Risk-Based Framework (RBF) for a UK pan-European Supergrid

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Abstract

Interconnected electricity networks, or Supergrids, are considered as a possible solution to tackle challenges associated with near and far-future supply of electricity. These include, but are not limited to, reducing Green House Gas emissions and reliance on non-renewable fossil fuels. Supergrids can help to tackle these challenges, for example, by providing a reliable interconnection platform for wider application (and development) of renewable technologies. However, there is a range of risks and uncertainties associated with selecting appropriate interconnections. Heretofore these have been a hindrance to developing interconnections and therefore a Risk-Based Framework (RBF) which addresses these risks and uncertainties could encourage the wider uptake of Supergrids.

This paper presents for the first time such a robust framework. The RBF comprises of four stages; (1) initial screening for selecting candidate countries, (2) risk identification, (3) risk semi-quantification and (4) risk quantification. In stage 4 the uncertainties associated with the identified risks are quantified using a cost-risk model under uncertainty based on a whole life appraisal approach. The usefulness of the approach, demonstrated using the UK as a case study, showed that greatest cost risks are associated with (a) regulatory framework, and (b) changes in energy policy. The most desirable interconnection option for the UK was identified as France.

Keywords

Interconnections; Risk assessment; Quantitative risk analysis; Trading electricity; Supergrid; Whole Life Appraisal.

Abbreviations

DP	Dynamic Positioning
E_e	Interconnection Capacities
HVDC	High-Voltage Direct Current
NPV	Net Present Value
RBF	Risk-Based Framework
RE	Renewable Electricity
STEEP	Social, Technical, Economic, Environmental and Political
PERT	Program Evaluation and Review Technique
PI	Profitability Index
PPPs	Public Private Partnerships
P80	80th percentile
WLA	Whole Life Appraisal

1. Introduction

Renewable energy is seen as a viable means of helping to tackle the global challenges of climate change whilst meeting a significant part of global energy demands (MacKay, 2009; Jacobson and Delucchi, 2011; WWF, 2011; DNV, 2014). However, in order to realise the full potential of these geographically dispersed and intermittent renewable energy supply resources it is necessary to provide a means of connection. An interconnected electricity network, utilising high capacity long transmission lines, is technologically feasible and can be economically competitive (Chatzivasileiadis *et al.*, 2013; DNV, 2014). Such a system, known as Supergrid, is currently being developed in Europe, and will be capable of transmitting power from renewable sources using a High Voltage Direct Current (HVDC) grid across the European continent and beyond.

Interconnections through this Supergrid are expected to provide a solution to many of the challenges associated with renewables. These include, for example, their intermittency, variability and cyclic nature (Chatzivasileiadis *et al.*, 2013; Elliott, 2013; Edmunds *et al.*, 2014; Pöyry, 2016). In addition a Supergrid can improve security of energy supply issues through provisioning of multiple supply pathways that connect countries across different time zones with different (yet complimentary) electricity generating profiles, consumption demands and patterns (Van Hertem and Ghandhari, 2010; Hirschhausen, 2012; Torriti, 2014; Pöyry, 2016).

However, there are a number of social and political barriers for the implementation of a Supergrid (Jacobson and Delucchi, 2011; Tobiasson and Jamasb, 2016). Not least, the decision-making process required for their implementation is often a protracted procedure. For example, lengthy negotiations between France and Spain were initiated in 1980 but the interconnection only started operating 35 years later (Tobiasson and Jamasb, 2016). Part of the reason is related to uncertainties associated with: changes in energy policy within countries concerned; availability of spare electricity; security of supply issues; comparatively lengthy construction periods and unsubstantiated predicted life-times for the physical interconnections (Great Britain Parliament, 2011a; Pöyry, 2016).

A crucial early-stage decision regarding the development of interconnections is identifying the most appropriate country(ies) and region(s) with which to make an interconnection(s). A proven means of facilitating similar decisions in other industries is through utilising an appropriate risk assessment process that enables early-stage risk identification, better understanding, and mitigation for potential impacts before they occur (Flyvbjerg *et al.*, 2003; Read and Rizkalla, 2015). Within this context a common language and shared understanding between all engaging countries can help resolve disputes and shape common priorities (Tobiasson and Jamasb, 2016). However, such a Risk-Based Framework (RBF) to facilitate decision-makers is yet to be developed to encourage the uptake of Supergrids.

To address this, the goals of this paper are to describe a robust RBF for selecting the most appropriate country(ies) with which to make grid interconnections and to describe its use via a case study. Even though the need for such an RBF has been identified, this paper presents for the first time the development, application and components of the RBF and is therefore a major contribution to the existing literature (Great Britain Parliament, 2011b; Great Britain Parliament, 2011a; Pöyry, 2016; Tobiasson and Jamasb, 2016).

The RBF includes the identification, assessment, and quantification of uncertainties and whole life cost risks associated with electricity interconnections. Lifetime uncertainties and risks are incorporated, for the first time, within the newly developed risk cost-risk model under uncertainty. Therein, a quantitative risk analysis technique is utilised to compare candidate countries by incorporating the likelihood of the occurrence of identified risks and uncertainties together with their impacts associated with the construction and maintenance of interconnections. Lack of sufficient data can be one of the main reasons for not adopting a robust RBF. This paper shows how expert opinion can be utilised to fulfil such a shortfall. The successful implementation of the RBF in this paper, described through a case study, it is anticipated will encourage the development of interconnections and thereby maximise the utilisation of global renewable energy resources.

The major findings of the research described here are:

The proposed RBF provides a rigorous means of quantifying risks and uncertainties associated with making energy interconnections. Data scarcity can be successfully addressed using a robust process which incorporates expert opinion.

The greatest cost risks for the UK are associated with (a) regulatory framework, and (b) changes in energy policy. The most desirable interconnection option for the UK is with France.

2. Literature review: Risk assessment and its implication for interconnections

Methodologies for addressing and dealing with risk and uncertainties have been utilised for over 40 years. For example, Salter (1973) described a probabilistic forecasting methodology in which stochastic data and subjective probability estimates were used to achieve a probabilistically stated forecast of the USA's electricity consumption in the year 2000. Since then, similar analyses have been used to allocate probabilities to uncertainties regarding future energy supply/demand and the impact of climate change on energy supply among other things (see for example Song et al. (2013), Maleki *et al.* (2016), Kearns et al. (2012) and Hamlet et al. (2010)).

The literature is less well developed with respect to the risks and uncertainties of interconnections. Whilst economists such as Parail (2010) have introduced probabilistic methodologies to address economic uncertainty associated with electricity trading by way of interconnections, this work was not extended to uncertainties associated with the social, technical, environmental and political aspect of developing and operating interconnections. A recent study by Pöyry (2016) explores the costs and benefits of potential interconnections for the UK and describes some of the associated risks but without any further analysis.

Understanding the construction and maintenance risks of an interconnection requires comprehending their causes, likelihoods and consequences of occurrence to adopt appropriate mitigation measures. In conventional risk assessment these are typically considered as part of a framework which consists of three main processes, namely (BSI, 2010; Jutte, 2012; Bozek *et al.*, 2015):

1. risk identification;
2. semi-quantification; and
3. quantification.

Risk identification is the process of finding, recognising and recording risks whilst semi-quantification and quantification stages are to do with determining the consequences and likelihood of occurrence for identified risk events (BSI, 2010; Pritchard, 2014). Quantitative analysis is used to apportion values to consequences and their probabilities and thereby provide a quantified level of risk (BSI, 2010; Pawar *et al.*, 2013; Pritchard, 2014).

In the case of interconnections, the identified risks are directly related to, or influenced by, project complexity, construction time (up to 10 years for some seabed interconnections), duration of asset use (40 years or more), and the involvement of various industries and stakeholders (Chatzivasileiadis *et al.*, 2013). Allied to these, an interconnection project is notoriously risky because (at least) two countries, each with their own local priorities, conditions and policies, are involved.

A major challenge of carrying out risk assessment within this field, which can significantly reduce the cost of projects, is obtaining reliable information (IRG, 2013). This includes identifying a range of risks and thereafter assessing their likelihood of occurrence and ultimately impact. This is not straightforward when interconnection construction projects are essentially one-off enterprises (Eskandari Torbaghan *et al.*, 2015). In such cases knowledge obtained from a diverse range of experts in the field, who are well versed in terms of experience, judgement and application including rules-of-thumb can be usefully utilised (Dikmen *et al.*, 2007; Yildiz *et al.*, 2014). Such an approach has been used in the research described in this paper.

3. Methodological Approach

The developed RBF consists of 4 principal stages, summarised in Figure 1, and described below.

3.1 Stage 1: Initial screening

The screening stage was used to identify suitable and unsuitable candidate countries for interconnection. The procedure took into account the distance between countries in addition to Political, Economic, Environmental and Social factors. The outcome of this stage is shown for the UK case study application in Section 4.1.

3.2 Stage 2: Risk identification

This stage identifies the risks (and associated circumstances) that might affect the availability and security of interconnections and of trading electricity (BSI, 2010). The risks were identified from a review of the literature which was subsequently used to inform (and extract) expert opinion through questionnaires and one-to-one interviews. The outcome of this stage is shown for the UK case study application in Section 4.2.

3.3 Stage 3: Risk Semi-quantification

Risk semi-quantification allows identified risks to be determined according to the common definition of risk; *impacts* multiplied by *probabilities of occurrence*, for each risk in each country (Chapman and Ward, 2004; BSI, 2010). Calculated exposures for all identified risks are then combined to determine an overall risk level for each country.

The process includes mapping identified risks associated with activities to build and maintain interconnections. To measure the level of risk herein expert opinion is used to estimate the range of potential consequences that might arise from an event, situation or circumstance, (e.g. a power cut) and their associated probability of occurrence. Integer rating scales for impact and probability informed by expert opinion are used to produce a semi-quantified *risk evaluation*. The outcome of this stage is shown for the case study in Section 4.2.

3.4 Stage 4: Risk Quantification

Risk Quantification develops a measure of the cost of risks and uncertainties associated with a project, the so called project cost risk, using a combination of whole life appraisal (3.4.1) and risk modelling (3.4.2), to identify the most appropriate country for making an interconnection (Levander *et al.*, 2009; Flanagan, 2015). Project cost risk being primarily caused by one (or both) of the following factors:

1. Uncertainties associated with future revenues and costs ;
2. Risks related to the construction and operational phases (which ultimately have impacts on both future revenue and cost steams)

The least risky country with which to make an interconnection is that with the minimum, so determined, cost risk.

3.4.1. Developing a cost model through Whole Life Appraisal (WLA)

WLA is an economic tool which can be used to make an informed choice between various competing options (in this case for comparing candidate countries for interconnection).

The requirements of the WLA for task at hand are (Flanagan and Jewell, 2008):

1. Identification of an overall useful life (i.e. whole life) for the interconnections
2. Collection of *costs* and *revenues* associated with constructing, utilising and maintaining an interconnection
3. Consideration only of those costs and revenues which have a direct impact on the project itself. Thereby excluding for example employment generated through the construction of interconnections.
4. Consideration of time on the value of investment, this includes;
    a. The impact of inflation
    b. The opportunity cost of capital (i.e. by utilising a discount rate).

The Net Present Value (NPV) methodology was chosen as the most appropriate tool to implement the WLA.

3.4.2 Developing a Cost-Risk Model

Risks and uncertainties were accommodated in the RBF as follows:

1. Uncertainty with future cost estimation(s) identified by the literature together with a panel of experts
2. Construction and operational risks identified from the literature and further informed by an expert panel.

The cost risk model so developed is given in Equation 1.

$$\widehat{NPV} = \widehat{C}_I + \sum_{i=1}^{T} \frac{\widehat{C_{Oi}} - \widehat{R_{Ai}}}{(1+\hat{r})^i} \qquad (1)$$

Where:

$\hat{C}_I$ = Investment cost risk *(£)* (see Equation 2)
$\hat{C}_O$ = Annual operational cost (£*)* (see Equation 3)
$\widehat{R_A}$ = Annual revenue (£*)* (Equation 4)
(^) signifies uncertainty (i.e. risks)

$$\hat{C}_I = \hat{C}_C + \hat{C}_{CT} - S + \sum_{j=1}^{N} \left(I_j \times P_j\right) \qquad (2)$$

Where:

$\hat{C}_C$ = Cable cost *(£)* [uncertainties associated with cable cost such as inflation rate and currency exchange rate],

$\hat{C}_{CT}$ = Converter station cost (£) [i.e. High Voltage DC (HVDC) cables and DC-AC convertor stations; an HVDC connection within an AC system requires two converter stations]

S = savings equal to the equivalent cost of generating electricity [i.e. the savings accruing from supplying electricity from other countries compared to the average cost of various electricity generation technologies for the recipient country]

I_j and P_j = impact and probability (respectively) of N identified construction risks, j

$$\hat{C}_O = \hat{C}_M + \hat{C}_L + \hat{C}_{RE} + \sum_{n=1}^{K}(I_n \times P_n) \quad (3)$$

Where

$\hat{C}_M$ = Annual maintenance cost,

$\hat{C}_L$ = Annual cost of losing power due to heating of the line

$\hat{C}_{RE}$ = Cost of imported RE.

I_n and P_n = Impact and probability of K identified operational risks

$$\widehat{R_A} = \widehat{R_{A1}} \times \widehat{r_{RG}} \quad (4)$$

Where

$\hat{R}_{A1}$ = Revenue in the first year (i.e. 2030)

$\hat{r}_{RG}$ = Annual revenue growth rate

Within Equation 1, 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 and were modelled using statistical distributions, to accommodate the range of expert estimated values.

$\hat{R}_{A1}$ in Equation 4 is determined by the likely supply capacity (i.e. surplus energy availability) of the interconnection (E_e) and was determined using a *RE availability model* [for more information see Eskandari Torbaghan et al. (2014)]. The RE model is related to:

i) the ability of the host country to sell spare renewable energy to the recipient country (after meeting its domestic demand);

ii) CO_2 related cost savings (e.g. through reduced carbon credit payments).

Construction and operational risks were quantified by three point-estimates, derived from three defined scenarios; worst, most-likely and best case scenarios.

Triangular and binomial distributions were used to model all cost uncertainties, risks and their likelihood (probability) respectively, except for the growth rate for which a normal distribution was used.

4. Application of RBF to the UK

The RBF developed in Section 3.0 is demonstrated here via a case study which identifies the most appropriate country (in terms of the minimum cost risk) for the UK with which to make an interconnection.

4.1 Stage 1: Initial screening

Nine feasible candidate countries (Belgium, Denmark, France, Germany, Ireland, Netherlands, Norway, Spain and Sweden) were identified by an initial screening exercise for making interconnections with the UK (Eskandari Torbaghan *et al.*, 2015).

4.2 Stage 2 and 3: Risk identification and Semi-quantification

An initial extensive literature review, augmented by canvassing the opinion of a group of experts, through a series of structured interviews, identified 18 construction and 8 maintenance risks (Table 1) which could impact costs. In brief the process involved 20 experts, representing eight different European countries, with specialist skills and knowledge in electricity generation and distribution participated in the research.

The risks were subsequently semi-quantified, as described above and using a risk matrix (Figure 2) where the probability and cost impact values were determined by consulting with the panel of experts.

4.3 Stage 4: Risk Quantification

Within the risk quantification stage the probabilities and impacts of the identified construction and operational risks on the costs and benefits of an interconnection with the UK were evaluated using the cost risk model incorporating the NPV method as described above. The NPV for each interconnection was calculated according to Equation 1 for an assumed 40 year period of operation. Construction and operational costs adopted for the study are shown in Tables 2 and 3. For the purposes of the risk quantification the triangular probability distributions were determined by using within the Monte Carlo Simulation (MCS) the minimum, maximum and most likely values obtained from the literature. N.B. The value of S, Equation 2, is assumed to be £1400/kW, based on studies by Mott MacDonald (2011), Kannan (2009) and Parsons Brinckerhoff (2011).

For the purposes of the case study values of 80th percentile (P80) E_e were used (Table 4) for the countries considered (i.e. the result of simulations for E_e shows that 80% of them produced values equal to or smaller than the value shown in the Table 4). Using these values of E_e the revenues were calculated by considering i) the revenue from selling the UK's spare RE to the candidate country and ii) value of CO_2 emission cost savings (i.e. saving the cost of CO_2 emission taxation from generating electricity rather than importing it).

As an example, the revenue component for Norway is presented in Table 5 which shows the minimum, most likely and maximum availability of RE.

The uncertainty associated with estimating revenue growth (i.e. Equation 4) is based on an analysis by Nooij (2012) of the Norway-Netherland (NorNed) interconnection and assumes an annual 2 % growth rate with a standard deviation of 1 %.

The discount rate used was an after-tax rate of interest that is expected to be earned on investments over the stated period. In this analysis a value of 9% was assumed for all countries based on work by Nooij (2011) for the NorNed interconnection. For the purpose of this case study the discount rate was not considered to be uncertain.

The distribution of Norway revenue growth rate is shown as an example in Figure 3, from which it may be seen that there is a 5 % likelihood of achieving a growth rate of less than 0.355% and a 5 % likelihood of achieving one over 3.645 %. This highlights the chance of an overestimation or underestimation of growth estimation for an interconnection project. Therefore any decision regarding building a new interconnection should be informed by this uncertainty and whether it is tolerable.

In order to ensure a sufficiently accurate output 10,000 MCS iterations were undertaken to generate a frequency distribution of possible NPVs for each interconnection. Following risk analysis guidelines for the case study, the 80 percentile NPV (P80 NPV) was the chosen statistic with which to compare the possible interconnections (IRG, 2013; Oracle, 2009).

5. Results

5.1 Single point estimations - NPV (risks excluded)

Table 6 shows the NPVs, calculated using the most likely values, when excluding identified risks for each country concerned. The chance(s) of achieving an NPV equal to or greater (i.e. closer to zero) than the NPV's shown was calculated by running MCS. It can be seen that of the 9 candidate countries, only 5 have negative NPVs (i.e. the benefits are greater than the costs). An NPV score for the Netherlands could not be calculated as the projected 'spare' RE was not sufficient to consider an interconnection for this country (see Eskandari Torbaghan *et al.*, 2014). In contrast France was found to have the highest NPV (with a 70% probability of achieving it), whilst Spain had the lowest (with only a 53% probability of achieving it).

When considering NPV (with risks excluded) the results suggest that France is the preferential country 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 6). 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 6) and expanse of ocean between Spain and the UK is a major factor in a connection between the two resulting in highest investment costs (£2.6b) and a relatively low NPV.

The probabilities of achieving (as a minimum requirement) these initial NPV estimates are relatively low, for all countries. This demonstrates the uncertainties inherent in using a single-point cost estimation to appraise an interconnection project. This is one of the main reasons behind existing protracted decision-making processes.

5.2 NPV (risks included)

The P80 NPVs values when including identified risks and uncertainties associated with cost and revenue estimations for the 9 candidate countries are presented in Table 7. When comparing Tables 7 and 6 it can be seen that the hierarchy has remained relatively unchanged with the exception that Ireland is now placed above Denmark. P80 NPVs have however worsened (i.e. NPV values are higher), not least for interconnection(s) between the UK and France and UK and Germany (increasing by 30% and 25% respectively).

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 lower risks of a UK – Ireland interconnection are also to do with the comparatively short distance between Ireland and the UK, and broadly similar energy and distributing systems (physically and politically). Accordingly, an interconnection between Ireland and the UK was found to have low risk scores associated with identified electricity price and energy policy related risks.

Figure 4 shows the 80 percentile NPVs of the candidate countries. The bars on the figure represent the range of possible NPVs between the 5 and 95 percentile values. For instance the range of NPVs for France is -£31 to £3 billion (Figure 5). Spain and Germany have the greatest range of NPVs of approximately £50 billion between their 5 percentile NPVs and their 95 percentile NPVs reveals the high level of uncertainties associated with those two countries. The large range of possible NPVs for Spain and Germany respectively demonstrates the high level of uncertainty associated with the two countries and is in part to do with the large distance between the countries and the UK. Supplementary material in form of an Excel file is provided in Appendix A.

5.3 Profitability Index (PI)

For the case study, the Profitability index (PI) was calculated to take into account the possible capital limitation for developing a new interconnection (since more costly projects are likely to have larger NPVs).

The profitability index was defined as:

$$\mathrm{PI} = \frac{NPV_{[\mathrm{P80}]}}{\mathrm{C}} \qquad (5)$$

Where *(units in italics)*:

$NPV_{[P80]}$ = 80 percentile NPV *(£)*

C_I = Investment cost *(£)*

The calculated PIs are presented in Table 8.

Comparing Tables 6 and 8 it can be seen that the hierarchy has remained relatively unchanged with the exception that Germany is fifth (moving from second place in Table 6). This is due to the added consideration of the high investment cost (£1.717 billion) associated with the interconnection between the UK and Germany caused by the comparatively large distance between the two countries (Table 6).

The PI index for the France is the highest amongst the 9 candidate countries considered and shows that the interconnection could generate £12 for every pound invested.

5.4 Sensitivity analysis

In order to test the robustness of this approach, a sensitivity analyses was conducted to identify parameters that most influenced calculated NPVs, and therefore those which will require additional scrutiny.

The sensitivity analyses revealed the 1st Year Revenue and the Cost of Imported RE to be the most dominant contributors to the calculated NPVs for all candidate countries. This is due to the fact that yearly revenues are highly dependent on first year revenue and are a function of the growth rate. The cost of imported RE is one of the main components of the cost model with direct impact on the calculated NPVs. The other relative influences of the other 8 parameters on NPV vary according to the country considered, but they are related to the cost of maintenance and growth rate. An example for France in the form of a Tornado graph is shown in Figure 6.

Management efforts such as the development and adaptation of revenue and cost models which include various risks and uncertainties could be utilised to ensure that the 1st Year Revenue and the Cost of Imported RE will not jeopardise the viability of an interconnection.

6. Concluding Discussion

The literature review presented within this paper set the context for the need for a Risk-Based Framework to identify the least risky region or country with which to make an electricity interconnection. As such this paper set forward a robust methodological process by which this could be developed. The underpinning methodology consisted of:

(1) an initial screening process to identify countries to be excluded from further analysis,

(2) a risk identification process, utilising expert opinion, to identify uncertainties associated with both building interconnections and importing electricity,

(3) a risk semi-quantification stage which consisted of determining consequences and probabilities of occurrence to define a level of risk, and

(4) a risk quantification stage to forecast the risk contingencies for capital expenditure and operational excellence.

Once developed and in order to demonstrate the methodology fully, the RBF was applied to the UK as an example case study. After initial screening in Stage 1 the case study considered 9 potential candidate countries and after final processing in Stage 4 it was shown that the country with the highest $NPV_{[P80]}$ was France. Therefore France was identified as the best countries for the UK to make interconnections with, when considering NPV, PI and the associated probabilities. Additionally France was shown to be the preferred option as an interconnection between the UK and France has a relatively low capital cost forecast, a lower risk in general and there is 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. An interconnection with Germany has also been recognised in this paper as potentially attractive, although with high capital costs. Indeed Germany has already been recognised as a potential option by the UK government, albeit without any apparent numerical evidence. Whilst the *cost-risks* associated with the large distance between German and the UK are relatively high, these are offset by Germany's very large projected supply of RE. Spain is ranked as the least preferred country mainly because of the large distance between it and the UK which result in 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 estimation of the accrued benefits of selling electricity has a high level of uncertainty as the analysis considers RE availability and price over a 40 year time horizon. This aspect was addressed by generating and including various plausible energy scenarios to estimate RE availability reported. Future development of a modified and updated energy scenario projection model for the involved countries is desirable.

As far as the risk quantification process is concerned, a whole life appraisal (WLA) approach has been shown to work effectively when utilised within an MCS. The developed RBF has demonstrated the inherent need for such an approach and highlighted the benefits that can be reaped in terms of informed decision-making. The developed methodology can be used to encourage building new interconnections and can be used by any country, public or private organisation. This becomes readily apparent when it is being used to identify the highest and lowest NPVs, as an indicator for whole life economic benefit associated with construction and operation.

The RBF should be considered as a precursor within any risk analysis project and should be applied occur in the initial stages of any interconnection works.

One significant barrier to be overcome when adopting the proposed RBF 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 this paper, is to make use of expert opinion. The results of the analysis obtained however will ultimately depend upon the range and quality of the experts considered. Moreover it is important, where possible, when using experts' opinion to mitigate any possible bias. To this end, in this study a pool of 20 experts was drawn from across Europe, from both industry and academia, their opinions were recorded via targeted questionnaires and in-depth one-to-one interviews. This produced a well-balanced response making use of knowledge from experts who are well versed in terms of experience in electricity generation and distribution. However it is recognised also that the process of consultation could be improved further to help avoid any unintentional bias by involvement of a wider range of experts and other interview techniques, such as brain storming sessions, risk review meetings during workshops and/or Delphi technique(s).

Where possible the preliminary results should be verified against historical data in order to consider the relative weights (i.e. importance to stakeholder groups) of the identified risks (rather than identical weightages as considered here), allowing for more weighting to be placed against key identified risks.

In general, a fundamental impediment that acts as a significant barrier for the development of interconnections is changing government energy policy. Interviews with experts revealed that this is a major reason for the current protracted procedures for governmental approvals and can be avoided (in part) through improved engagement with the private sectors. This can be achieved through mechanisms such as public private partnerships (PPPs) in order to facilitate both the procedure and by providing knowhow to help reduce some of the risks that occur when considering the public (or private sector) alone. The procedure developed herein can also help with this process by identifying the causes of significant risks (e.g. the pressure of public opinion) leading to appropriate mitigation measures (e.g. raising public awareness).

The current trend for developing renewables can also help address the second major uncertainty found in this research, which related to the availability of tradable renewable electricity. This is also related to and affected by energy policy. Engagement of the private sector could also help here and may enhance the development of interconnections to provide a larger market for renewables.

The proposed RBF should also be utilised to model interdependencies and consequential impact of risks associated with construction and operational phases. Further, special attention should be given to develop the model to take into account highly disruptive risks (i.e. those with low likelihood and high impact), such as catastrophic failure, terrorist attacks and political instability of energy producing countries.

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