	0	6	0	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	6	0	0	12	0	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0	0

		c. Seabed topography	0	9		0	0	0	0	12	16	0	0	0
		d. Seabed contamination	0	8	0	0	6	0	1	0	6	0	0	0
		e. Unforeseen ship wrecks and other submarine junk	0	12	0	0	9	0	0	0	0	0	0	0
		f. Unforeseen sea depth										0	0	0
		g. Weak onshore grids										0	0	16
		h. Regulatory framework						16	3	16	25	6	0	6
		i. Marine activities	0	9	0	0	9	0	3	12	6	8	0	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	6	8	25	0	16	0	3	16	0	12	0	16
		b. Supply chain; contractor	0	6	5	0	16	0	4	16	0	6	0	0
		c. Solvency of contractor	6	15	4	0	0	0	4	0	25	0	0	0
		d. Inflated bid price	9	3	10	0	16	0	2	16	0	0	0	16
		e. Cost of material	4	16	12	0	0	0	0	9	0	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	2	12	0	0	6	0	3	0	9	9	0	0
		b. Climate change	1	9	0	16	0	0	0	16	0	4	0	0
	Political	Changes in energy policy of candidate country	4	10	6	16	9	16	9	9	12	6	0	16
Operational risks	Social	Demonstrations caused by raised price	1	1	0	0	0	0	0	4	0	0	0	0
	Technical	a. Availability of electricity from renewable resources	4	0	16	12	9	16	1	9	0	0		16
		b. Earthquake	6	0	0	0	0	0	1	0	0	0	0	0
		c. Marine activities	0	12	3	0	9	0	0	9	0	0	0	0
		d. Weak onshore grids	0	4	0	0	6	0	0	16	0	0	0	0
		a. Disturbing habitats and ecosystems										0	6	9
	Environmental	d. Climate Change	4	8	0	0	6	0	0	9	15	0	0	0
	Economic	Increase in prices of imported electricity	9	0	16	9	12	0	8	16	0	0	0	16

Denmark

			List of experts identified by number											
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**19**	**18**
Construction risks	Social	Public acceptability	4	4	16	9	9	0	1	0	0	9	4	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	4	0	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0	0
		c. Seabed topography	0	12	0	0	0	0	0	2	9	0	0	0
		d. Seabed contamination	0	12	0	0	9	0	4	0	9	0	0	0
		e. Unforeseen ship wrecks and other submarine junk	0	12	0	0	9	0	0	0	0	0	0	0
		f. Unforeseen sea depth	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0	0	0
		g. Weak onshore grids	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0	4	16
		h. Regulatory framework	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	4	6	16	20	4	0	6
		i. Marine activities	0	6	0	0	9	0	3	6	9	4	0	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	1	4	25	0	6	0	3	9	0	9	0	16
		b. Supply chain; contractor	0	4	5	0	9	0	4	16	0	4	0	0
		c. Solvency of contractor	1	6	4	0	0	0	1	0	12	0	0	0
		d. Inflated bid price	1	3	10	0	4	0	2	9	0	0	0	16
		e. Cost of material	4	16	12	0	0	0	0	9	0	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	6	12		0	9	0	3	0	9	6	0	0
		b. Climate change	2	9	0	16	0	0	0	16	0	4	0	0
	Political	Changes in energy policy of candidate country	2	5	6	12	6	4	2	16	12	4	0	12

Operational risks	Social	Demonstrations caused by raised price	2	1	0	9	0	0	0	2	0	0	0	0
	Technical	a. Availability of electricity from renewable resources	4	0	2	12	16	4	1	6	0	0	0	4
		b. Earthquake	2	0	0	0	0	0	1	0	0	0	0	0
		c. Marine activities	0	12	3	0	9	0	0	9	0	0	0	0
		d. Weak onshore grids	0	4	0	0	4	0	0	16	0	0	0	0
		a. Disturbing habitats and ecosystems										0	4	9
	Environmental	d. Climate Change	4	8	0	0	9	0	0	9	25	0	0	0
	Economic	Increase in prices of imported electricity	1	0	12	16	16	0	8	6	0	0	0	16

Germany

			List of experts identified by number											
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**19**	**18**
Construction risks	Social	Public acceptability	3	2	16	15	16	0	1	0	0	9	12	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	16	0	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0	0
		c. Seabed topography	0	12	0	0	0	0	0	9	6	0	0	0
		d. Seabed contamination	0	12	0	0	12	0	4	0	6	0	0	0
		e. Unforeseen ship wrecks and other submarine junk	0	12	0	0	12	0	0	0	0	0	0	0
		f. Unforeseen sea depth										0	8	0
		g. Weak onshore grids										0	0	20
		h. Regulatory framework						9	3	16	20	3	0	6
		i. Marine activities	0	6	0	0	12	0	3	9	4	2	0	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	2	4	25	0	16	0	2	4	0	6	0	16

		b. Supply chain; contractor	0	2	5	0	16	0	4	4	0	2	0	0
		c. Solvency of contractor	2	3	4	0	0	0	1	0	4	0	0	0
		d. Inflated bid price	2	3	10	0	16	0	2	4	0	0	0	16
		e. Cost of material	4	16	12	0	0	0	0	4	0	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	6	12	0	0	12	0	3	0	6	9	0	0
		b. Climate change	4	9	0	20	0	0	0	9	0	4	0	0
	Political	Changes in energy policy of candidate country	4	5	6	20	16	9	6	9	9	4	9	12
Operational risks	Social	Demonstrations caused by raised price	2	1	0	9	0	0	0	4	0	0	0	0
	Technical	a. Availability of electricity from renewable resources	6	0	2	25	16	9	1	4	0	0	0	4
		b. Earthquake	3	0		0	0	0	1	0	0	0	0	0
		c. Marine activities	0	12	3	0	9	0	0	4	0	0	0	0
		d. Weak onshore grids	0	4		0	4	0	0	9	0	0	0	0
		a. Disturbing habitats and ecosystems	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0	8	16
	Environmental	d. Climate Change	2	8	0	0	9	0	0	4	15	0	0	0
	Economic	Increase in prices of imported electricity	3	0	12	16	16	0	8	9	0	0	0	16

Netherlands

			List of experts identified by number										
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**18**
Construction risks	Social	Public acceptability	4	2	16	15	9	0	1	0	0	6	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	2	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0
		c. Seabed topography	0	9	0	0	0	0	0	9	16	0	0
		d. Seabed contamination	0	12	0	0	9	0	4	0	16	0	0

		e. Unforeseen ship wrecks and other submarine junk	0	12	0	0	2	0	0	0	0	0	0
		f. Unforeseen sea depth										0	0
		g. Weak onshore grids										0	16
		h. Regulatory framework						4	3	16	12	6	6
		i. Marine activities	0	3	0	0	6	0	3	9	9	1	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	1	4	25	0	6	0	3	4	0	6	16
		b. Supply chain; contractor	0	4	5	0	4	0	4	4	0	2	0
		c. Solvency of contractor	1	6	4	0	0	0	1	0	6	0	0
		d. Inflated bid price	1	6	2	0	1	0	2	4	0	0	16
		e. Cost of material	1	16	12	0	0	0	0	4	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	2	12	0	0	9	0	3	0	9	6	0
		b. Climate change	2	9	0	20	0	0	0	9	0	9	0
	Political	Changes in energy policy of candidate country	2	10	6	15	9	4	4	9	16	9	12
Operational risks	Social	Demonstrations caused by raised price	1	1	0	12	0	0	0	4	0	0	0
	Technical	a. Availability of electricity from renewable resources	1	0	16	25	16	4	1	4	0	0	9
		b. Earthquake	3	0	0	0	0	0	1	0	0	0	0
		c. Marine activities	0	4	3	0	9	0	0	4	0	0	0
		d. Weak onshore grids	0	4	0	0	16	0	0	9	0	0	0
		a. Disturbing habitats and ecosystems										0	9
	Environmental	d. Climate Change	1	8	0	0	9	0	0	4	9	0	0
	Economic	Increase in prices of imported electricity	1	0	12	20	6	0	8	9	0	0	16

Belgium

			List of experts identified by number										
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**18**
Construction risks	Social	Public acceptability	1	2	9	9	9	0	1	0	0	6	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	2	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0
		c. Seabed topography	0	12	0	0	0	0	0	4	6	0	0
		d. Seabed contamination	0	12	0	0	2	0	2	0	16	0	0
		e. Unforeseen ship wrecks and other submarine junk	0	12	0	0	2	0	0	0	0	0	0
		f. Unforeseen sea depth										0	0
		g. Weak onshore grids										0	16
		h. Regulatory framework						9	3	16	20	6	6
		i. Marine activities	0	6	0	0	9	0	3	16	6	4	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	1	4	9	0	4	0	2	9	0	6	16
		b. Supply chain; contractor	0	4	9	0	4	0	2	9	0	3	0
		c. Solvency of contractor	2	6	9	0	0	0	1	0	12	0	0
		d. Inflated bid price	4	6	9	0	4	0	2	9	0	0	16
		e. Cost of material	2	16	9	0	0	0	0	9	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	2	12	0	0	4	0	3	0	6	6	0
		b. Climate change	2	9	0	20	0	0	0	9	0	6	0
	Political	Changes in energy policy of candidate country	1	10	9	15	4	9	2	9	12	6	12

Operational risks	Social	Demonstrations caused by raised price	1	1	0	15	0	0	0	4	0	0	0
	Technical	a. Availability of electricity from renewable resources	3	0	9	12	16	9	1	4	0	0	4
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0
		c. Marine activities	0	12	9	0	9	0	0	4	0	0	0
		d. Weak onshore grids	0	4	0	0	4	0	0	9	0	0	0
		a. Disturbing habitats and ecosystems										0	9
	Environmental	d. Climate Change	1	8	0	0	9	0	0	4	12	0	0
	Economic	Increase in prices of imported electricity	1	0	9	16	9	0	8	9	0	0	16

Ireland

			List of experts identified by number												
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**12**	**14**	**17**	**19**	**18**
Construction risks	Social	Public acceptability	4	2	16	0	4	0	6	0	12	0	16	0	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	2	0	0	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0	0	0
		c. Seabed topography	0	6	0	0	0	0	0	4	0	6	0	0	0
		d. Seabed contamination	0	9	0	0	2	0	2	0	0	4	0	0	0
		e. Unforeseen ship wrecks and other submarine junk	0	9	0	0	2	0	0	0	0	0	0	0	0
		f. Unforeseen sea depth											0	6	0
		g. Weak onshore grids											0	0	16
		h. Regulatory framework						4	2	16	15	20	8	0	12
		i. Marine activities	0	6	0	0	9	0	3	16	0	6	2	0	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	4	4	25	0	4	0	3	9	6	0	6	0	16

		b. Supply chain; contractor	0	4	5	0	4	0	4	9	0	0	4	0	0
		c. Solvency of contractor	4	6	4	0	0	0	4	0	0	20	0	0	0
		d. Inflated bid price	4	6	5	0	4	0	2	9	6	0	0	0	16
		e. Cost of material	4	16	5	0	0	0	0	9	0	0	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	2	9	0	0	4	0	3	0	0	6	6	0	0
		b. Climate change	6	9	0	0	0	0	0	9	0	0	6	0	0
	Political	Changes in energy policy of candidate country	1	10	10	0	6	4	4	9	8	25	6	0	12
Operational risks	Social	Demonstrations caused by raised price	2	1	0	0	0	0	0	4	0	0	0	0	0
	Technical	a. Availability of electricity from renewable resources	1	0	6	0	4	4	1	4	4	0	0	0	4
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0	0	0
		c. Marine activities	0	4	16	0	9	0	0	4	0	0	0	0	0
		d. Weak onshore grids	0	4	0	0	4	0	0	9	0	0	0	0	0
		a. Disturbing habitats and ecosystems	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0	6	16
	Environmental	d. Climate Change	2	8	0	0	9	0	0	4	0	9	0	0	0
	Economic	Increase in prices of imported electricity	4	0	25	0	6	0	2	9	9	0	0	0	16

France

			List of experts identified by number											
	Risk category	Identified risk	**3**	**6**	**7**	**8**	**9**	**10**	**15**	**11**	**14**	**17**	**19**	**18**
Construction risks	Social	Public acceptability	12	4	16	6	9	0	1	0	0	12	8	0
	Technical	a. Loss of Dynamic Positioning (DP)	0	9	0	0	2	0	0	0	0	0	0	0
		b. Earthquake	0	0	0	0	0	0	1	0	0	0	0	0
		c. Seabed topography	0	6	0	0	0	0	0	4	12	0	0	0
		d. Seabed contamination	0	9	0	0	2	0	2	0	16	0	0	0

		e. Unforeseen ship wrecks and other submarine junk	0	9	0	0	2	0	0	0	0	0	0	0
		f. Unforeseen sea depth										0	0	0
		g. Weak onshore grids										0	6	16
		h. Regulatory framework						9	3	16	20	9	0	6
		i. Marine activities	0	3	0	0	9	0	3	16	25	6	0	4
	Economic	a. Uncertainty in cost estimation (quantity and rates)	6	4	25	0	4	0	3	9	0	12	0	16
		b. Supply chain; contractor	0	4	5	0	4	0	2	9	0	2	0	0
		c. Solvency of contractor	4	6	4	0	0	0	1	0	16	0	0	0
		d. Inflated bid price	4	6	10	0	4	0	3	9	0	0	0	16
		e. Cost of material	8	16	12	0	0	0	0	9	0	0	0	0
	Environmental	a. Disturbing habitats and ecosystems	6	9	0	0	4	0	3	0	16	8	0	0
		b. Climate change	9	9	0	12	0	0	0	9	0	8	0	0
	Political	Changes in energy policy of candidate country	4	10	6	25	4	9	4	9	16	12	0	16
Operational risks	Social	Demonstrations caused by raised price	6	2	0	9	0	0	0	4	0	0	0	0
	Technical	a. Availability of electricity from renewable resources	6	0	6	16	9	9	1	4	0	0	0	16
		b. Earthquake	3	0	0	0	0	0	1	0	0	0	0	0
		c. Marine activities	0	4	16	0	9	0	0	4	0	0	0	0
		d. Weak onshore grids	0	4	0	0	4	0	0	9	0	0	0	0
		a. Disturbing habitats and ecosystems										0	0	9
	Environmental	d. Climate Change	6	8	0	0	9	0	0	4	9	0	0	0
	Economic	Increase in prices of imported electricity	8	0	16	2	4	0	6	9	0	0	0	16

Appendix G

Appendix G. Normal distribution

A normal distribution gives the ability to allocate the probability for instance give the same probability to all responses and averaging risk scores (Urdan, 2005; Ott and Longnecker, 2008). In order to decide if a curve belongs to a normal distribution or not observing the shape of the curve to be bell-shaped can be used however to have a more accurate assessment the following equation taken from (Gaten, 2000; Ott and Longnecker, 2008) can be used to check a sample to see whether the data is normally distributed:

$$Z = \frac{1}{\sqrt[\sigma]{2\pi}}\, e^{\frac{-1}{2}}[\frac{Y-\mu}{\sigma}]\text{\^{}}2$$

Where z is the height of the curve at measurement Y, μ is the mean and sigma is the standard deviation of the curve. The mean is defined as:

$$\frac{\sum x}{n}$$

That is, the sum of all the measurements divided by the number of measurements made. The spread of the normal distribution (variance) is the sum of how much the measurements (x) differ from the mean:

$$\sum (x-\mu)^2$$

That is, the sum of the difference between each of the measurements and the mean. From this equation it can be seen that if many measurements are much greater or smaller than the mean then the variance will be large (Gaten, 2000). A mean is generally quoted with its standard deviation which is simply the square root of the variance.

By multiplying z by the total number of observations the number of observations would expect to see for a particular measurement can be calculated (Gaten, 2000).