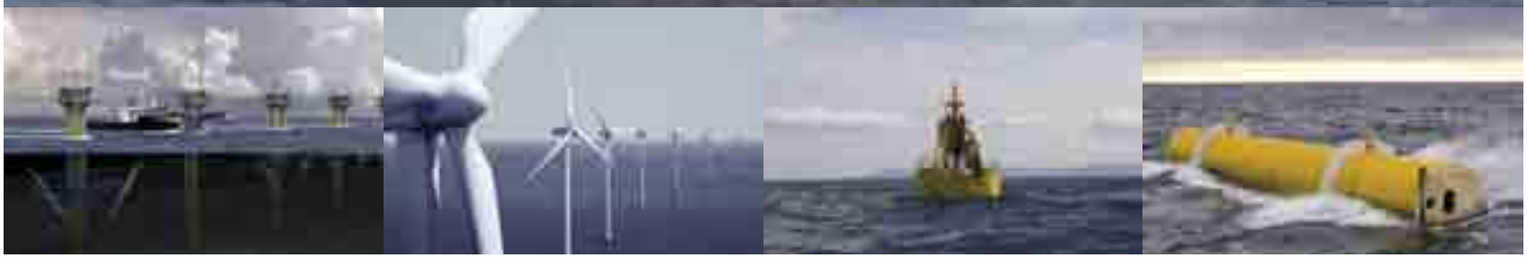
# Offshore Grid Study

## Analysis of the Appropriate Architecture of an Irish Offshore Network

### Executive Report




*Advancing the Technological Development to Harness Offshore Power*



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# Executive Foreword:

**EirGrid is pleased to present the findings of this Offshore Grid Study.**

The study was prompted by the first transmission connection offers to be made to offshore generation in the Republic of Ireland and the need for a holistic view of the future development direction of a potential offshore grid.

The study does not purport to define a precise network solution. Rather, it provides sound information on the most efficient development methodologies and standard configurations for developing incrementally an Irish Sea offshore network.

To ensure the robustness of the results, the sensitivity of changes to key assumptions have been examined and the impact to the methodologies and configurations investigated.

The findings of the study will be used to guide future EirGrid policy decisions regarding offshore networks development.

In addition to EirGrid's own needs it is expected that this information will provide a valuable source of information to stakeholders. It will also inform debate on a number of issues relating to offshore network development in not only Irish waters but also in a wider European and International sense.

The techniques used, discussed in length in this report, to provide the findings of this report are in EirGrid's opinion uniquely applied to this task. These techniques may provide interesting opportunities internationally for other similar applications requiring the reduction of large numbers of strategic development options within a reasonable time period to an optimum strategy.

The report is structured to provide information as concisely as possible to meet the needs of the individual reader with the non-technical executive report, providing the key conclusions to the findings, and a more technically focussed detailed report. The detailed report discusses the methodology, assumptions and techniques used in the study, the full spectrum of the findings, and conclusions drawn.

Finally, it is the aim of EirGrid to provide informative, pertinent and accessible information. We would therefore welcome and value your feedback on the presentation, style and content of this report and any of our other reports at all times.



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# Executive Report:

Driven in part by European objectives, the development of renewable energy has gone from strength to strength, culminating in Irelands Government Target of 40% energy used to be from Renewable sources by 2020, in the framework for "20-20-20" EU initiative.

At the end of 2010, in the region of 1500 MW of renewable generation had been installed in the Republic of Ireland, approximately 25 MW of which comes in the form of off-shore plant. The committed development of the group processed renewable generation applications in Gate 11 and Gate 22, in association with those currently being processed in 'Gate 3' have the capacity to supplement the existing developed renewable generation to meet or exceed the Irish 40% renewable energy target by 2020. 'Gate 3' is committed to providing three connection offers totalling approximately 800MW of additional offshore renewable wind generation.

Given that Ireland has some of the most favourable offshore wind, tidal and wave conditions in Europe, offshore development in Irish waters is expected to grow rapidly over the coming years. This is demonstrated by the scale of applications already present, in development, or awaiting an offer for connection to the network totalling a further c.11000MW of wind (c.4000MW in Irish territorial waters and a further c.7000MW in British waters) in the Irish Sea alone.

Although offshore generation applications represent a lower proportion of the overall applications, the abundant resources of both wind and wave in the Atlantic Ocean off Irelands west coast, offer an almost unlimited potential energy source for additional future offshore generation.

The need to develop a philosophy, and policies for the development of an offshore network to meet the immediate need of formulating offers for the generation in Gate 33 in association with the need for information to a develop strategic position on offshore networks culminated in EirGrid initiating this Offshore Grid Study.

## 1.1 SCOPE OF STUDY

The need to understand not only the immediate requirements for connection of the Gate 3 generation applications, but also how these connections would ideally be constructed to fit into longer term network development was a main driver in determining a scope for the study. This information could then form the basis for the connection of this generation.

Gate 1 – 2004 Direction under which the Commission for Energy Regulation (CER) directed EirGrid and ESB Networks to provide offers for connection to 373MW of renewable capacity

Gate 2– 2006 Direction (CER/06/112) under which the CER directed EirGrid and ESB Networks to provide offers for connection to c.1300MW of renewable capacity

Gate 3 – 2008 Direction (CER/08/260) under which the CER directed EirGrid and ESB Networks to provide offers for connection to c.3,900MW of renewable capacity



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A further driver for the study was the need to establish a whole new suite of standard equipment to supplement the existing onshore standard equipment. Standard equipment is used worldwide to develop networks to provide economies of scale in manufacture, limit the number of spare parts required, and simplify construction.

Onshore Irish equipment standards and experience have developed over 80 years; there have effectively been none over this period for offshore equipment.

Best practice for determining both the resilience of an initial optimum network design (or 'Expansion Strategy Plan (ESP)') into the future and in defining standard equipment to be used in network development is to determine the requirements from an predicted initial scenario and then test this network development with a wide range of alternative scenarios to see if the development is still acceptable.

The outcome of this analysis demonstrates the robustness of the development to possible alternative and longer term development requirements placed upon it.

A transmission network Expansion Strategy Plan (ESP) for a scenario must consider not only the cost of the capital assets i.e. lines, cables and stations, but also the cost of producing the electrical energy and associated electrical power losses to supply load demand year round. EirGrid in partnership with RSE (the Italian nationally funded research centre for electricity) has developed software and a new methodology to calculate the most efficient ESP considering these three costs.

Engineering judgement based on factual information and experience is critical in defining the wide range of network scenarios to be studied. However, the impact of necessary assumptions chosen can be further mitigated by carrying out 'sensitivity' analysis. This analysis varies each key assumptions whilst fixing all of the other assumptions that have been made and studies the impact to the results and hence the sensitivity of each choice to the final results.

EirGrid selected the Irish Sea as the focal point of the studies. This decision took account of both existing offshore generation applications identified with a high probability for immediate development, and also its geographical location lending to a high probability for the future development of additional interconnection from Ireland.

The study area selected was further desirable as the largest two of the three offshore generation applications in Gate 3 are also located in the Irish Sea and the study supplies additional specific information for both these proposed connections.

The total generation that had been applied for at the time that this study commenced was selected as a base case level for the purpose of this study (c.3GW) to be examined. To put this into context this figure is greater than the Gate 1 and Gate 2 grouped renewable generation applications processed between 2001 and 2007, or roughly 60% of the peak load demand in Republic of Ireland in 2010.



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Discussion with these applicants also confirmed that they had future development plans to expand their sites and this increased generation (c.5GW) was selected as the first alternative ESP development scenario. During the course of the study further offshore generation applications has increased the total from c.3GW to over 4GW.

To examine the effects of geographical dispersion of generation the c.5GW scenario was split into two alternatives one with c.5GW in the existing five locations and one with this c.5GW spread over ten sites. The additional five sites were selected by creating a series of additional stations further offshore into the Irish Sea in a North South line from the initial five applications.

In order to reflect reality, both the 3GW and 5GW generation scenario were assumed to have a phased development and a completion date for all generation by 2030 was assumed. Consequently not only the final stage of an ESP could be compared, but also steps along the way.

These phased increases in generation within the scenarios are in addition to the existing generation fleet in Ireland, generation which EirGrid is contractually bound to connect, and the generation within 'Gate 3' which is in the process of being provided connection offers. 'Gate 3' has been assumed to be connected in its entirety based on uptake of offers in the previous two gates.

The examination of the generation scenarios was further divided into two distinct concepts for the studies, an Irish only development and an interconnected development. The Irish only study examined developing network from only the Irish transmission network, whilst the interconnected development looked at the potential added benefits, deficits or changes as a result of interconnection to other networks.

**'Sensitivity analysis'** was selected to look at the key assumptions:

- Scale of development in the Irish sea
- Development of offshore generation off Ireland being centred in the Irish Sea
- Market cost of reducing offshore generation and its impact on the network development
- The use of different technologies on network development

To examine the scale of generation in the Irish Sea a third generation increase to c.7GW was selected as another alternative scenario. This increase was proportionate at c.2GW to the previous scenarios, and provided sufficient increase to drive an export scenario to adequately accommodate the scale of generation, and the consequential impact that this might cause to the offshore network structure.

**'Sensitivity analysis'** scenarios were also developed to examine the assumption that generation would be centred in the Irish Sea. These looked at the impact of the additional generation in the ISLES project (c.2GW's off the West of Scotland), and wave energy off the west coast of Ireland (c.4GW).

[4] Presently for the first 15 yrs



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The software used in the study provides the optimum network ESP, which minimises the combined cost of network development capital costs, the costs of ongoing electrical losses from the network and the cost of production. Therefore, the assumed 'penalty' to the cost of changing the generation selection in the electricity market from its most cost effective to another more costly selection is important. Counter intuitively, a higher cost generation selection may prove ultimately to be a lower cost solution if the cost of development or losses at the same time can be reduced.

Therefore sensitivity analysis was conducted on the market penalty costs and the resulting changes to the Expansion Strategy Plan's (ESP's) between the normal market price for electricity (system marginal price), the current guaranteed[4] price available to be paid for renewable generation (REFIT5), and a penalty level which would ensure that renewable energy was never reduced.

These three variables provide the widest possible diversity of the resulting ESPs.

The technology choices for an offshore network are in many ways similar to those for an onshore network. However, as a network purely for the connection of generation and/or the bulk transfer of power to onshore demand, the technological selections for an offshore grid may be markedly different to those of an onshore.

Also unlike onshore networks, offshore networks are almost exclusively cable networks. Technical and cost considerations of a cable network affect the technology choices.

Due to the practicalities in the software of processing millions of possible ESPs to find the optimum solution, the base case analysis was provided different sizes of connection limited to only one possible technological cable solution.

'**Sensitivity analysis**' was performed with a range of technological solutions to determine what affect this had on the ESPs.



## 1.2 FINDINGS

The outcome of the analysis answered a number of key questions about the design of the optimum robust offshore network. This network should be:

- 'Meshed' or interlinked and not a series of single connections from generators to the onshore network
- Developed incrementally
- Symbiotic with the onshore network
- In line with the existing GRID25 strategy
- Developed with interconnectors from offshore generators to other networks as well as from onshore points
- Developed making use of 'smart' devices to enhance network flexibility and minimise the scale of the offshore network
- Developed at a high voltage level typically at least 200kV
- Both an AC and DC offshore cable network interlinked
- Designed with the potential for even further future expansion

### 1.2.1 'Meshed' Or 'Radial' Network Design

A fundamental aspect of this study was to examine whether the offshore network should be built 'Meshed' or 'Radial'.

A 'Meshed' offshore network would be designed with interlinked stations to transfer power between various points offshore, whilst a 'Radial' network would be a series of links from collection points for offshore generation directly to onshore networks which would then transfer the power.

Historically in Ireland the transmission network developed from effectively a 'Radial' network in the early 1930s to the present day highly complex 'Meshed' network. The main rationale for this development strategy has been to minimise the cost of network development while simultaneously maintaining an appropriate level of reliability.

However the cost of offshore networks are markedly higher than those of onshore networks and hence the question arose as to whether it is more efficient to build a 'Meshed' network, which by its nature would require offshore assets as oppose to delivering the power to shore with the minimum amount of offshore assets with a 'Radial' network.

Both 'Meshed' and 'Radial' philosophies need to be able to provide adequate capacity to transmit the power generated across the onshore network to where it is required to be utilised. The difference is that a 'Meshed' network does some of this transmission offshore whilst the 'Radial' does this entirely onshore. Hence there are typically greater assets offshore for a 'Meshed' network.

[5] REFIT – Renewable Energy Feed in Tariff, as set by the Department of Communications Energy and Natural Resources (DCENR)



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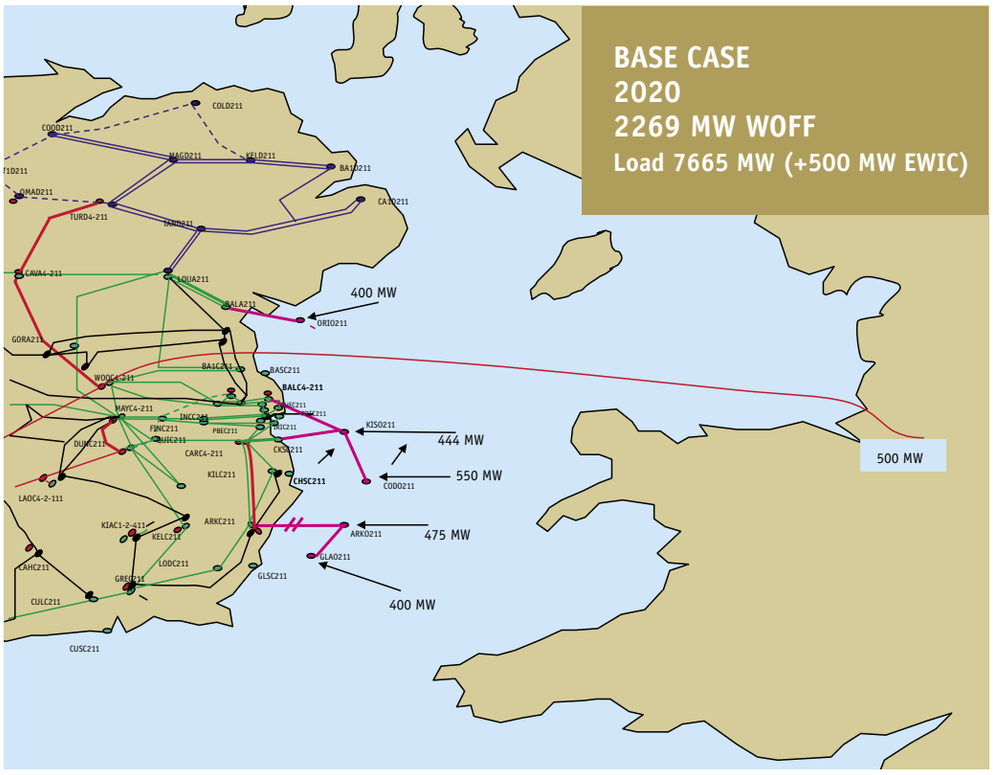
All of the ESP scenarios conclusively elected to develop a 'Meshed' network. Initial development to connect the first generating facilities as examined in the 3GW Irish only ESP, is developed in some instances as radial connections (see ORIO211 in the Figure below). However even in this earliest year of the c.3GW ESP, four of the five generators are connected together and then connected to shore, with an offshore 'Meshed' connection from North to South of Dublin.




In later years and in other alternative scenarios the network becomes progressively more meshed.

The consistence of the ESPs to elect 'Meshed' networks to minimise the overall cost of offshore generation is conclusive.



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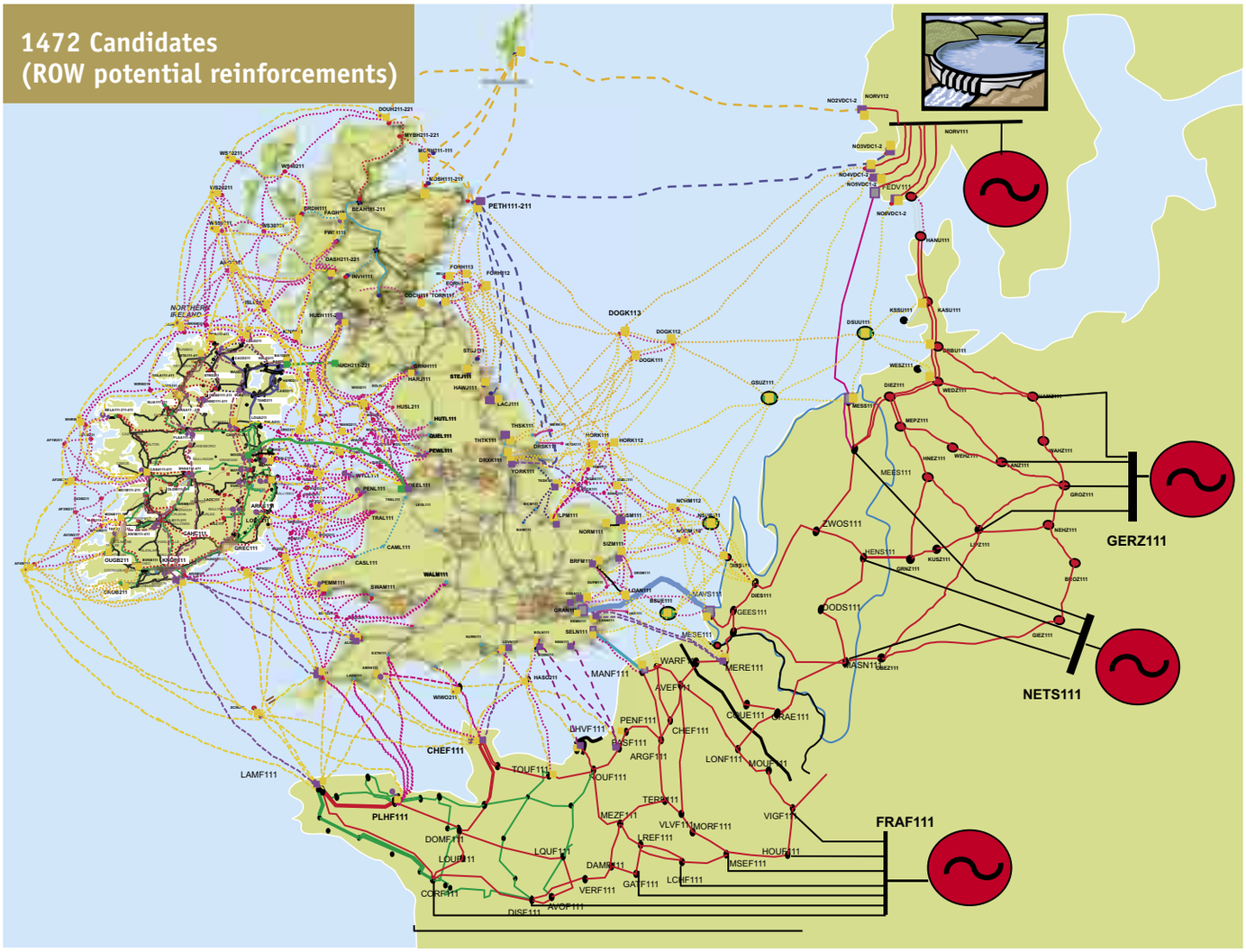
## 1.2.2 Incremental Development

Possibly the highest risk to efficient development of any transmission network is the risk that a current development project will not be ideally suited to act as part of the network in future. The result would be either costly modifications or at worst the asset becoming stranded and unusable.

Given the currently higher costs of building equivalent offshore assets to onshore assets and the difficulty in practically changing or modifying assets, this risk offshore is compounded.

A major finding from this analysis is that the ESPs show a consistency in their structure for a wide variation of scenarios. Increases in generation either at individual offshore generators or with the introduction of other generation points, results in the majority of the network in the



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ESPs being strengthened with additional parallel circuits and not in radical change to the layout or topography of the network.

Similarly examinations of different generation scenarios show that the phases of network development of an ESP out to 2030 are structurally consistent, often with the only apparent changes being when the elements of the network are required. In this way a higher level of generation may require the same network at an earlier point than a lower level of generation scenario.

It should be noted that the software methodology starts with a 'clean sheet' both offshore and onshore for each scenario. As the software is provided with a very diverse list of candidate reinforcements (see the figure below showing with dotted lines an example of the candidate reinforcements) it could choose a radically different set of reinforcements to fulfil the requirements.

As a result the analysis shows that although it is entirely possible for an asset to become stranded the risk of occurrence is likely to be low. This greatest risk is that of insufficient capacity into the future.

A number of options to mitigate capacity risk including, conversion of AC to DC circuits, and the use of smart devices are discussed below.

### 1.2.3 Symbiosis With The Onshore Network

Almost every development to a transmission network has an interaction with the existing network. The level of this interaction and the resulting impact defines whether the development is symbiotic in nature.

The results of the study show that reinforcement onshore is required for the introduction of generation offshore. This is not purely as a result of the need to strengthen the path from the offshore generation into the network to load demand centres, but also to provide routes through the onshore networks to other parts of the offshore network for bulk power transfer (for example to export to another country). Similarly, pre-identified restrictions in the onshore network are alleviated by having alternative routes provided by new meshed offshore infrastructure

Consequently both onshore and offshore networks are symbiotic in nature, i.e. they assist one another and thereby minimise the overall development requirements.

This finding is best demonstrated in the ESP for the 3GW Irish only scenario, which has a connection from Dublin North via Kish Banks offshore generation to Dublin South (see Figure below). The power transfer through Dublin has been identified6 as a problem and this link provides an alternative path for power transfer, solving both power delivery from the offshore generation and alleviation of an existing network problem.



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Other scenarios have variations on this link, some more convoluted (see Figure below) than others but principally each ESP provides resolution to this problem using the inherent development requirements to cater for the additional generation considered in that scenario.







## 1.2.4 GRID25 Strategy

The Grid Development Strategy GRID25 provides a common understanding of how the development of the Grid should be undertaken to support a long-term sustainable and reliable electricity supply.

Although levels of offshore generation where considered in line with the Government's energy white paper, these levels are significantly smaller than those considered in the scenarios in this report.

The reinforcements identified in the GRID25 process were not restricted to only the needs for offshore generation, but the needs of the system in its entirety to deal with a wide spectrum of load demand and generation scenarios out to 2025.

The GRID25 reinforcements were provided as candidate reinforcements with many other additional reinforcement options, allowing investigation into whether the GRID25 reinforcements which were likely to be required over the period to 2025 where aligned with the needs of the offshore scenarios.

For each of the scenarios some reinforcements are consistently required, and other reinforcements required for some of the scenarios. These are almost exclusively GRID25 identified reinforcements and hence provide confirmation not only to the methodology of the offshore study, but also reaffirmation of the GRID25 reinforcements for even more diverse scenarios.

[6] See Figure A4 of EirGrid Transmission Development Plan



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### 1.2.5 Interconnector Arrangements

Interconnection has historically been developed from onshore points in the network due to the low number of interconnectors, the cost of offshore equipment, and limited existing offshore stations providing no opportunities to do otherwise.

However with the increasing development of offshore generation and hence offshore stations the opportunity exists to make use of these connection points to limit the overall length of an interconnection between networks.

In the Irish Sea this provides a major opportunity due to the distance to the British network and the location of suitable generating sites both of Ireland and Britain. Outside of the Irish Sea development the Celtic sea also offers opportunity to develop from offshore points to either Britain or France.

Not unsurprisingly the ESPs for the scenarios make use of these offshore station opportunities at many points to develop interconnection capacity. This is not exclusive however and the strength of some offshore points may make it preferential to develop a direct onshore to onshore interconnector for capacity reasons.

Aside from the needs for capacity, technology will also influence the location that interconnection is terminated into. Although it is not an assumption of this study that all circuits that are interconnectors should be DC, in reality for technical and market reasons this is likely to be the case for the foreseeable future. The properties of DC technology may also dictate its use.

There are two different types of DC technology LCC and VSC. While based on information currently available LCC has a lower lifecycle cost (is cheaper) it requires a network with its own self powering generating source, which most offshore generation is not designed to be able to provide; further, large power filtering devices would create space constraints for offshore applications. Hence LCC is restricted to onshore to onshore network links in this study.

Therefore the currently more expensive VSC has been considered as possible offshore to offshore/ onshore candidate reinforcements. For connections to offshore stations it has been assumed that VSC DC technology is used, rather than the cheaper LCC DC technology.

However, both LCC and VSC are developing technologies and as such are subject to fluctuations including their respective capital costs, ultimately influencing their choice in future development.

The final scenarios considering both AC and DC technological options have shown development of both British and French interconnection with both onshore LCC technology and offshore VSC technology.



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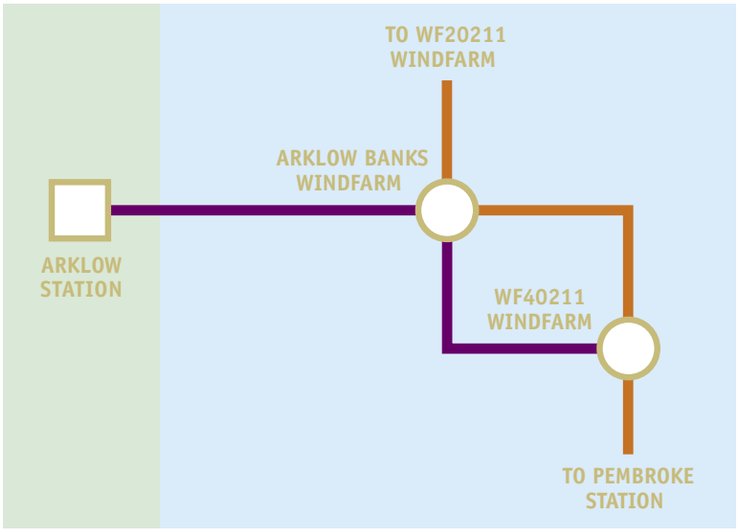
## 1.2.6 'Smart' Device Use

The definition of 'Smart' devices in the context of this study refers to devices which can be remotely controlled to control power flows in the network. Examples of these would be devices which can convert AC power to DC power (and vice versa) and Phase Shifting Transformers.

The use of DC devices in ESPs for the scenarios has been selected by the software either specifically for their abilities to control power or as a consequence of the need for that technology in that circuit i.e. for interconnection between networks.

Where power flow devices have been selected as oppose to another capitally cheaper alternative it is because of the ability to control the power on that circuit will minimise the overall cost of the ESPs. These cost savings are made by reducing network build, reducing generation production costs or both.

An example of the use of an AC to DC convertor smart device is shown in the figure below, with the links between ARK0211 and WF40211 offshore stations east of Arklow in the Irish Sea being linked by an AC circuit (shown in Red) and a DC circuit (shown in Yellow). The lowest capital cost solution in this case would have been two AC lines but instead the ESP has utilised a smart device, i.e. the AC/DC/AC conversion devices for the DC circuit, to provide control to the power.




The higher capital cost of the DC circuit will be offset in the ESP by either, the cost of re-balancing generation in certain situations to avoid the risk of overloading equipment, or the cost of additional network infrastructure to resolve this equipment overload risk or both.



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Early appraisal of the methodology and software (not contained in this report) examined an AC power controlled network. The results of which show that similar results can be achieved with AC power flow control as DC technology.

Given that the combined cost of AC cables and Phase Shifting Transformers (PSTs), which would allow AC power flow control, is lower than its equivalent DC devices, (it is likely that) some DC circuits shown in the analysis of this report should be examined to see if they are technically acceptable and be replaced by an AC equivalent where possible. Confirmation of technical acceptance requires a more detailed analysis than the present level undertaken in this report.

An important assumption made in this analysis is that a suitable control philosophy can be found and implemented to operate all of the onshore and offshore networks in perfect unison. In reality this would require a highly complex and intelligent automated system which may take some time to be fully resolved. Therefore simpler or numerous smaller control schemes are more likely with the impact of an increase the number of circuits in the network (closer to an AC only equivalent solution).

### 1.2.7 Developed At A High Voltage Level At Least 220 kV

The predicted7 typical size of offshore individual wind generators is c.5MW , wave up to 5MW and tidal 1MW, and based on historical experience each in future maybe even larger. Current experience from the existing wind generator applications used in this study is that they are mainly based on a final potential of 1GW, with a typical application for c.300MW for initial commercial scale.

In addition resources for both wind, wave and/or tidal exist in the same area.

Consequently the initial assumptions for the size of a cluster of generation at a point offshore should be expected in the future to also be at least 1GW typically in size.

The analysis has shown that to deliver the quantity of generation and corresponding interconnection capacity requirements in the Irish Sea alone that typical size links between offshore stations of the order of c.1GW will be required, not dissimilar to the size of an offshore generation point. However in many places this can be as high as 3GW links.

To put the size of these circuits into context 1GW is approximately the capacity of two of the standard 220kV lines used in Ireland. The diagram below shows how the various cable technologies and voltage could provide an equivalent rating.

Practically and economically speaking high quantities of parallel circuits to provide high capacity circuits is not desirable. Consequently higher transfers would preferably be built with higher voltage cables.



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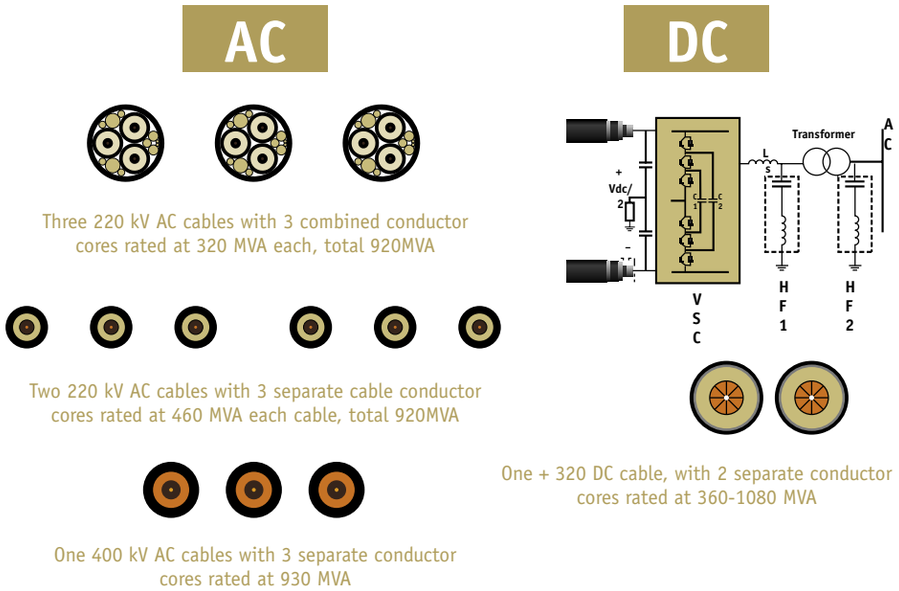
However both the cost of development and increasing technical problems associated with 400kV (EHV) cables may prove ultimately to restrict their use. Currently the associated equipment needed to develop offshore EHV cables does not exist, although it is in development, and it may be many years before its use is considered mainstream.

Another consideration is the termination of any offshore circuit onshore in many cases deeply inland which require either multiple overhead lines or cables to be built from shore to the termination point. The practicality (even viability) in comparison to offshore of doing so, and also the associated costs can be magnified when considering the choices of voltage.

Therefore driven by the requirement for multiple circuits and additional transformation between voltages, a circuit at 220kV or higher voltage is deemed appropriate from the analysis, providing the most economic network development voltage.




Three 220 kV AC cables with 3 combined conductor cores rated at 320 MVA each, total 920MVA

Two 220 kV AC cables with 3 separate cable conductor cores rated at 460 MVA each cable, total 920MVA

One 400 kV AC cables with 3 separate conductor cores rated at 930 MVA

One + 320 DC cable, with 2 separate conductor cores rated at 360-1080 MVA

[7] See Table 8 of Strategic Environmental Assessment (SEA) of the Offshore Renewable Energy Development Plan (OREDP) in the Republic of Ireland at http://www.seai.ie/Renewables/Ocean_Energy/Offshore_Renewable_SEA/Environmental_Report/SEA_ER_Final.pdf



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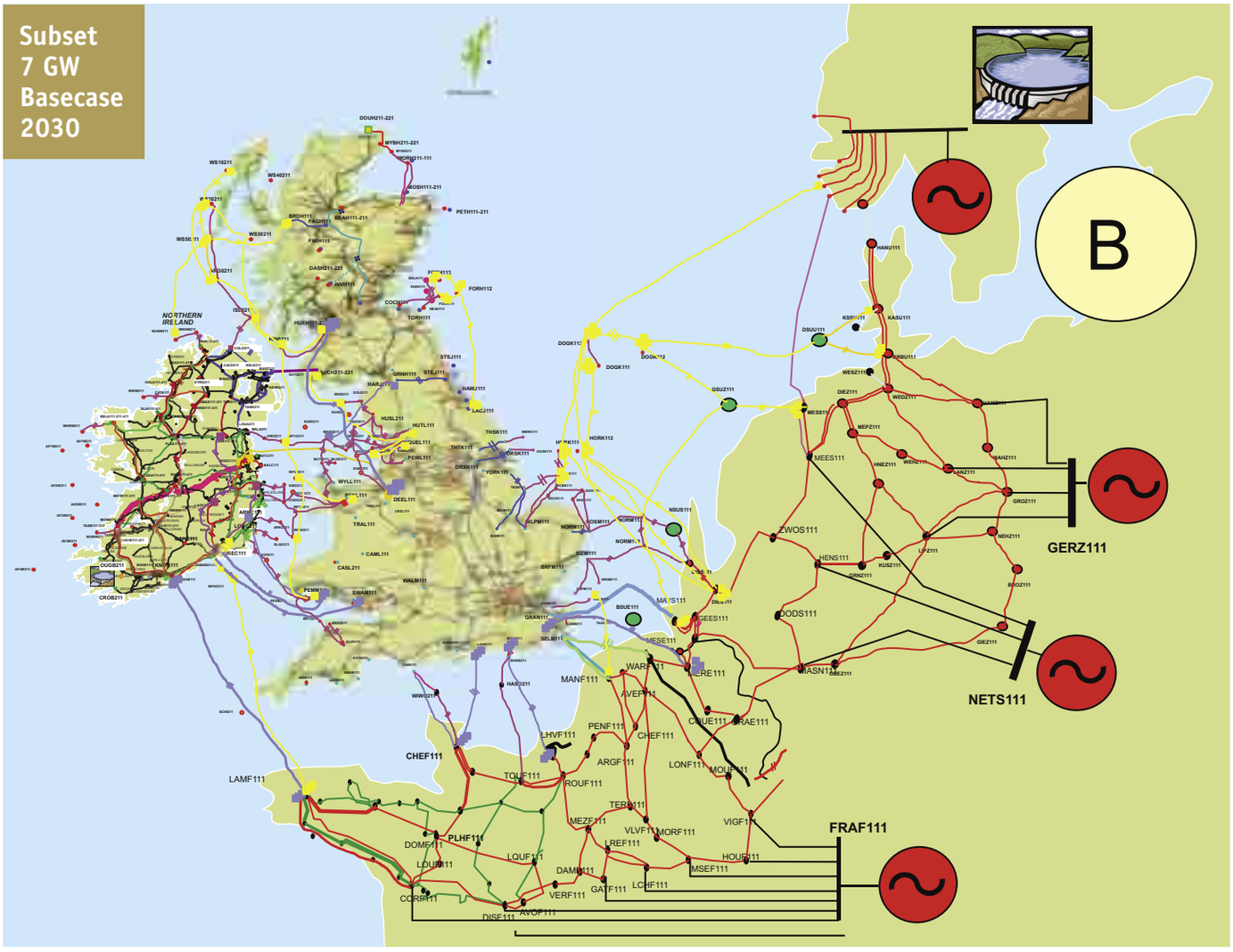
One interesting increased capacity option is to install 220kV AC cables initially and then seek to convert these to DC operation, which can provide appreciable increases in their rating, at a later stage if the initial capacity is insufficient. Technically this is considered possible but further investigation into the requirements, new standards, qualifications, testing procedures, practicality and cost of the additional AC/DC conversion devices will be needed. In principle this would provide future proofing without initial commitment of higher capital costs until such time as a need arises.



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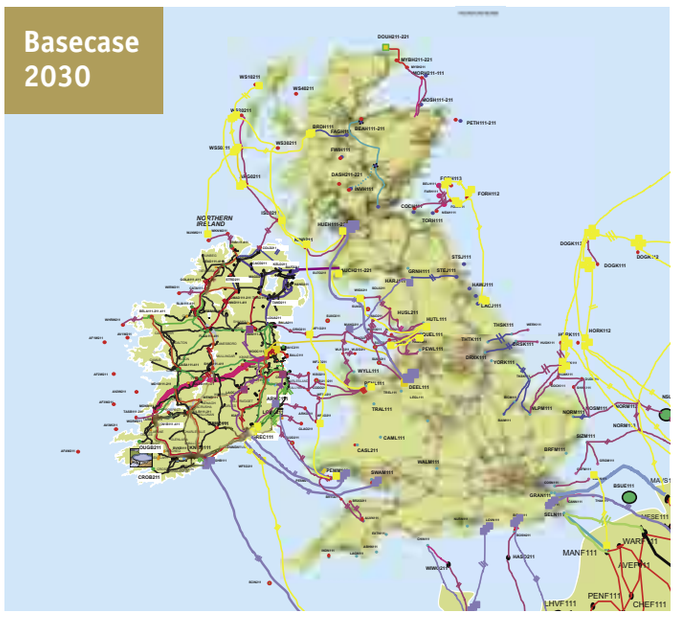
## 1.2.8 AC or DC Offshore Network

Another fundamental decision in building a new transmission network is whether the network will be Alternating Current (AC) or Direct Current (DC). Both have their pros and cons, but as historically transmission networks onshore have been built as AC the use of DC in an offshore network requires conversion from AC to DC and vice versa when making links between both network types.

Although DC can be a more efficient method of power transmission it is very expensive. Consequently, DC technology is only economically viable over long distances. In the case of offshore cable networks this has been calculated in this study as being higher than c.60km. Also long aggregate lengths of EHV AC cables have a number of technical issues favouring the use of DC cables. These issues have not been examined in-depth in this report and may make the use of DC preferable at even shorter distances.

The analysis performed with the variety of candidate AC and DC technologies, has shown that neither AC nor DC is exclusively selected but rather a mixed approach with the cost of the two technologies dictating heavily their use. Further detailed technical analysis will need to be conducted to confirm the final quantities of each that will be acceptable.

The diagram below shows that LCC DC technology (shown in purple) forms the majority of the onshore to onshore interconnector circuits, where as the VSC DC technology forms (shown in yellow) the majority of the longer circuits that start from an offshore point. The shorter links are predominately AC (shown in Red); however in some applications the use of DC technology has been used at a higher capital cost presumably to control power (See 'Smart' device use above for more details).



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## 1.2.9 Future Expansion

Developments to the transmission network must be designed to meet not only initial needs on the network but also must be resilient to the needs of the network into the future.

Predicting the future needs with any level of certainty is a challenge for all system planners worldwide. The best practice approach is to envisage a number of future scenarios which cover the widest plausible range of developmental changes to the network. If a development project addresses the needs for all scenarios then it is considered robust, i.e. able to meet the widest envisaged range of needs on the network.

Part of the driver for this study was to assess the probability of future development from offshore stations over future years. This information would define whether spare capacity for future expansion should be built into these stations design.

For clarity, this does not mean that additional electrical equipment would necessarily be installed immediately. What it does mean is that consideration for potential future needs should be built into the development particularly when designing civil works i.e. offshore platforms, cable routing, etc.

The examination of a number of future generation levels and dispersion provided a diverse range of future scenarios. Consistently across all of the ESPs offshore development was extensive and 'meshed', with continuing incremental strengthening between these stations with additional circuits of various technologies. The technologies selected would all require additional station equipment, with varying implications for offshore station design.

While expansion should be catered for, additional in-depth analysis of the detailed design options to identify how this would be best achieved is a body of work which was beyond the scope of this study.

However, some key functional requirements can be identified from this study.

Standards and policies for offshore stations should seek a modular electrical design that will permit changes from AC to DC and vice versa on some circuits, for the installation of Phase Shifting Transformers and dynamic or variable reactive compensation.

Standards and policies for offshore reactive compensation, AC to DC conversion, high voltage switchgear equipment, transformers and associated plant should be developed.

Options for expansion of offshore platforms themselves to accommodate future plant should be evaluated to find the most cost effective method of delivering expansion, including but not restricted to whether to front load expansion requirements.



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## 1.3 CONCLUSION

This Offshore Grid Study has successfully provided EirGrid with the necessary information and understanding on which to base its functional requirements for offshore generator connections, and standards or policies for offshore equipment.

It raised and investigated a number of issues relating to the offshore network and its development, and is envisaged to provide useful insight and source of information into these issues for interested parties.



# 2 Findings quick list

The findings detailed in the main report are shown below:

## 2.1 HIGH LEVEL FINDINGS

- 'Meshed' or interlinked and not a series of single connections from generators to the onshore network
- Developed incrementally
- Symbiotic with the onshore network
- In line with the existing GRID25 strategy
- Developed with interconnectors from offshore generators to other networks as well as from onshore points
- Developed making use of 'smart' devices to enhance network flexibility and minimise the scale of the offshore network
- Developed at a high voltage level typically at least 200kV
- Both an AC and DC offshore cable network interlinked
- Designed with the potential for even further future expansion
- Large Transfer of Renewable Power to Mainland Europe and Britain 'via' HVDC electricity highway concept

## 2.2 DETAILED FINDINGS

- Developing the Dublin network with a 400kV 'ring' around the city is a robust solution to wide variations in generation and demand projections (Chapter 8.1)
- AC offshore grid off Irish coast feasible with suitable compensation strategy (8.2.2)
- Fixed and Variable compensation are required to cope with Wind variability(8.2.3)
- An AC submarine cable constructed offshore grid may create assets prone to parallel resonances, especially in the early stages(8.2.4)
- Development of interconnection is phased first to Britain and subsequently to France using AC only development analysis (Chapter 8.3.2.5)
- Significant development of interconnection with Britain may be economically justifiable prior to the development of additional offshore renewable (Chapter 9.3.2.1)
- Large variations in constraint payments in the short term (10 years) has little impact on justifiable network development at perceived early stages on offshore development (Chapter 9.3.2.1)
- Longer term offshore network development requirements can be significantly impacted by generation constraint costs assuming major offshore generation deployment (Chapter 9.3.2.1)
- Offshore wind can displace onshore generation due to REFIT price when interconnection developed is constrained (Chapter 9.3.2.1)
- Changes in constraint costs in the main only effect the timing of the same network being built rather than radically changing network topography (Chapter 9.3.2.1)



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- Offshore wind in the Irish Sea is never curtailed because symbiotic to developments of further interconnector with Britain and France (9.3.2.2)
- Multiple Mixed/Meshed AC/DC offshore grid poses coordinated control issues to optimise power transfer in different wind generation scenarios (9.4.4)
- Location of HVDC backbone to link Scottish generation from North to South is highly dependent on development off west coast of wave generation and possibility of building onshore assets (Chapter 9.4.4-5)
- VSC HVDC becomes economically viable compared to an AC (single circuit 220kV) for 1GW on distances over c.115km (Chapter 13.4)
- LCC HVDC becomes economically viable compared to an AC (single circuit 220kV) for 1GW on distances over c.75km (Chapter 13.4)
- VSC-HVDC economically viable for distances lower than the “break-even” point in a multi-terminal expansion strategy (14.3)
- VSC-hub provides power flow control on multiple AC links (14.3,fig.A3.1)
- AC to DC Technology may offer Smart Planning opportunities to TSOs in implementing flexible investment strategies over the planning period (14.3 Example)



# 3 Introduction

## 3.1 OVERVIEW

In 1997 the European Commission published a White Paper [6] on renewable energy which set targets for the exploitation of Europe's renewable energy resources. Since then there has been dramatic growth in the amount of wind farms installed in EU nations, especially in those countries where wind conditions are particularly favourable.

At present the targets set out in the White Paper have been respected and even surpassed, with 55.9 GW of wind generation installed in the original 15 nations of the EU at the end of 2007. Projections for the 27 nations of the expanded EU indicate a total installed capacity of 78 GW of wind generation in 2010, surpassing targets by some 5%.

The directive on the promotion of the use of renewable energy resources published by the European Commission in 2008[2] has given further impetus to the development of Europe's wind energy resources. The directive sets targets for total installed wind generation in the EU-27 of 180 GW by 2020 and 300 GW by 2030. The European Wind Energy Association (EWEA) believes that between 20 and 40 GW of the 2020 target will be met through the installation of offshore wind farms[8]. The vast majority of wind farms in the EU have thus far been installed onshore, with just 1100 MW of offshore wind generation making up the 55.9 GW total [9].

In the Republic of Ireland, by the end of 2007 approximately 800 MW of wind generation had been installed, c.25 MW of which comes in the form of off-shore generation.

Given that Ireland has some of the most favourable wind conditions in the whole of Europe, wind farm development in Ireland and off the coast of Ireland is expected to grow rapidly over the coming years, as evidenced by the fact that some 6,000 MW of wind generation is currently awaiting connection to the grid.

In addition to having abundant resources in terms of wind energy, the island of Ireland, with the Atlantic ocean on its west coast, is also in a favourable location in terms of tidal and wave energy resources. For the island as a whole, studies carried out for EirGrid's Grid Development Strategy (GRID25) assumed levels of installed offshore renewable generation, of all kinds, ranging up to and in excess of 950 MW in 2025.

The meeting of these targets have been reinforced by the recent Government Targets in the framework of "20-20-20" EU initiative, set for ROI a challenging 40% of Renewable Energy for 2020.



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## 3.2 OFFSHORE NETWORKS

Given the massive potential for the exploitation of renewable energy resources off the coast of Ireland it would seem prudent to develop an informed perspective on how best to facilitate connection of this type of generation. Thus far, a radial point-to-point approach to connecting offshore generation to the onshore transmission network has been used both in Ireland and across Europe. This approach has been used for expediency given the relatively low levels of offshore generation connected to date, the dispersal of this generation, and the relatively short distances of this generation to the shoreline.

Many European utilities are currently investigating offshore transmission networks into which offshore generation can connect. Offshore network development from radial transmission of power to power transmission through meshed networks mirrors the development of onshore transmission networks that improved the reliability and flexibility of power supplies but led to decreased utilisation of transmission assets (10%-20% average capacity utilisation).

It should be noted that in some countries, including Germany, transmission system operators are required by law to pay for and build the transmission infrastructure required to connect offshore renewable generators. This makes it imperative for them to develop a cost-effective long term strategy for offshore networks. This is reason many utilities in the rest of Europe are currently investigating the viability of offshore transmission networks.

Uniquely, in Britain, current arrangements are for 3rd parties to become independent offshore asset owners.

Thus far, the government and the regulatory authorities in Ireland have not introduced any specific legal framework for offshore networks with respect to the connection of offshore generation. This may change in the future and EirGrid wishes to be able to pro-actively inform this process should it arise.

As part of Gate 3, EirGrid is also obliged to provide transmission connection offer to at least 2 offshore developers. A third has applied to the distribution system operator for connection whose impact on the transmission system EirGrid will also review. Further connection applications from offshore developers, moreover, are expected in due course.

Therefore to develop the functional requirements for connection of the offshore generation in Gate 3, to develop its capacity as an authoritative voice in the industry, and its role to provide support to any regulatory decision, EirGrid performed an Expansion Planning Study. This study addressed the following questions:

- What should the architecture of an offshore grid structure optimally be?
- Which technology will be more technically and economically viable for offshore connections?
- Are there synergies between offshore and onshore systems?

[8] EWEA Annual Report 2007
[9] http://www.ewea.org/index.php?id=203



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# 4 Objective

## 4.1 FOREWORD

EirGrid investigated different approaches for Expansion Planning Studies for the purposes of this study. A software tool developed by ERSE (ENEA-Ricerca sul Sistema Elettrico) former CESIRICERCA was identified as providing a wide range of preferential attributes that could be applied to this type of study.

This methodology was first conceived in the 80s by ENEL Research Centre (CRE Italy) and it has been used extensively in International Studies [7], [8]. In the 1990s, the approach was used for the development of the Maghrebin Network, within the framework of Systmed and MEDRING projects. The experience of local utilities using the software has been utilised to further enhance the software's capabilities and facilities[9].

Further improvement and testing has been included under the framework of Ricerca di Sistema (RdS) a government initiative financially supporting Research on the Electric System.

Consequently the software has been progressively developed, verified and tested prior to its use for this project, which mitigates potential software related anomalies in the study results.

The software allows for a large number of potential system reinforcements to be evaluated, and a subset of these selected to provide an optimally developed network, which will deliver the energy of disparate new offshore generating sources, whilst making best use of existing generation and network to minimise overall costs. The costs considered include not only network infrastructure costs, but also production costs and system losses.

Based on preliminary investigations and some worked examples, EirGrid entered into a Cooperation Agreement with ERSE, to utilise this software in its examination of an offshore network in the Irish Sea.

## 4.2 SCOPE OF THE STUDY

The aims of the Study were to develop a vision for the long term development of a future Offshore Grid with specific focus on the Irish Sea.

The Irish Sea was selected to focus on for two key reasons. The first is that it provided the greatest opportunity for a large complex network to develop in the near term given that applicants already exist in the area, notably two Gate 3 applicants already receiving connection offers. The second reason is that it provides the most likely location for interconnection to European networks.



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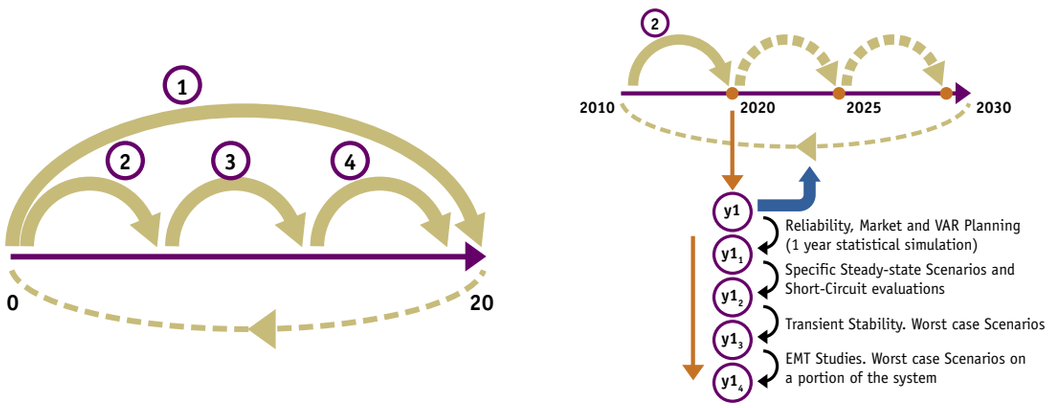
**The main objectives of the investigation were to determine:**

- the most suitable technology: AC or DC;
- the grid structure able to accommodate the massive potential of offshore wind energy;
- the schedule of new reinforcements over the planning period;
- the impact of 'Smart' devices at the expansion phase;
- the impact of changing scenarios to the architectural topology of the offshore grid, and;
- the sensitivity of the scenarios to key assumptions made in the production of the scenarios.

# 5 Methodology

A methodology for Expansion Planning Studies was developed for a previous study[9]. The methodology has a two step approach that is explained here (see Figure 5.1):

a) Long Term Expansion Planning (LTEP)
b) Short term Planning for specific issues (STP)




a) Long Term Expansion Planning

b) Short Term Planning

**Figure 5.1** Expansion Planning Study



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## 5.1 LONG TERM EXPANSION PLANNING (LTEP)

The purpose of the LTEP problem is twofold:

1) select new infrastructure to fulfil an horizon target
2) decide the schedule of the reinforcements based on some intermediate years load and generation scenarios

An Expansion Strategy Plan (ESP) is a process to select, among several possible combination of candidate alternatives the most cost effective solution which provide the best power system performances.

The decision making criteria is based on a suitable optimisation process which selects the least cost subsets of candidate infrastructure reinforcement with the highest reliability and flexibility.

### 5.1.1 Optimisation Candidates

The selection is performed on a set of candidate reinforcements, either to connect new generation points, or to reinforce the existing system or both.

It is duty of the planner to introduce as many candidates as possible in order not to create 'artificial' restriction in the ESP. Restricting the use of reinforcement as a candidate can only based on an environmental constraint, i.e. impossibility of developing any infrastructure in certain areas.

The onshore reinforcements which were drawn from EirGrid's GRID25 strategy have already been assessed as part of a country wide high level examination of environmental constraints; this information has been used for the other candidate reinforcements to select the use of appropriate technology.

It has been assumed that no environmental constraints would prevent a candidate being possible offshore.



## 5.1.2 Optimisation Algorithm

The Optimisation function is shown below

$$\begin{cases} Z = \sum_{i=1}^{6}\left(\sum_{k=1}^{29}\left(N_{ik}\cdot c_{Gik}\cdot PG_{ki} + N_{ik}\cdot c_{LSHik}\cdot P_{LSHik} + N_{ik}\cdot c_{ENGik}\cdot P_{ENGik}\right) + BB_i\right) \\ \quad + \sum_{j=1}^{205} Y_j \cdot C_j \\ \\ Y_j = 0,1 \quad \forall j \end{cases}$$

Where:

i = number of representative scenarios
$BB_i$ = Busbar solution
$N_{ik}$ = number of hours for each scenario and each contingency
$C_g$ = generation cost
$P_G$ = generated power
$C_{lsh}$ = load shedding cost
$P_{lsh}$ = Load shedding Power
$P_{eng}$ = Energy not produced
$C_i$ = annuity of investment
$Y_i$ = binary variable for candidate system
K = number of contingencies

Two major parts to the function can be underlined:

- Continuous cost composed of generation production costs, reliability and energy not delivered penalties
- Discrete cost related to weather and if infrastructure is chosen or not

An ad hoc algorithm, based on Mixed Integer Programming (MIP), has been used to provide the best solution to the optimisation function, selecting the optimum expansion solution to minimise the combined cost of power production, system losses, and network development.

The solution is based on a DC load flow, whilst respecting network equipment rating restrictions.



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The Branch and Bound Method is used by the program to provide a solution, given the combinatorial nature of the problem; this method is very effective in reducing the number of scenario combination to be effectively examined. A tree is made, where each node in the tree corresponds to some combination of integer variables which are constrained to be 1 or 0 only. In the case of this problem the 1 or 0 relates to whether a candidate reinforcement (e.g. an offshore cable circuit) is in or not.

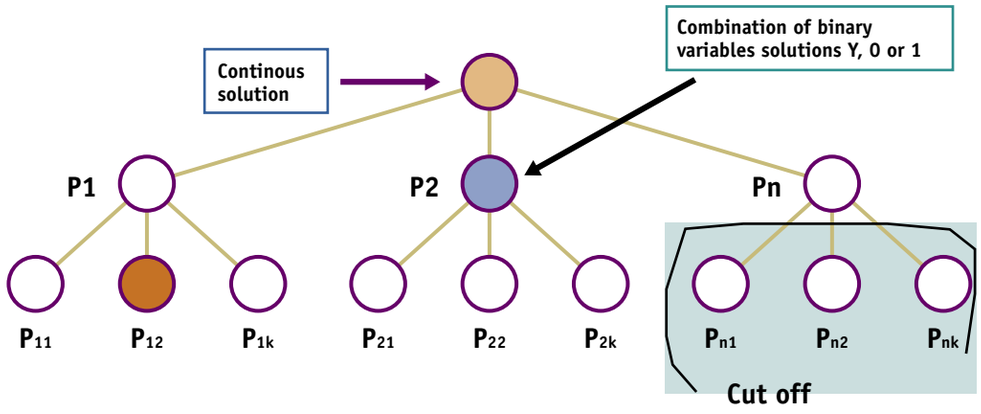


**Figure 5.3.** Branch and Bound methodology

The number of combination depends on the binary variables to be defined. For large MIP problems long computation time may be expected.

The program first considers one of the potential solutions to provide a Current Best Solution (CBS). Then one of the combinations of integers is changed (e.g. a circuit removed or added) and the resulting new solution is considered, in so doing the new solution may prove to be optimum and hence a new optimum is obtained. Once, all the integer variables are fixed a Current Best Solution (CBS) is reached, i.e. P12.

The program re-dispatches generation in each of its potential solutions to minimise the production cost to permit, which in association with reinforcement and system loss costs provide a final cost for that solution to be compared to the CBS.

Other branches are explored starting from the most attractive stage, i.e. P1. If during the process of fixing integer variables a more expensive solution than the CBS is found, i.e. Pn, then the node Pn and al the branches downstream, Pn1, Pn2, Pnk are eliminated (Cut off).

In the process of proceeding through the tree, the algorithm calculates an Estimated Best Solution (EBS); a tolerance is calculated between EBS and CBS. This provides a reference as to how far the CBS is from the optimum solution.



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Given that the EBS is only an estimated value, and may not provide to be accurate (i.e. the EBS may not exist), a tolerance level is selected within which the current CBS solution is considered acceptably optimised to terminate the process within a reasonable timeframe.

### 5.1.3 Horizon Expansion

The first stage of the solving the LTEP problem is setting the conditions, including load and generation, of the horizon year.

Since the most likely candidate reinforcement projects to cope with the future generation scenario to be examined is unknown, the planner has to introduce as many potential candidate reinforcements as allowed by the grid and the new load and generation locations.

The number of candidates typically is very large to the subset at the end.

The horizon year Expansion is aiming at screening the set of candidates, to select the most attractive subset, as shown in Figure 5.4.

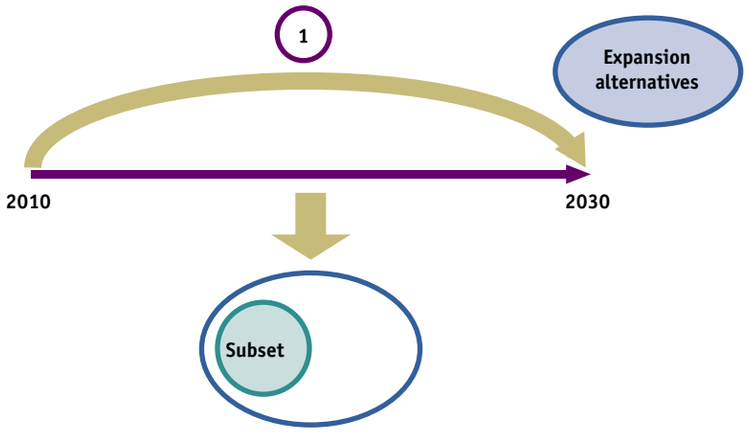


**Figure 5.4.** Horizon Year Solution reduction in candidates to a smaller subset

The subset is then used to define the Expansion Strategy Plan over the intermediate years from present to the horizon year.

It should be noted that the use of this subset may result in higher generation constraints in the intermediate years; this is especially true when boundary conditions expansion scenarios, i.e. loads and offshore wind generation, are not uniformly expanded over the geographic locations and the planning period.

Also the level of accuracy that can be made on an immediate jump to 2030 results in a larger subset of candidates which can be optimised at a later stage



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### 5.1.4 Intermediate Years Expansion

The solutions for the intermediate year are calculated by providing the program the restricted subset of candidate reinforcements and the assumed load/generation conditions for each intermediate year, as shown in figure 5.5.

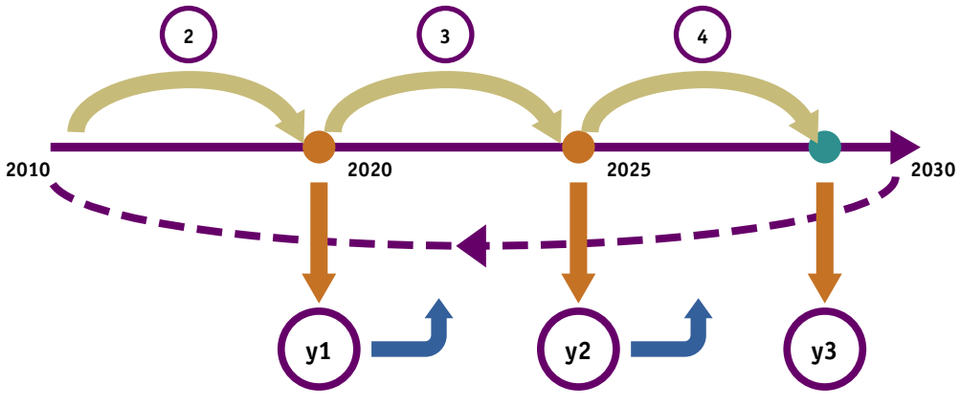


**Figure 5.5.** Intermediate Year Solutions

The purpose of this phase is twofold:

- find the candidates from the subset, Yi needed for each of the intermediate years and remove these from the subset for the subsequent years;
- define a timeline of transmission investments in infrastructures over the 20 year period.



### 5.1.5 Contingency Analysis

Both the Expansion Phases (Horizon and intermediate) are submitted to a deterministic contingency analysis. A list of most critical contingencies is provided to the program to use.

Ideally the optimisation process would perform these analyses within the branch and bound selection optimising the power flow to avoid a single contingency problem. This would allow better selection of new reinforcements which solve multiple contingencies at the same time.

However, due to increased complexity to process that multiple contingency analyses would involve, as well as the memory occupancy, such a problem may only be solved in simple cases. Therefore, an approximation has been implemented which considers the contingency analysis in a loop as shown in figure 5.6.

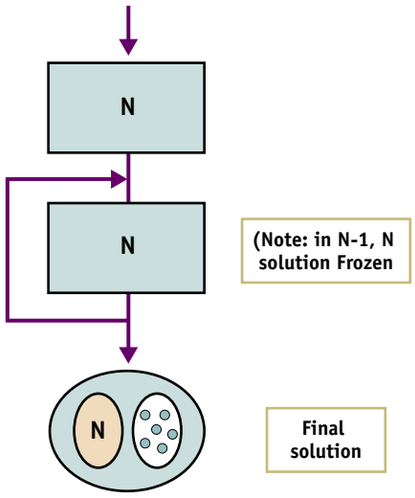


**Figure 5.6.** Contingency Analysis

It is worth noting that during contingency, the selected N network is considered 'frozen'.

In addition, during contingency analysis, transfer capability of the Transmission Grid is permitted according to the Irish Transmission Planning Criteria (TPC), as shown in Table 5.1

| | N | N – 1 |
|---|---|---|
| **Overhead Line** | **1** | **1.1** |
| **Underground and Subsea Cables** | **1** | **1.25** |
| **Transformer** | **1** | **1.5** |

**Table 5.1.** Coefficients for the transfer capacity



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## 5.2 SHORT TERM EXPANSION PLANNING (STP)

The LTEP analysis provides an Expansion Strategy Plan (ESP) which is able to accommodate the power flows for the selected load/generation scenarios over the planning period.

However, the network solutions must also be studied to ensure their viability because of the following approximation:

- Limited number of Load/Generation scenarios
- Contingency analysis is restricted to a pre-defined list
- Steady State operating conditions have only been taken into account
- Power Flow is considered with a DCLF approach

It is not possible to implement these multiple Power System analysis issues together and therefore the tasks are broken down, which sets the framework of the Short Term Planning (STP) Analysis.

Diagrammatically a typical framework is shown in Figure 5.7.

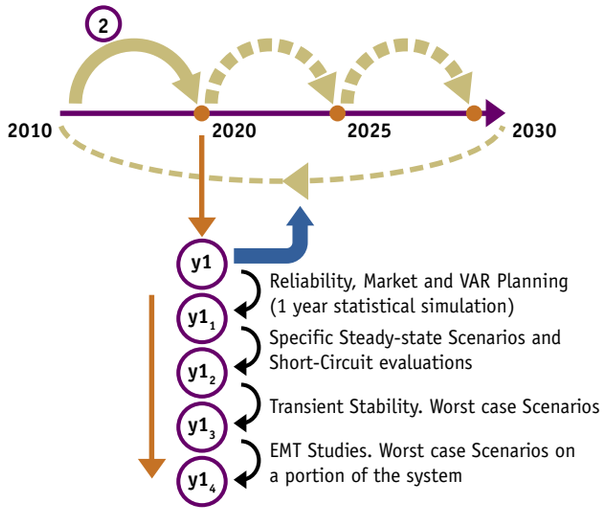


**Figure 5.7.** Short Term Planning following LTEP

An LTEP Intermediate solution is sequentially submitted to a number of power system analyses following the traditional planning approach that is Steady State, Transient Stability and Electromagnetic Transients.

In this study only steady state analysis will be performed at present, considering an adequacy evaluation of the LTEP solution using a Software tool developed by ERSE, named REMARK.



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### 5.2.1 Reliability And Market (REMARK)

This tool performs an adequacy evaluation considering the hourly Load/Generation curves. It is based on a Non Sequential Probabilistic Montecarlo method approach, using a DC load flow.

The algorithm randomly generates network assets and Load/Generation scenarios and evaluates, using a DC optimal power flow load flow analysis.

A number of technical constraints are considered in the optimisation process:

- Maximum and minimum generation limits
- Generator emission limits
- Thermal constraints of transmission grid components
- Economical constraints between Market Areas
- Operation constraints between Interconnected Areas

Also the probability of occurrence of faults and time to repair as well as maintenance plan of grid components, line, cables, generators and transformers are taken into account.

The following Economical data is also provided and used in the optimisation process:

- Generation costs
- Emission costs by fuel
- Load-Shedding costs
- Energy curtailments costs

#### 5.2.1.1 Optimisation Problem

Using a DC load flow approach the optimisation problem is solved minimising an overall objective function cost including:

- Generation production costs
- Emission costs
- Reliability costs
- Energy curtailments costs





Four optimal power flows, at incremental constraints, are sequentially performed:

- Bus Bar system (unconstrained)
- Market Zones
- Interconnections
- Entire Transmission System

**Busbar System Analysis**

Information about Generation Adequacy can be obtained. Furthermore, the final costs is the absolute minimum for the System

**Market Zones and Interconnection**

If the Market is divided into multiple Market Zones, this stage allows the evaluation of whether congestion is affecting the market division. By adding the physical interconnections, in can be understood if physical flows really determine congestion between areas and reinforcement must be introduced.

**Entire Transmission System**

Finally the whole transmission system is included and further calculation allows the verification of internal congestion in each area.

### 5.2.1.2 Outputs Of The Evaluation

For each phase a large number of outputs are provided:

- LOLP, LOLE and EENS indexes
- Nodal LMP
- Generator, Area, System Energy productions
- Energy exchange between Areas
- Marginal cost of congestions (if any)

## 5.2.2 Application To Offshore Grid

LTEP cannot deal with low probability events that are combination of Load/Generation scenarios, which can give further congestions problems, load shedding and Energy curtailed.

REMARK hourly investigation with a probabilistic approach allows evaluation of whether the system may suffer from such events. Consequently further reinforcement's may be identified that are not provided by LTEP alone.

In the framework of the Cooperation Agreement, ERSE used REMARK to evaluate the LTEP solution related to the Basecase scenario.



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It should be noted that ideally a more comprehensive AC OPF would be required, in order to properly evaluate Reactive Power and Voltage Control issues for a large number of scenarios given the large extension of subsea and underground cables.

### 5.2.3 Other Power System Issues

Other Power System analysis as described in figure 5.7, with exception of a few test cases (in chapter 8.2) has not been examined in this study and will be carried on in other studies.

These include:

- Reactive support impact, Compensation Strategy, VAR Planning and Voltage Stability
- Transient Stability in Area which suffers of sudden lack of wind Power due to faults in the Offshore Grid
- Electromagnetic transients with Large Cable Extension

These further investigations may also lead to changes in the selections of offshore technologies, in particular by limiting the extension of the AC offshore circuits, introducing HVDC in some places, providing the system of suitable power flow controllers or compensation devices for voltage control.



# 6 Transmission Alternatives

Offshore Grids are unique because they are developed entirely in the sea meaning cable technology must be used. EirGrid performed a brief investigation on the available technologies for Offshore Transmission [4]. A more detailed investigated is to be undertaken in 2011.

Costs estimations have been completed as part of the LTEP study, based on a European Average of infrastructure costs.

## 6.1 OFFSHORE

Subsea cables have been in service from the 1950s worldwide. Advancement in technology made three-core HVAC 150 kV Extruded Cables available for subsea application in recent years following offshore Wind Farm connections in the North Sea.

Today technology is under development for higher HVAC Voltages, 220kV and 400 kV. In particular three-core configuration can be developed for 220 kV, whereas only single core is likely to be developed for 400 kV.

For the Offshore Grid study it has been assumed that three AC technologies were available at 220 and 400 kV.

In Figure 6.1 a general configuration of an offshore connection is shown from the gathering platform on shore.

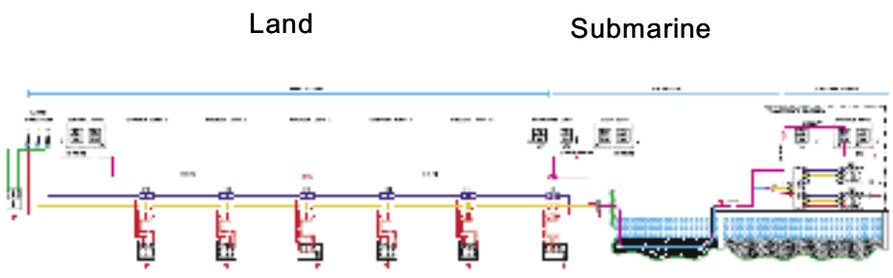


**Figure 6.1** Three-core cables

The separation between submarine and land portion needs to be broken out. The gathering platform is equipped with HV/MV transformers and switching devices.

Land cable can be laid in cross-bonded configuration of the sheath and is normal practice within Ireland. If connection is close to the sea, the land cable is usually omitted.



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DC technology is also being considered for longer distances. In particular the recent development of multilevel Voltage Source Converter (VSC) technology is of interest in particular in a Meshed AC context for the concept of an "Offshore" Supergrid. Furthermore VSC DC technology allows the use of XLPE cables.

In this study, land cable sections have been modelled using typical parameters for EirGrid's standard cable types and installation methods (as applicable), and both conventional LCC and VSC has been considered with PPL and XLPE cable respectively.

### 6.1.1 AC 220 kV three-core

At present all the offshore wind farm connections have been realised using a cable shown in Figure 6.2

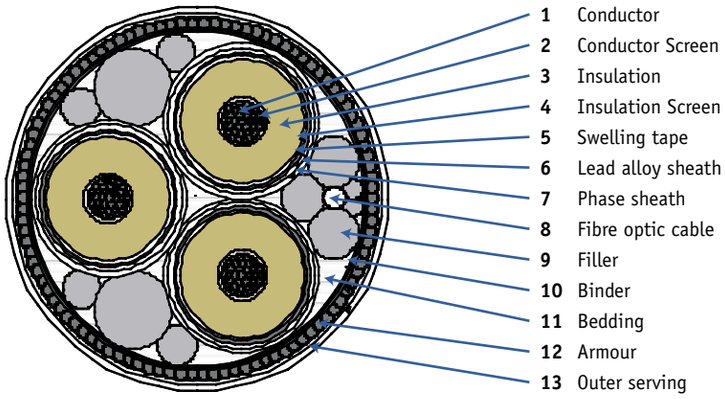


**Figure 6.2.** Three-core cable

This particular technology allows some cost savings in installation as in principle only a single cable needs to be laid. At present the AC technology offshore is predominately at 150 kV although some smaller section at 220 kV has been installed.

At 150 kV, with a 1000 cu mm2 section no more then 180-200 MVA can be transferred on shore.

However, by increasing the voltage, dimension of the three-core hits the edge of present manufacturer plants and investment are needed to set up the supply cable chain.

At present the rating limit for 220 kV is about 320 MVA. Larger core sections although theoretically possible but are likely to require enhancements in cable manufacturer factories, which is not expected to be developed at present.



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The cable can also provide a fibre optic conductor for signal transmission purposes from the export platform, and has been assumed to provide communications links as applicable for studies.

Table 6.1 provides the electric parameters utilised in the studies

| | R Ohm/km | X Ohm/km | C nF/km | tg° p.u. | S [MVA] |
|---|---|---|---|---|---|
| **Three core 220 kV 1000 mm² Cu** | **0.057** | **0.09** | **200** | **1.00E-04** | **320** |

**Table 6.1.** Electrical Parameters

## 6.1.2 AC 220 kV single-core

For a larger ampacity, a single core arrangement must be used.

Cable and accessories are available for this technology. In figure 6.3 an example of the laying is shown.

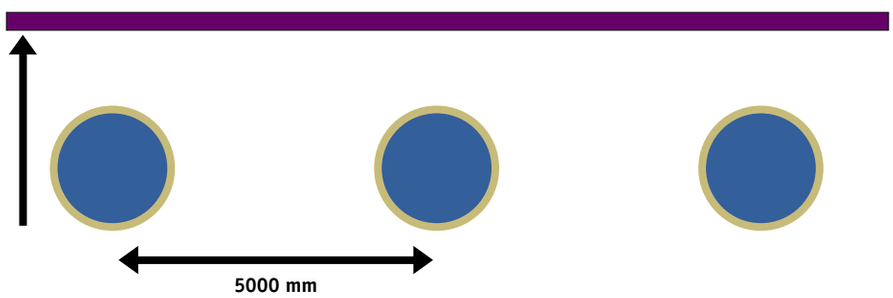


**Figure 6.3.** Laying Example of Single core

Generally the cable is placed undergrounded at a depth of c.1m at the bottom of the sea, to protect against anchor strikes.

The single core phase are laying at least 50 m apart each other in order to avoid any potential damage during installation of subsequent phases, and has been assumed in determining the electrical parameters used in the studies.



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The cable itself is generally and armour cable as shown in Figure 6.4.

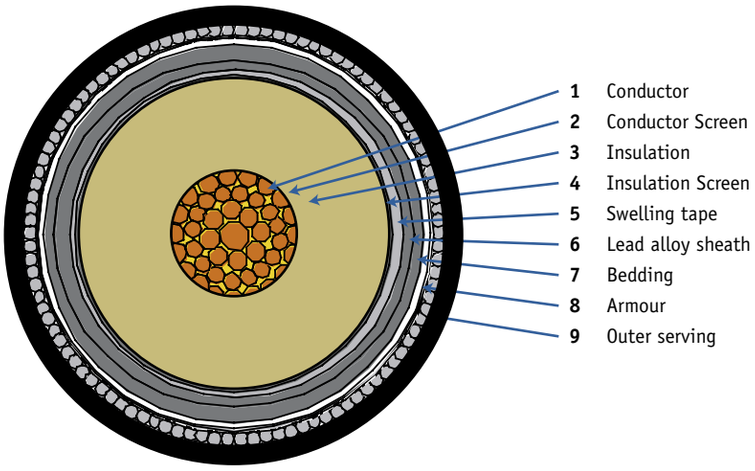


**Figure 6.4.** Cross Section of Subsea Single core

This is generally a more expensive solution because of the cable manufacture and installation complexity. However a higher transfer capacity can be obtained. In table 6.2 the Electrical parameters are shown.

| | R Ohm/km | X Ohm/km | C nF/km | tg° p.u. | S [MVA] |
|---|---|---|---|---|---|
| **Single core 220 kV 1200 mm² Cu** | **0.046** | **0.07** | **198** | **1.00E-04** | **460** |

**Table 6.2.** Electrical Parameters for 220 kV Single Core

## 6.1.3 AC 400 kV Single-core

The solution is similar to the previous but at 400 kV voltages. It is worthy of note that the technology is under development at present for accessories and the solution will be viable in the near future.

The electrical parameters used in the studies are shown in Table 6.3.

| | R Ohm/km | X Ohm/km | C nF/km | tg° p.u. | S [MVA] |
|---|---|---|---|---|---|
| **Singlecore 400 kV 1400 mm² Cu** | **0.043** | **0.07** | **216** | **1.00E-04** | **930** |

**Table 6.3.** Electrical Parameters for 400 kV Single Core



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## 6.1.4 DC Technology

DC technology has been proven technically viable since the 50s, using the Line Commutated Technology (LCC).

The HVDC units were very expensive and break-even points with AC only happened around 100 km for submarine.

Applications, mostly point-to-point and technology, have been used in very specific cases, like interconnections between un-synchronised countries, or compulsory use of long distance cables. Oil filled and PPL cables have been used as Cable Transmission technology. They are available up to 600 kV.

In recent years advancement in the technology has produced Voltage Source Converter technology (VSC).

The launching of initiatives to develop offshore grids has boosted the possibilities for this technology as it appears attractive in principle to design a DC meshed system in a multi-terminal arrangements. VSC does not need a generating source at both ends of the circuit (unlike LCC) and therefore is the obvious choice for DC circuits required to energise offshore stations.

VSC can use the same XLPE cable technology as power can be reversed by reversing the current instead of the voltage. At present, DC XLPE cables are available up to 300 kV voltages.

### 6.1.4.1 DC LCC Systems

A maximum 2GW LCC system was considered as available for power transfer in the future for the purpose of these studies. This can be obtained by a bipolar configuration using a 500 kV DC voltage with a 2000 Amps MI cable.

The system can have a 1 GW modularity in construction as well as in operation; as a bipolar system can actually work in monopolar configuration.

An example of the cable and DC units are shown in figure 6.5



**Figure 6.5.** Mass Impregnated cable in Bundle arrangement



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### 6.1.4.2 DC VSC Systems

A 1 GW system is expected available and assumed for the purposes of this study, using a 300 kV DC rating with a 1667 Amps XLPE cable.

At present, no monopolar configuration has been proposed and the system can therefore be only in an ON/OFF states.

An example of DC units and Cables are shown in figure 6.6



**Figure 6.6.** Extruded Cable

Table 6.4, shows the electrical parameters for both LCC and VSC cable technologies used in the studies.

| **DC cable**<br>Type | **R**<br>Ohm/km | **X**<br>Ohm/km | **Tgd**<br>(p.u.) | **C**<br>(nF/km) | **Snom**<br>MW |
|---|---|---|---|---|---|
| **XLPE 1800 mm² Cu 320 kV** | **0.0101** | **na** | **na** | **na** | **1000** |
| **PPL 2000 mm² Cu 500 kV** | **0.009** | **na** | **na** | **na** | **1000** |

**Table 6.4.** Electrical Parameters for DC cables





## 6.2 ONSHORE

The existing onshore infrastructure is overhead line based, with cables only usually applied in densely populated areas. Overhead line is considered as the main technology for onshore reinforcements especially at higher voltages. To reduce the need for new overhead line corridors EirGrid has recently undertaken a strategy of uprating existing circuits to maximise the use of existing assets.

### 6.2.1 AC OHL

Figure 6.7 shows a typical 400 kV overhead line of the Irish transmission system. New lines have been considered in these studies with similar type of structure.

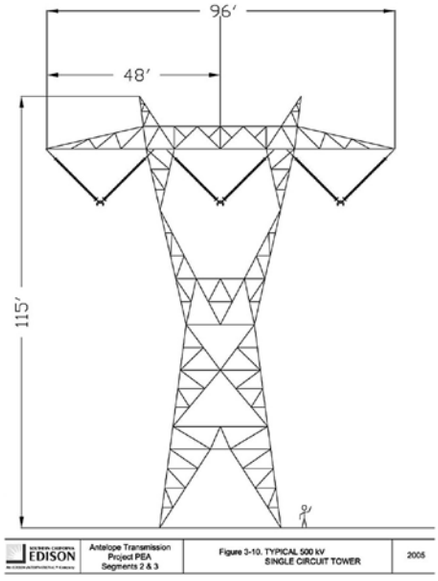


**Figure 6.7.** Existing Overhead Lines

For 220 and 110 kV uprating, the use of HTLS technology has been considered which enhance the thermal capacity of about 50% [11].

Table 6.5, shows the electrical parameters for both LCC and VSC cable technologies used in the studies.

| | R Ohm/km | X (Ohm/km) | Tgd (p.u.) | C (nF/km) | Snom MVA |
|---|---|---|---|---|---|
| **Overhead 380 kV** | **0.03** | **0.28** | **0** | **13** | **1500** |

**Table 6.5.** Electrical Parameters for 400 kV Overhead lines



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## 6.2.2 AC UNDERGROUND CABLES

AC cable technologies have been described in [12].

At present XLPE technology, which has been applied since the 1990s, is the cable of choice in Ireland, in comparison to oil filled cables mainly because of its lower maintenance, less environmental impact, and costs. This technology is available up to 500 kV.

In this study we consider the use of AC XLPE cable from onshore points up to the interface point with subsea submarine cable and also consider XLPE cable as an alternative to overhead lines as applicable.

According to the different ampacity requirements the table shows the Underground for submarine interface.

| Type | R Ohm/km | X (Ohm/km) | Tgd (p.u.) | C (nF/km) | Snom MVA |
|---|---|---|---|---|---|
| **Buried cable 220 kV for submarine threecore 630 mm² Cu** | **0.0431** | **0.174** | **1.00E–05** | **150** | **311** |
| **Buried cable 220 kV for sub. SINGLEcore Cu 1600 mm² Cu Flat d=150 mm²** | **0.025** | **0.152** | **1.00E–05** | **240** | **460** |
| **Buried cable 380 kV for sub. SINGLEcore Cu 1600 mm² Cu Flat d=350 mm²** | **0.0176** | **0.195** | **1.00E–05** | **200** | **920** |

**Table 6.6.** Electrical Parameters for Underground/Submarine Interface

For onshore network reinforcements EirGrid's 220kV cable standard is considered.

At 400 kV, a basic 2500 mm2 solution, which has been used in the TEPCO analysis, has been considered. This technology has been already used in some projects [13].

To match the overhead line ampacity a larger than traditional cable core spacing of 700 mm, has been considered and used in the studies, shown in Table 6.7.

| **DC cable** Type | **R** Ohm/km | **X** Ohm/km | **Tgd** (p.u.) | **C** (nF/km) | **Snom** MW |
|---|---|---|---|---|---|
| **Buried cable 380 kV 2500 mm² Flat 700 mm** | **0.0105** | **0.223** | **1.00E–05** | **240** | **1500** |
| **Buried cable 220 kV 1600 mm² Flat 350 mm** | **0.025** | **0.152** | **1.00E–05** | **200** | **600** |

**Table 6.7.** Electrical Parameters for 400 and 220 kV Underground Cables



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## 6.3 COST OF TRANSMISSION INFRASTRUCTURE

### 6.3.1 Investments

The cost of transmission investments has been considered based on a European average scenario. The use of European costs is driven by the multiplicity of systems included in the investigation, which includes Ireland, Northern Ireland, Britain and France.

Three reference sources have been considered for a benchmark:

1) Realisegrid
2) Offshore Development Information System ODIS database, National Grid
3) Direct information from cable manufacture

### 6.3.2 Losses

The cost of losses has been embedded directly into the infrastructure costs. These could have been managed by the model directly into the optimisation objective function, however, in order to keep the solution faster this approach has not been utilised.

### 6.3.3 Compensation

Due to the charging and operational effects of HVAC cables, it is typical to require Var Compensation to maintain adequate voltage control.

In the case of an offshore grid, Var Compensation is optimally composed of both a fixed base level of compensation provided by Shunts and a Variable element provided by Statcoms.

In the study it is assumed that these cables should as a minimum level be reactively compensated to 80%. This is therefore assumed as part of the requirements for each circuit.

Overall Transmission investment costs of any transmission technology has been annualized including losses, by applying the Net Present Value using allowable rates of return, set by the Commission for Energy Regulation in Ireland.

At this stage 40% for AC and 80% of DC as average yearly utilisation factor has been assumed. Results are summarises in Table 6.8.





| Type | | | |
|---|---|---|---|
| **Submarine:** | | | |
| Offshore XLPE 400 kV 1200 mm2 | **328.24** | kEuro/km/y | 920 |
| 2 X Offshore XLPE 400 kV 1200 mm2 | **656.49** | kEuro/km/y | 1840 |
| Offshore XLPE 220 kV three-core Cu 1000 mm2 | **120.67** | kEuro/km/y | 311 |
| Offshore XLPE three-single-core 220 kV Cu 1000 mm2 | **216.06** | kEuro/km/y | 460 |
| **Onshore:** | | | |
| Buried Cable 220 kV for submarine threecore 630 mm2 Cu | **152** | kEuro/km/y | 311 |
| Buried Cable 220 kV for submarine SINGLEcore Cu 1600 mm2 Flat d=150 mm2 | **183** | kEuro/km/y | 460 |
| Buried Cable 380 kV for submarine SINGLEcore-Cu 1600 mm2 Flat d=350 mm2 | **207** | kEuro/km/y | 920 |
| 2 X Buried Cable 380 kV for submarine SINGLEcore-Cu 1600 mm2 Flat d=350 mm2 | **414** | kEuro/km/y | 1840 |
| Overhead 380 kV | **62** | kEuro/km/y | 1500 |
| Overhead 380 Kv operated at 275 (Power derating) | **62** | kEuro/km/y | 1031 |
| Buried cable 380 kV 2500 mm2 Flat 700 mm | **307** | kEuro/km/y | 1500 |
| Ducted Cable 380 kV | **378** | kEuro/km/y | 1500 |
| Buried Cable 220 kV 1600 mm2 Flat 350 mm | **186** | kEuro/km/y | 600 |
| Ducted Cable 220 kV | **229** | kEuro/km/y | 600 |
| Overhead 220 kV 600 mm2 Curlew | **47** | kEuro/km/y | 431 |
| Overhead 110 kV 430 mm2 ACSR bison | **32** | kEuro/km/y | 180 |
| Transformer 500 MVA 400/220 | **483** | kEuro/y | 500 |
| 2 X Buried Cable 380 kV for submarine SINGLEcore-Cu 1600 mm2 Flat d=350 mm2 | **967** | kEuro/km/y | 1000 |
| 3 Transformer 500 MVA 400/220 | **1450** | kEuro/y | 1500 |
| 6 Transformer 500 MVA 400/220 | **2900** | kEuro/y | 3000 |
| Transformer 250 MVA 220/110 | **453** | kEuro/y | 250 |
| Transformer 63 MVA 110/38 | | kEuro/y | 63 |
| Transformer 500 MVA 400/110 | **483** | Keuro/y | 500 |

| | bundled | separate | | | Extra Plattform for VSC only |
|---|---|---|---|---|---|
| (1 DC HV cables + 1 MV cable ), 500 kV 1 GW | 47 | 50 | kEuro/km/y | 1500 | |
| **2 DC XLPE CABLES, 300 kV, 1 GW** | **138** | 158 | kEuro/k/y | 1000 | |
| **(1 HVDC Converter), (2*300) kV, 1 GW Onshore** | **12327** | 12327 | kEuro/y | 1000 | |
| **(1 HVDC Converter), (2*300) kV, 1 GW Offshore** | **12327** | 12327 | kEuro/y | 1000 | 5374 |
| (1 HVDC Converter), (1*300) kV, 0.5 GW Offshore | 6164 | 6164 | kEuro/y | 500 | 3359 |
| (1 DC HV cables + 1 MV cable ), 500 kV 1 GW | 80 | 91 | kEuro/km/y | 1000 | |
| ( 1 AC/DC Converters), 500 kV 1 GW | 8893 | 8893 | kEuro/y | 1000 | |

**Table 6.8.** Annualised costs of Transmission Infrastructure

## 6.4 AC VS. DC TECHNOLOGY

There are technical and economical reasons for the selection of AC or DC technologies. However, when dealing with cable connections the area can overlap and a large 'grey zone' results, which is dependent on the power transmitted, the load factor of the connection, the technology used, the voltage level and the system configuration.

In principle, some technical issues prevent the use of AC for long distances. This is due to the AC electrical parameters of the cable which determine a large charging current and voltage rise in particular system loading. A suitable reactive compensation strategy can be utilised, but even if employed provides a limit in the range of 100-150 km for 400 and 220 kV respectively.

When exceeding these distances DC connection is necessary. The technical advantages for a DC link, is related to the transmission losses, as no skin effect and induced currents take place. However, high losses are also part of the AC/DC unit so that only after a suitable length the DC system is economically preferable.



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In Appendix A.1, a thorough analysis of the breakeven point is carried out based on an example of 1 GW transfer, point to point. The results are shown in figure 6.8. No reliability criteria are taken into account.

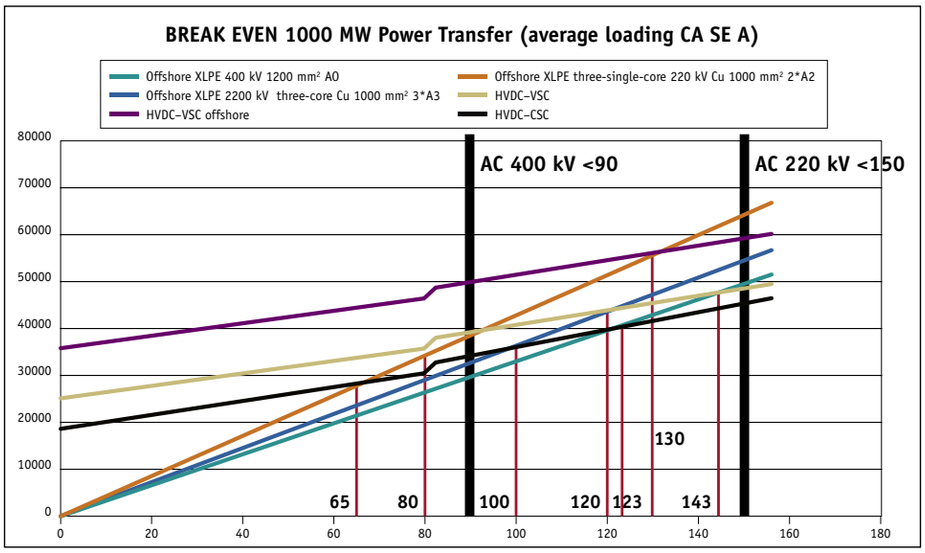


**Figure 6.8.** Cable break-even distances

The best AC cable solution is 400 kV XLPE. It benefits from a smaller number of cables to achieve the same capacity, which reduces cable laying. It should be noted, however that the feasible maximum single length is in the range of 90 km.

No break-even point exists with HVDC technology within the length that is feasible with AC cable technology.

The AC 220 kV can be extended further due to the lower charging current of the cable. The limiting distance is in the range of 150 km.

It should be noted that both 220 kV technologies (single and 3 core) are more expensive than the 400 kV in the analysis, because of the number of circuits required to deliver the same power.

The AC single core (magenta line), quickly becomes the most expensive, the break-even point is reached with LCC technology at 65 km, VSC onshore at 80 km and VSC offshore/onshore at 130 km.

Alternatively, AC three-core cable has a breakeven point at 100, 120 and above 150 km for LCC, VSC and offshore VSC, respectively.



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For distances above 150 km only DC technologies is feasible with LCC more efficient for a point to point circuit. For distances below 65 km, AC technology is feasible with AC 400 kV more efficient for a point to point circuit.

For length between 65 and 150 km, both technologies can be applied with limits on the 400 kV. VSC is always more expensive than conventional due to higher losses, however, it can be the only feasible solution for connection offshore or in an evolving from a point-to-point to meshed DC system scenario.

Based on this techno-economic analysis the offshore reinforcement options where reduced. Due to cost, LCC technology was the only option provided point to point interconnectors between onshore networks. For all circuits up to 90km with one termination offshore, both AC and VSC reinforcement options were provided, otherwise only VSC technological reinforcements were considered

## 6.5 SMART PLANNING AND OPERATION OF AN OFFSHORE GRID

### 6.5.1 AC/DC Designed Circuits

A preliminary understanding with contacts with manufactures has introduced an interesting long term planning smart technology approach, which is the capability of XLPE cable to be operated at either AC or DC. The two technologies are manufactured in a slightly different way and the insulation compound needs further treatment if it is used for DC; furthermore, insulation design parameter may be different; in AC the maximum gradient is on the internal conductor surface, whereas for DC, the gradient is temperature dependant and the average over the insulation has to be considered.

However, in principle a multipurpose compound could be designed which allows an AC infrastructure to be converted to DC and vice versa.

Due to different Electromagnetic phenomena a double circuit AC could be upgraded into three DC circuits gaining 2.5-3 times the AC overall capability. This is because the AC cable can be used at 1.7 the AC star voltage and the cable ampacity increases by 50% due to lack of skin effect and induced sheath current.

Therefore, in the longer term period, an infrastructure that is born AC because of short initial length and that becomes either not technically feasible or desirable to be operated as AC after some years, may be modified to DC operation by placing AC/DC convertor units into the circuit.



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## 6.5.2 Flexibility at Expansion Stage

'Smart' means also adaptive to different load/generation conditions. An offshore Grid could typically be subjected to wind variability conditions. In order to minimise the scale of circuits/ capacity needed, the offshore network could benefit from power flow controllers which allow a better exploitation of the infrastructure by suitably re-routing power flows on a minimum subset of connections.

This potential must be tested at the expansion phase, when the additional infrastructure costs can be included. The application of power flow controllers may results in an overall optimisation benefit reducing network expansion as well as providing further system flexibility to better optimise dispatch of conventional generation.

Flexible power flow control devices are:

- Phase Shifter Transformers
- HVDC technologies

Both smart approaches have been investigated in the studies.

## 6.5.3 Optimum Asset Management

Any offshore grids will also offer the possibility to optimise renewable resources and increase competitiveness through better integration of the European Transmission System. Compared to Onshore, Offshore infrastructure will almost certainly result in much more expensive investments as well as higher operating costs of O&M.

Therefore to maximise the investment in offshore infrastructure the system configuration to maximise energy export is also essential and inherent the methodology and assumption in the studies.



# 7 LTEP Scenarios assumptions

## 7.1 GENERAL

The Expansion Strategy Plan (ESP) studies are a technical/economical investigation of possible grid topologies aiming at transferring onshore energy produced offshore.

Different parameters may influence the results and must be considered in a scenario approach. This is aimed at understanding if:

- Common developments are envisaged;
- What technology and parameters most influences grid structure;
- And, what the optimisation process can add to reducing cost and maintaining security in the development of the Transmission System as a whole.

Data collection and a preliminary investigation was performed in EirGrid in 2008/9 and a guide [4] has been written where some cost benchmarks, available technologies and scheduling of wind farm installation offshore has been shown.

Building on this work the Irish Sea was selected as the focus on which to perform these studies. The area was selected as it is the most urgent area of investigation prompted by existing wind farm developers to be processed in Gate 3 group process, and with the exception of one applicant all offshore applications received have been in the Irish Sea. Combined these applications are already in excess of 3GW.

General parameters include the horizon and intermediate years of investigation, some economic parameters such as the discount rates, growth rates of demand and generation (in particular wind) and infrastructure investment costs.

The scenarios are broken down into three areas:

1. Basecase Scenario aimed at investigating:
   - Expansion planning grid structure;
   - Technology to be used;
   - Dynamic of Investments over the planning period 2010-2030.
2. Variants may investigate the following issues:
   - Synergy between Offshore and onshore systems;
   - Interconnection enhancements with GB and EU;

The following parameter may be used for a sensitivity analysis:

- Cost of Wind penalty factor.
- Location of new Wind farms further off east coast
- Increase injected wind power



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Results offer an indication on:

- Best places for onshore connection
- Multirole of Interconnections i.e. intermarket power trading and generation connection
- Offshore Transmission System as extension of onshore or a separate specific TSO, or connection left to customers?
- Reliability Minimum Requirements at Transmission Planning Criteria
- Type of regulatory framework to be arranged
- Offshore Grid Ownership
- Market model impact on expansion results

## 7.2 GEOGRAPHICAL AREA

The main focus of the studies is an area composed of the following countries: Ireland, Northern Ireland and Great Britain.

In order to take account the impact of the European system its network was also modelled. Part of the EHV network including North of France, Belgium, Netherlands, Germany, and Denmark were represented. Norway was also introduced as a node that could be connected into several points. A diagrammatic representation of the network is shown in Figure 7.1.

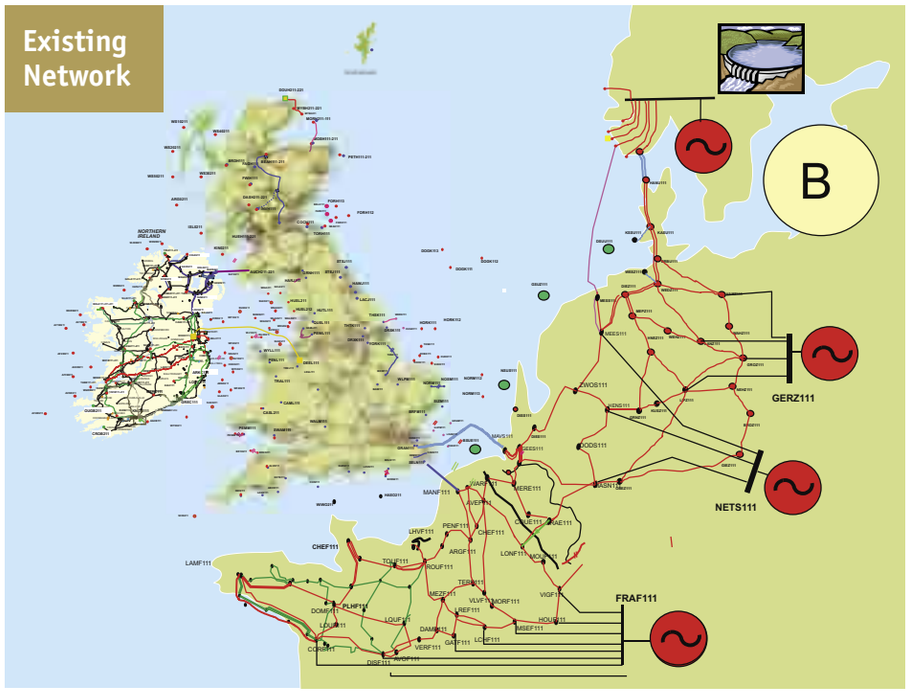


**Figure 7.1** Geographical Areas



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## 7.3 HORIZON AND INTERMEDIATE YEARS

The horizon year is fundamental to the study and to the Expansion Strategy Plan (ESP) to fulfil the targets. A shorter time frame will provide limited strategic expansion planning; a longer time frame will face too many uncertainties.

For development of an offshore grid, the major issue is 'how to accommodate a large amount of generation offshore and connect it onshore'.

Based on the present situation and the future perspectives of expansion and data provided by many International Agencies [1], [2], [6], a 20 year Interval period from 2010 to 2030 fits with the features of a LTEP study.

The following have been chosen as intermediate years: 2013, 2015, 2018, 2020, 2023, 2025, 2028, and 2030.

A horizon year of 2030 is also harmonious with the time period that EirGrid has reliable future requirements for the onshore network. These sources include data available in the framework of the GRID25 Strategy, a thorough analysis of the requirements in the Irish Grid for a number of scenarios up to 2025, and the recent output analysis from Gate 3 for scheduled infrastructure projects up to 2023.

## 7.4 WIND ONSHORE

The deployment of wind resources started in Ireland in early 2000, with the first onshore installation. Current government targets for renewables for 2020 have been specified in the context of EU directives aimed at a lower carbon emission strategy.

### 7.4.1 Republic of Ireland

The Commission for Energy Regulation in Ireland has to date issued 3 group processing campaigns known as Gates (a group of generation applications to be processed simultaneously).

Within these processes a total of 5000 MW of connection applicants were for onshore wind. In Figure 7.2 the broad location of these and amounts are shown. Information for Northern Ireland up to 2020 has also been included.



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## 7.4.2 Northern Ireland

Government targets for 2020 are in line with that of ROI, at 40 % in term of energy yearly produced by renewables. In total this is c.2000 MW, see Figure 7.2.

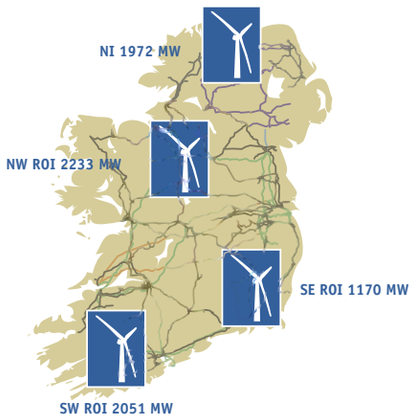


**Figure 7.2** Wind onshore in Ireland

## 7.4.3 Great Britain Onshore

Great Britain has set target values of 17% by 2020. Onshore development is progressing but is slow because of the difficulties in building new infrastructure. Consequently government targets are expected to be obtained mainly with an aggressive offshore deployment strategy. The expected amount of onshore is shown in Figure 7.3.

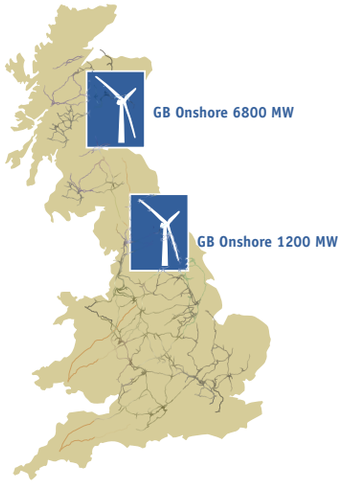


**Figure 7.3** Wind Onshore United Kingdom



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## 7.5 WIND OFFSHORE

The deployment of offshore generation is expected to become increasingly favourable, especially given the increasing difficulty in finding suitable onshore sites. Offshore wind is at an early stage of deployment, however, and many issues make its deployment a major challenge compared to onshore. Major challenges include:

- The number and scale of generation to be accommodated into the market
- The need of offshore connections
- The complex supply chain for the deployment.

### 7.5.1 Republic of Ireland

From a preliminary EirGrid investigation a potential for in excess of 5000 MW of offshore generation (based on applicants) in the Irish Sea for the All Ireland jurisdictional area was predicted. At the time studies commenced, five applicants were seeking connection for offshore wind farms in the Irish Sea.

These are shown in table 7.1.

| | | Post Gate 3 | |
|---|---|---|---|
| **Wind Developer** | Gate 3 | Phase 1 | Final |
| **Arklow Bank (Aitricity)** | none | **435** | **1100** |
| **Codlin Park (Fredolsen)** | none | **660 - 1100** | **1200 - 2000** |
| **Kish and Bray (Saorgus)** | **364** | **300** | **664** |
| **Oriel Windfarm** | **300** | | **700** |
| **Glossgorman** | none | **200** | **300** |
| **Aran Island (FSP West)** | 100 | | 300 |
| **Total** | **764** | **1160 - 1600** | **4528 - 5328** |

**Table 7.1.** Offshore windfarm applications with EirGrid at commencement of studies with breakdown

Table 7.1 shows the scale of these applicants and identifies their connection offer in Gate 3, the 1st phase of development they applied for and ultimately what their individual sites could be developed to.



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## 7.5.2 Northern Ireland

The scale and location of offshore generation in Northern Ireland is in line with the Isles Project [5], a separate cross jurisdictional government funded study which is in progress at the time of writing. Figure 7.4 shows the distribution generation assumed in the studies between ROI and Northern Ireland.

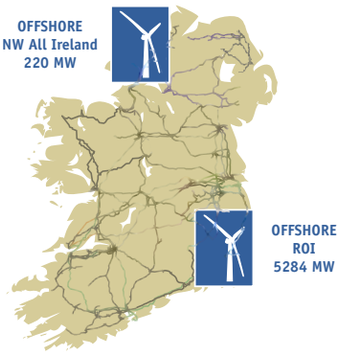


**Figure 7.4.** Wind Offshore in ROI and NI

## 7.5.3 NW-NE of Scotland

The scale and location of offshore generation in NW Scottish waters is in line with the Isles Project [5], a separate cross jurisdictional government funded study which is in progress at the time of writing. The scale and location of offshore generation in NE Scottish waters is in line with the National Grids, Offshore Development Information System[14].

Figure 7.5 shows the distribution of generation assumed in the studies in Scottish waters.

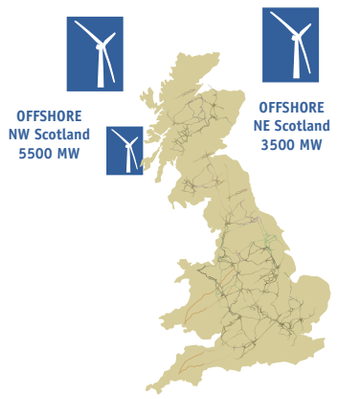


**Figure 7.5.** Wind Offshore Scotland



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### 7.5.4 Rest of Britain

Britain has launched a programme for the development of offshore wind. The Crown Estate has pursued a series of leasing rounds under which areas of seabed have been made available for the development of offshore wind farms. At present some 30 to 50 GW have been considered for development up to 2030.

#### 7.5.4.1 Irish Sea and the Channel

The offshore licences granted by the Crown Estate in the Irish Sea offers potential opportunities for further interconnection between Ireland and the UK whilst simultaneously connecting the offshore generation. These licences currently total about 11.5 GW of generation.

Furthermore, the installation in the Channel may facilitate further Britain-France interconnection, partially induced by the export from Ireland.

#### 7.5.4.2 North Sea

The North Sea area is the largest potential development area in British waters with the Dogger Bank zone alone accounting for a potential of up to 13 GW. This area is 200-300 km off the east British coast. Connection of these generators offers potential synergies to interconnect with Norway, Denmark and North of Germany.

Further south, at Norfolk and East of the Thames estuary, there are potential synergies for interconnection with Belgium, Netherlands and France.

Figure 7.6 shows the distribution of generation assumed in the studies in British waters (excluding Northern Ireland and Scottish waters).

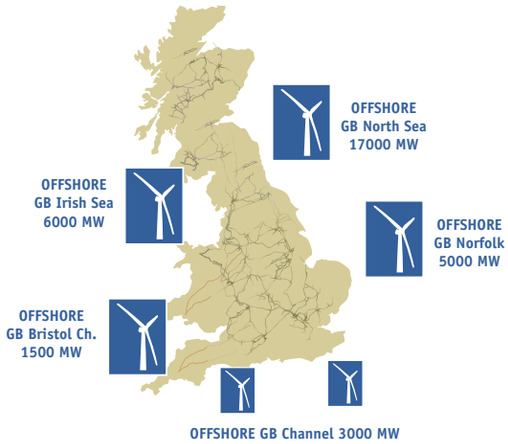


**Figure 7.6.** Wind Offshore England and Wales



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## 7.6 LOAD/GENERATION COMBINATIONS

The Load/Generation scenarios are of major importance for the results. In particular the following requisite must be fulfilled in selecting scenarios to be analysed:

- Limited number of combinations
- Representative of the worst cases
- Balanced with the probability of occurrence
- Representative of the Yearly Energy produced and consume in the system

The System is modelled in detail for Ireland, Northern Ireland and Britain. The remaining European Network is represented as equivalent.

### 7.6.1 High Wind Low Load

This combination is important in the identification of the need for interconnection. Both countries in Low Load conditions can offer an excess of wind energy which might be exported to mainland Europe.

The probability of occurrence has been calculated according to available historic wind and load data profiles.

### 7.6.2 Low Wind High Load

This combination is fundamental as it is the most frequent over the year.

In this scenario most of the conventional generation has to supply the load. The scenario therefore provides the most onerous case for the expansion to cater for conventional generation.



### 7.6.3 Intermediate periods

The aforementioned scenarios are not sufficient to fully represent the yearly behaviour.

Historic data show that some intermediate scenarios may occur in particular for windy conditions, where some conditions across Ireland and the UK do not match those in both 7.6.1 and 7.6.2. This mainly depends on the geographical distribution of the wind resources.

Three intermediate scenarios have been considered which better integrate the equivalent yearly behaviour:

- (HWind-Med Load)AI with (HWind Low Load)GB
- (HWind-Low Load)AI with (HWind-Med Load+Med Wind- Low Load)GB
- (HWind-Med Load+Med Wind- Low Load) AI with (HWind-Low Load)GB

### 7.6.4 Summary and weighting factors

Scenarios summary and weighting factors are shown in table 7.2.

| Scenarios | ALL IRELAND | GREAT BRITAIN | Hours |
|---|---|---|---|
| 1 | HWind-Low Load | HWind-Low Load | 589 |
| 2 | HWind-MedLoad+MedWind-Low Load | HWind-Low Load | 609 |
| 3 | HWind-Low Load | HWind-MedLoad+MedWind-Low Load | 385 |
| 4 | HWind-MedLoad+MedWind-Low Load | HWind-MedLoad+MedWind-Low Load | 3705 |
| 5 | Low High Load | Low High Load | 3473 |

**Table 7.2.** Scenarios Summary and Weighting factors

In Table 7.3 the definition of High Medium and Low is shown, as well as the probability of each Wind and Load scenario to occur.

| Scaling coefficient | Wind AI+NW SCO | WIND G B | Load |
|---|---|---|---|
| high | 1 | 1 | 1 |
| medium | 0.37 | 0.34 | 0.58 |
| low | 0.11 | 0.11 | 0.37 |
| **Probability** | **Wind AI+NW SCO** | **WIND G B** | **Load** |
| high | 0.15 | 0.10 | 0.23 |
| medium | 0.58 | 0.58 | 0.46 |
| low | 0.28 | 0.32 | 0.32 |

**Table 7.3.** Scaling factors and probability

Note that Wind in the NW of Scotland has been considered synchronised with the All Ireland Wind Curves.



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### 7.6.5 Energy

To cross-check the previous assumptions, an Overall Yearly Energy calculation must be performed on the discretised curve assumed to represent the Load Generation scenarios combinations.

This is important to obtain a good estimate of the Production Costs in the objective functions. An incorrect energy estimation would favour or oppose the benefit of expanding the network infrastructure.

The results are shown in Table 7.4

| 2030 5GW | | Installed MW | Energy GWh/y | Capacity Factor % |
|---|---|---|---|---|
| **ROI** | Wind Offshore Irish Sea | 5284 | 16967 | 0.367 |
| | Wind Onshore | 5401 | 17376 | 0.367 |
| **NI** | Wind Offshore NWest | 0 | 0 | 0.000 |
| | Wind Onshore | 1952 | 6282 | 0.367 |
| **GB** | Wind Offshore Irish Sea + Channel | 9077 | 26495 | 0.333 |
| | Wind Onshore East | 24353 | 76648 | 0.359 |
| | Wind Onshore | 1205 | 3793 | 0.359 |
| **Scotland** | Wind Offshore NWest | 5438 | 17496 | 0.367 |
| | Wind Onshore NEast | 3565 | 11220 | 0.359 |
| | Wind Onshore | 6895 | 21701 | 0.359 |
| **Loads** | Load AI | 8875 | 49200 | 0.633 |
| | Load GB | 74284 | 409862 | 0.630 |

**Table 7.4.** Yearly Energy and capacity factor of Generation and Load



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## 7.7 INCORPORATING GATE3/GRID25 REINFORCEMENTS

Gate 3 is the third round of connection offers that are currently being issued to generators under the Group Processing Approach (GPA). The GPA allows for strategic processing of generation applications for grid connection and was introduced by the Commission for Energy Regulation (CER) in 2004. It allows applications to be processed by the System Operators (EirGrid and ESB Networks) in groups or batches known as 'Gates'.

The Gate 3, ITC Programme is an innovative methodology adopted by EirGrid to assess the capability of the transmission grid to accommodate Gate 3 applications on a firm basis.

The results of the ITC Programme were incorporated in our models in order to represent the growth of the onshore generation in the Republic of Ireland. The generation added each year and the accumulative figure can be seen in the graphic below. The ITC used GRID 25 identified reinforcements to alleviate network problems to permit additional generation to be connected to the network.

Consequently GRID 25 is also incorporated with the use if the ITC Programme results.

### 7.71 Additional Reinforcements from GATE3/GRID25

The addition of all the generation requires both new reinforcements in the network as well as the enhancement of existing links (upratings). The new lines scheduled were included as a candidate in the list (please refer to Methodology section). The uprating of lines were included as implemented according to the year of its completion. This can be seen in Figure. 7. 7.

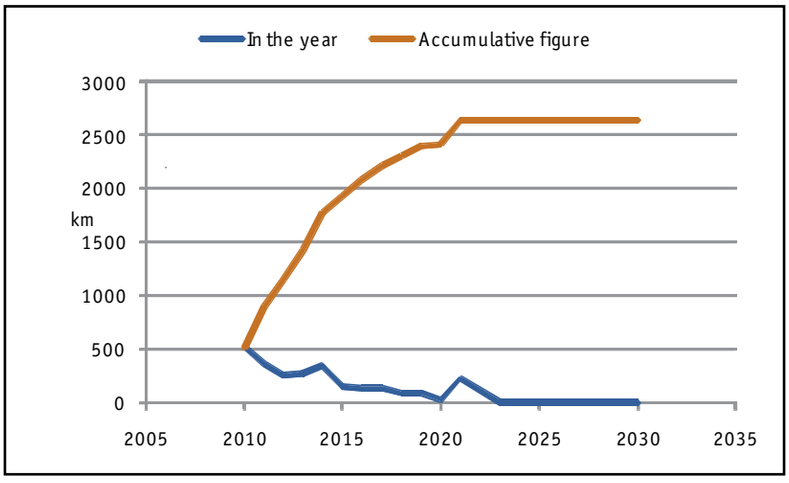


**Figure 7.7**. Grid Reinforcements as for ITC results



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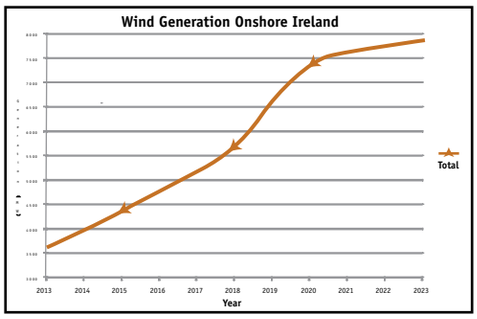
## 7.7.2 Wind Expansion Onshore

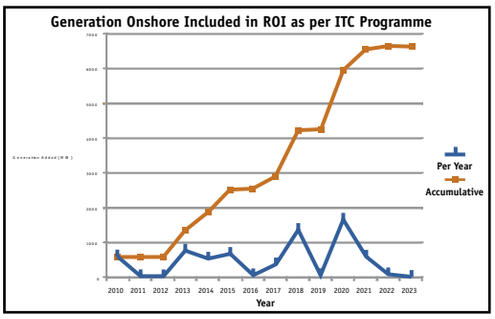
The assumptions have considered the lead-time it takes to construct a reinforcement.

Combining these with different Load/Generation Scenarios and Wind Conditions, a feasible expansion installation program of Wind Onshore has been obtained for ROI. Fig.6.8a shows the results.

For Northern Ireland, a proportional figure has been considered, see Figure.7.8b.




a) ITC Results




b) +NIE Onshore

**Figure 7.8.** Wind Onshore Expansion in AI

## 7.7.3 Wind Expansion Offshore

In order to define an expansion strategy for offshore, an assumption has been taken on the pace of installation, for each site. A quadratic curve has been used in order to account for a learning curve on the technology and the supply chain for manufacturing and installing, i.e. factory location, ports, barges, platforms.

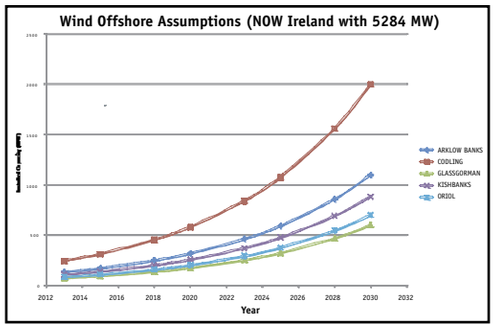



**Figure 7.9.** Expansion Offshore in ROI



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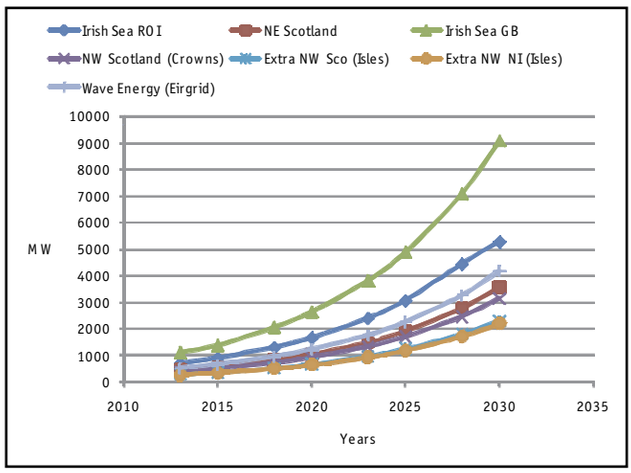


**Figure 7.10.** Expansion Offshore

## 7.7.4 Business as Usual Generation Expansion for Comparisons

A conventional generation expansion strategy, Business as Usual (BasU), has also been considered in order to compare with the performance of adding in offshore generation. In this case NO Offshore expansion is undertaken in the Irish Sea within jurisdictional waters of ROI. Extra Thermal Gas (CCGT) Generation has been added onshore to the model to provide the same energy as the offshore generation. Figure 7.11 shows location and size of the thermal units.

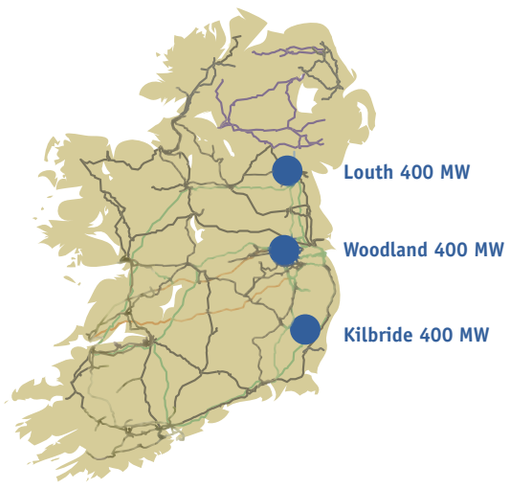


**Figure 7.11.** Conceivable Generators



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# 8 Irish Only Results

In the following paragraph, results are shown in terms of Offshore Expansion strategy over the planning period. In Figure 8.1, Candidate Network and Existing Grid are shown. Solving a Mixed Integer Problem (MIP) optimisation problem, the optimum Expansion Strategy is selected in order to connect the offshore wind generation gathering platforms to the All Ireland transmission system.

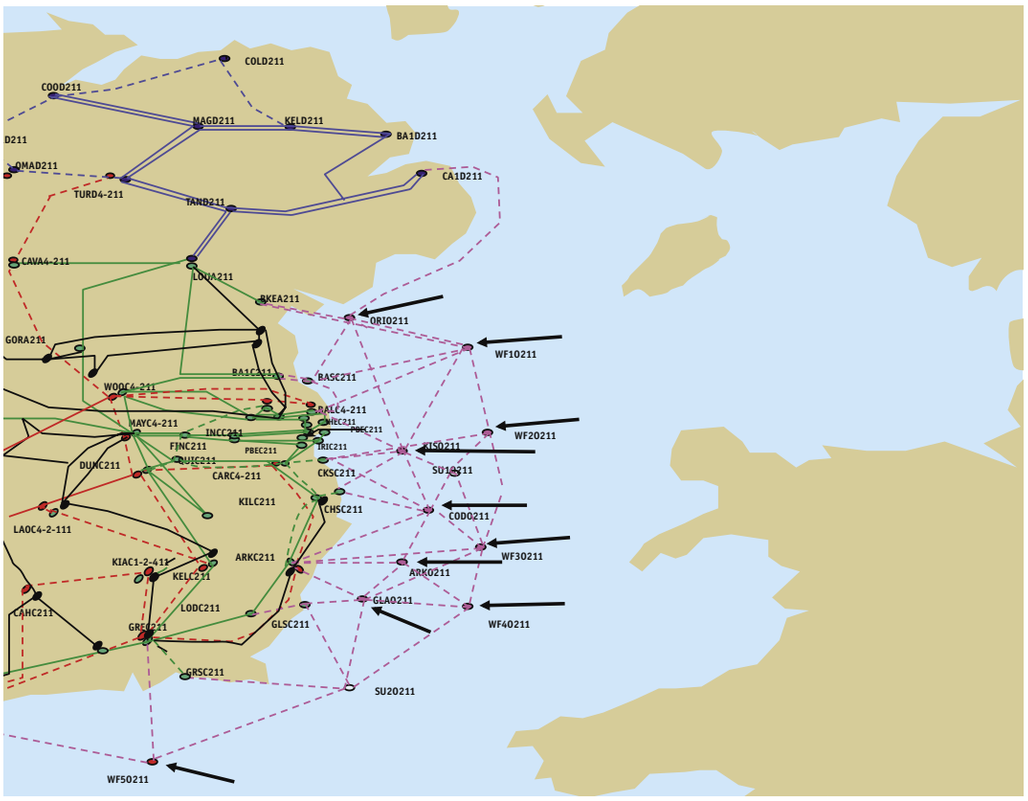


**Figure 8.1.** Existing Grid (solid lines) and Candidate Network (broken lines)



## 8.1 LONG TERM EXPANSION (ESPAUT)

### 8.1.1 Scenario BaseCase

Results of the Expansion Strategy Plan (ESP) are shown in Figure 8.2.a, b, c, for the 2020, 2025 and 2030 year respectively.

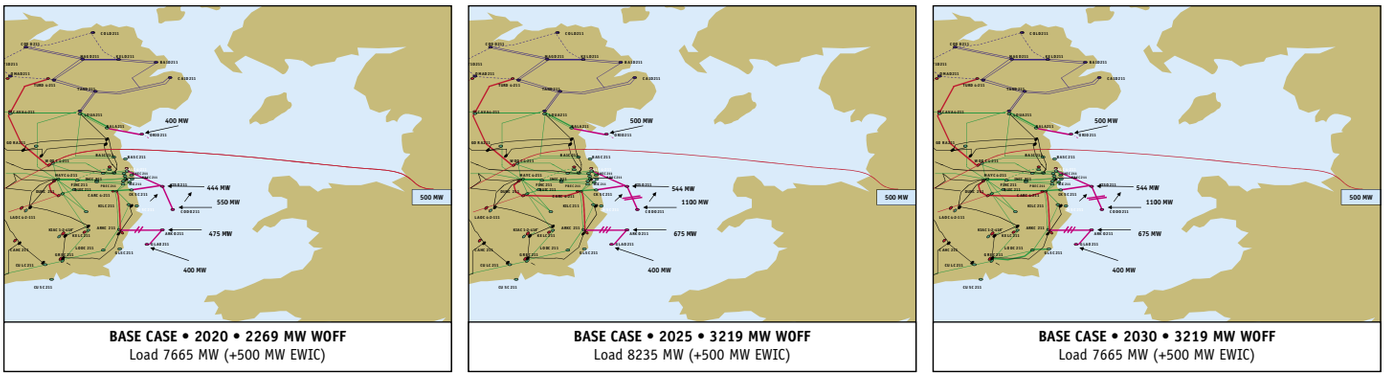


**Figure 8.2.** ESP for 'BASECASE' scenario, 2020, 2025, 2030

This scenario examines the Expansion Strategy Plan (ESP) for 5 offshore generation sites producing c.32GW of generation by 2030.

The results show a mainly radial network initially connecting the offshore generation into the network in 2020.

However, a meshed solution has been selected across Dublin Bay, using Kish Banks offshore platform as a multiple connection point. Note that this meshed structure is also used to connect Codling Park Wind Farm.

The offshore connections are supplemented by a 400 kV onshore circuit between Arklow-Carrickmines and Dunstown-Maynooth, and also favoured is the already initiated Tandragee-Woodland 400kV interconnector circuit.

Further south, Arklow connection is developed to allow for Glass Gorman wind farm connection as well.

By 2025, the same offshore structure is kept with additional reinforcements strengthening from Codling to Kish and on the Arklow to shore routes.

Onshore, the 400 kV strategy progresses with further connection from Carrickmines to Dunstown, creating a southern 400 kV ring of the Dublin metropolitan Area.



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No further expansion is observed for 2030.

During the whole expansion period Oriel is radially connected. This is probably due to the relative distances of this gathering platform from the others and the connection option into Louth-Tandragee, which has a reduced loading as a result of the Turleenan - Woodland (North-South) 400kV Interconnector. These impacts do not encourage any synergies with other offshore connections as well as onshore reinforcements.

The offshore looped connection from Balgriffin 220kV stations through Kish Banks Platform to Carrickmines 220kV stations is an example of synergies with the onshore system. This reinforcement fulfils a number of objectives, namely:

- Connecting Kish Banks generation
- Shortening Codling Parks generation connection
- Solving congestion in the Dublin Area

### 8.1.1.1 Focus on Carrickmines-Kish-Balgriffin

With reference to Figure 8.3 the east offshore by pass of the Dublin area is shown. This corresponds to the 2020 stage of the Expansion strategy.

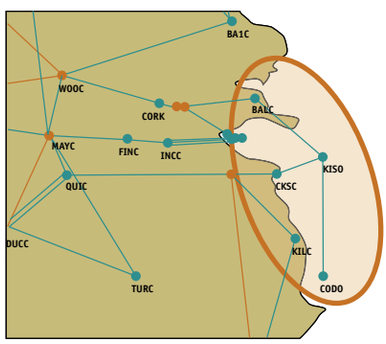


**Figure 8.3.** East Coast Dublin Bay focus



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In figure 8.4 a DC load flow solution is represented of one of the six Load/Generation scenarios selected for the Optimal Power Flow (OPF) expansion analysis (see Table 7.3).

This is the High South (HS) - Low North (LN) wind onshore condition coupled with Low Wind OFfshore (LWOF) which creates high North to South power flows onshore. At this time of the demand is High Load in the All Island system (HLAI)

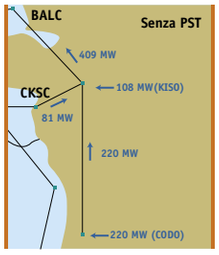


**Figure 8.4.** DC load flow of HS-LN-HLAI-LWOF scenario

It is interesting to note that despite injection of power from either Kish Bank or Codling Park wind farms, the flows on the Carrickmines to Kish Banks circuit are from onshore to offshore and they keep flowing to Balgriffin, using effectively the offshore East Dublin Bypass.

This demonstrates the use of the offshore network to support the onshore network and therefore the symbiotic nature of the onshore and offshore networks in this case.

## 8.1.2 Scenario Mid5

Results of the Expansion Strategy Plan (ESP) are shown in Figure 8.5.a, b, c, for the 2020, 2025 and 2030 year respectively.

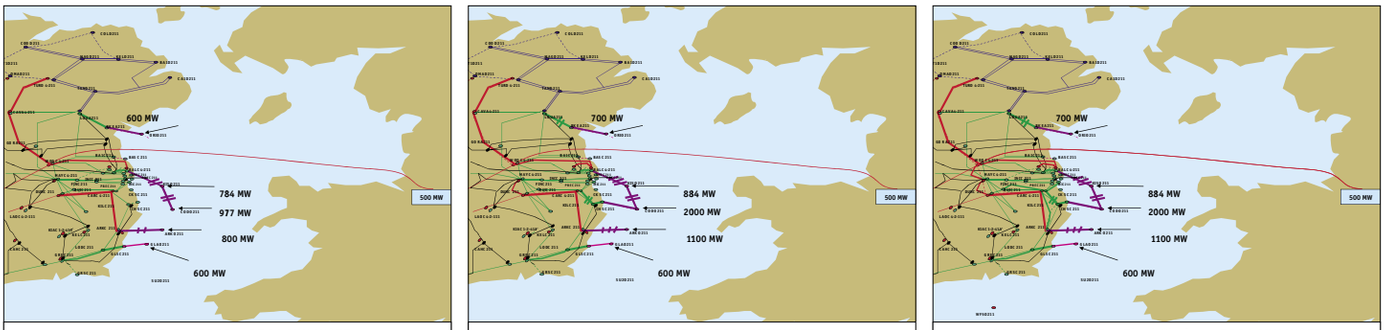


**Figure 8.5.** ESP for 'MID5' scenario, 2020, 2025, 2030



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This scenario examines the Expansion Strategy Plan (ESP) for the previous 5 offshore generation sites from the BASECASE scenario, but at a higher installed capacity of c.5.2GW of generation by 2030.

In year 2020 the offshore solution is basically radial. In two areas multiple circuits deliver offshore power into Arklow and Balgriffin respectively, triggering the development of 400 kV circuits onshore in the North and the South of Dublin as well as the North-South Interconnector.

However by 2025 a mesh is generated East of Dublin Bay similar to the BASECASE network, connecting Codling offshore generation site to Charlesland (Kilpedder); this strategy is completed by a 220 kV double circuit line from Kilpedder to Carrickmines 220kV station.

Further 400 kV is developed in the North from Balgriffin-Huntstown and in the West between Dunstown-Maynooth.

Finally, in 2030, further 400kV reinforcement on the western side Dublin creates a predominately 400kV ring around Dublin, part of which is offshore. This ring creates a very strong network development for both delivery of power into and around Dublin from both onshore and offshore sources.

## 8.1.3 Scenario MID10

Results are shown in figure 8.6a, b and c. It should be noted that compared to MID5, this scenario shares the same total amount of offshore wind on ten locations instead of five.

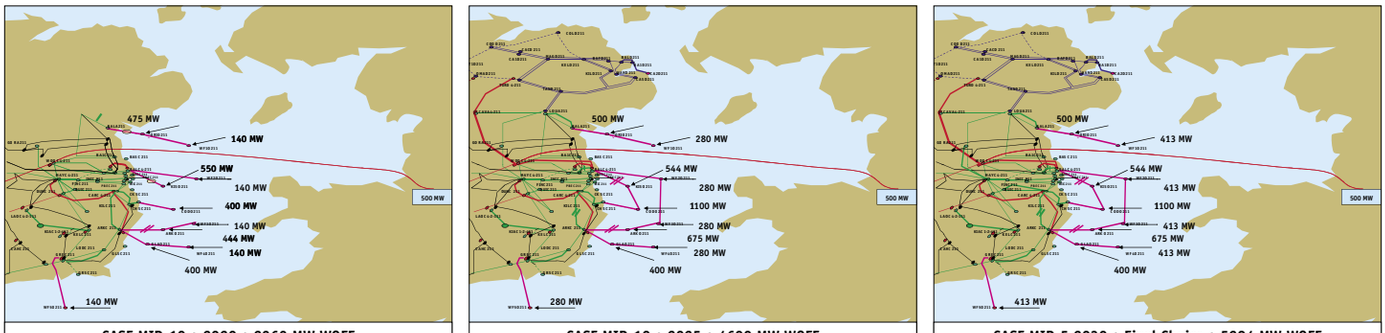


**Figure 8.6.** ESP for 'MID10' scenario, 2020, 2025, 2030

This scenario examines the Expansion Strategy Plan (ESP) for 10 offshore generation sites, 5 of which are defined by the applications received, and 5 for geographic variation in a row of further offshore, in total producing c.5.2GW of generation by 2030.



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In year 2020 similar to both the CASECASE and MID5 scenarios a full radial strategy is chosen for the offshore network. Most of the radial circuits from the shoreline connect at least two of the offshore generation sites. Consequently even as a radial circuit, offshore stations have the potential to economically become a centre for the development of further infrastructure to connect additional generation.

Onshore, 400 kV expansion is chosen where large offshore power is injected into the network, i.e. Arklow, Charlesland, Carrickmines, Balgriffin, to southwest ring circuits, from Arklow-Carrickmines-Dunstown-Maynooth and an initial North Ring circuit from Balgriffin-Huntstown.

Outside of Dublin the upper part of Turleenan - Woodland (North-South) Interconnector is selected, to permit power flows to be driven North-West to the Northern Ireland network.

By year 2025, an east of Dublin offshore by-pass appears this arrangement accommodates the increasing Wind in Kish Bank and Codling Park in a flexible way to the onshore network in the Dublin area. As a result the power can not only be directed to the North and South of Dublin, but also allow an onshore power transfer across Dublin via this link. It should be noted that there is reinforcement on the Kish Bank-Balgriffin Offshore connection.

Elsewhere an offshore radial structure is maintained.

Onshore, 400kV reinforcement from Balgriffin-Woodland and the second part of the North-South Interconnector is developed. Together these reinforcements, coupled with the offshore reinforcement of Kish-Balgriffin make a low impedance path which would permit easy power transfer from the Kish and Codling offshore generating sites into the onshore network.

By 2030 further increases to the offshore meshed network topology is included. This primary reason is likely to be the increasing generating capacity installed in the offshore five locations. However this increase of offshore network capacity also provides enhanced flexibility for power transfer onshore through the symbiotic nature of the transmission network.

Structurally the offshore network in 2030 is very similar to that of the MID5 network with the difference being the dispersed double circuit link across the east of Dublin from Balgriffin - Kish Banks - Codling - Carrickmines and also Balgriffin to Arklow via two of the additional offshore (WF2 & 3) generating sites further offshore from Codling and Kish Banks. Combined these circuits provide approximately the same capacity as the single Balgriffin - Kish Banks - Codling - Carrickmines offshore link in the MID5 scenario and can therefore be considered comparable.

Similarly onshore, further 220kV reinforcement on the western side Dublin from Maynooth to Gorman creates a convoluted predominately 400kV ring around Dublin, part of which is offshore. This ring creates a very strong network development for both delivery of power into and around Dublin from both onshore and offshore sources.

Other 220 kV connections are also chosen from Arklow to Carrickmines and Carrickmines-Quinsborough.

In all the years WF1 and WF5 are radially connected. Due to the distance from the other gathering platforms no economic synergies are found.



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## 8.2 SHORT TERM EXPANSION

Due to the limited number of Scenarios, the ESPAUT solution is a first screening of the strategic development plan of infrastructures. However the planning process requires further technical/ economical investigation, see figure. 8.7.

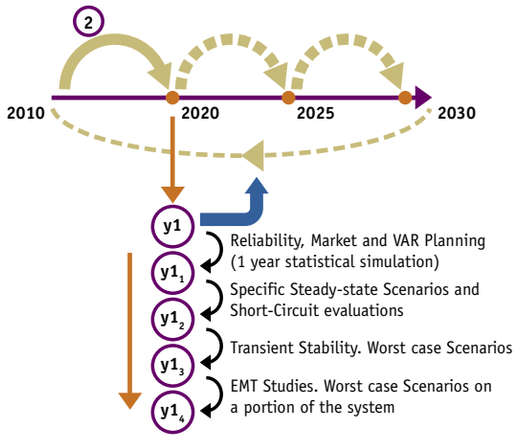


**Figure 8.7.** DC load flow of HS-LN-HLAI-LWOF scenario

### 8.2.1 Reliability and MARKet (REMARK)

The Expansion Strategy Plan of the 'BASECASE' scenario has been examined with REMARK tool developed by ERSE for the Statistical Reliability evaluation.

In table 8.1 the Expected Energy Not Served (EENS) reliability Index is shown.

| | 2020 | 2025 | 2030 |
|---|---|---|---|
| A | 1.75 | 1.83 | 1.92 |
| B | 2.47 | 2.58 | 2.71 |
| C | 6.36 | 5.37 | 6.60 |
| D | 7.85 | 8.39 | 8.40 |
| O | 0.00 | 0.00 | 0.00 |
| System | 5.12 | 4.88 | 5.42 |

**Table 8.1.** Expected Energy Not Served*1.e-5
(Area A-C is in RoI, D in NI, and O is offshore)



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For all the years, the solution show a Reliability Index in the region of '5 nine' (99.999%) reliability either for the whole system or uniformly distributed through the regions in Ireland.

Although there is no fixed criteria in Ireland for EENS, internationally a reliability of "5 nine" is considered a reliability target.

In Table 8.2 Generation dispatches are shown with increasing network constraints by 2020, 2025 and 2030 respectively.

| Generation | Area | Unconstrained | Energy [GWh] | Costs [Euro] | add section | Energy [GWh] | Costs [Euro] | add Interconnections | Energy [GWh] | Costs [Euro] | real system | Energy [GWh] | Costs [Euro] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TotalConventional | A | | 234 | 11007 | | 234 | 11007 | | 234 | 11041 | | 243 | 11530 |
| TotalConventional | B | | 12332 | 662373 | | 12332 | 662373 | | 12311 | 661208 | | 11987 | 643108 |
| TotalConventional | C | | 5319 | 175808 | | 5319 | 175808 | | 5341 | 177005 | | 5644 | 194168 |
| TotalConventional | D | | 2455 | 132149 | | 2455 | 132149 | | 2455 | 132162 | | 2480 | 133633 |
| TotalConventional | O | | 0 | 0 | | 0 | 0 | | 0 | 0 | | 0 | 0 |
| TotalConventional | System | | 20340 | 981337 | | 20340 | 981337 | | 20342 | 981417 | | 20354 | 982439 |
| TotalFixed | A | | 502 | | | 502 | | | 502 | | | 502 | |
| TotalFixed | B | | 785 | | | 785 | | | 785 | | | 785 | |
| TotalFixed | C | | 1582 | | | 1582 | | | 1582 | | | 1581 | |
| TotalFixed | D | | 0 | | | 0 | | | 0 | | | 0 | |
| TotalFixed | O | | 0 | | | 0 | | | 0 | | | 0 | |
| TotalFixed | System | | 2869 | | | 2869 | | | 2869 | | | 2868 | |
| TotalWind | A | | 5707 | | | 5707 | | | 5708 | | | 5707 | |
| TotalWind | B | | 4857 | | | 4857 | | | 4858 | | | 4850 | |
| TotalWind | C | | 2858 | | | 2858 | | | 2859 | | | 2857 | |
| TotalWind | D | | 681 | | | 681 | | | 681 | | | 682 | |
| TotalWind | O | | 5701 | | | 5701 | | | 5697 | | | 5694 | |
| TotalWind | System | | 19805 | | | 19805 | | | 19803 | | | 19790 | |
| TotalAITS | | | 43013 | | | 43013 | | | 43013 | | | 43012 | |

**Table 8.2a** Generation Results 2020

| Generation | Area | Unconstrained | Energy [GWh] | Costs [Euro] | add section | Energy [GWh] | Costs [Euro] | add Interconnections | Energy [GWh] | Costs [Euro] | real system | Energy [GWh] | Costs [Euro] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TotalConventional | A | | 259 | 12591 | | 259 | 12591 | | 261 | 12672 | | 266 | 12921 |
| TotalConventional | B | | 12711 | 684692 | | 12711 | 684692 | | 12687 | 683403 | | 12349 | 664786 |
| TotalConventional | C | | 5770 | 204473 | | 5770 | 204473 | | 5797 | 205923 | | 6112 | 223827 |
| TotalConventional | D | | 2607 | 141568 | | 2607 | 141568 | | 2607 | 141564 | | 2636 | 143258 |
| TotalConventional | O | | 0 | 0 | | 0 | 0 | | 0 | 0 | | 0 | 0 |
| TotalConventional | System | | 21347 | 1043324 | | 21347 | 1043324 | | 21352 | 1043562 | | 21364 | 1044792 |
| TotalFixed | A | | 499 | | | 499 | | | 499 | | | 499 | |
| TotalFixed | B | | 781 | | | 781 | | | 781 | | | 781 | |
| TotalFixed | C | | 1573 | | | 1573 | | | 1571 | | | 1571 | |
| TotalFixed | D | | 0 | | | 0 | | | 0 | | | 0 | |
| TotalFixed | O | | 0 | | | 0 | | | 0 | | | 0 | |
| TotalFixed | System | | 2853 | | | 2853 | | | 2851 | | | 2851 | |
| TotalWind | A | | 5656 | | | 5656 | | | 5663 | | | 5656 | |
| TotalWind | B | | 4819 | | | 4819 | | | 4821 | | | 4813 | |
| TotalWind | C | | 2812 | | | 2812 | | | 2810 | | | 2812 | |
| TotalWind | D | | 676 | | | 676 | | | 676 | | | 676 | |
| TotalWind | O | | 8041 | | | 8041 | | | 8031 | | | 8032 | |
| TotalWind | System | | 22004 | | | 22004 | | | 22000 | | | 21989 | |
| TotalAITS | | | 46204 | | | 46204 | | | 46204 | | | 46203 | |

**Table 8.2b** Generation Results 2025



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| Generation | Area | Unconstrained | Energy [GWh] | Costs [Euro] | add section | Energy [GWh] | Costs [Euro] | add Interconnections | Energy [GWh] | Costs [Euro] | real system | Energy [GWh] | Costs [Euro] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Conventional | A | | 351 | 18150 | | 351 | 18150 | | 354 | 18322 | | 352 | 18106 |
| Total Conventional | B | | 14346 | 775932 | | 14346 | 775932 | | 14315 | 774249 | | 13944 | 754343 |
| Total Conventional | C | | 6817 | 259971 | | 6817 | 259971 | | 6850 | 261805 | | 7204 | 282056 |
| Total Conventional | D | | 3101 | 170447 | | 3101 | 170447 | | 3101 | 170438 | | 3133 | 172217 |
| Total Conventional | O | | 0 | 0 | | 0 | 0 | | 0 | 0 | | 0 | 0 |
| Total Conventional | System | | 24615 | 1224500 | | 24615 | 1224500 | | 24620 | 1224814 | | 24632 | 1226723 |
| Total Fixed | A | | 502 | | | 502 | | | 502 | | | 502 | |
| Total Fixed | B | | 785 | | | 785 | | | 785 | | | 785 | |
| Total Fixed | C | | 1584 | | | 1584 | | | 1583 | | | 1583 | |
| Total Fixed | D | | 0 | | | 0 | | | 0 | | | 0 | |
| Total Fixed | O | | 0 | | | 0 | | | 0 | | | 0 | |
| Total Fixed | System | | 2871 | | | 2871 | | | 2870 | | | 2870 | |
| Total Wind | A | | 5714 | | | 5714 | | | 5720 | | | 5714 | |
| Total Wind | B | | 4866 | | | 4866 | | | 4868 | | | 4860 | |
| Total Wind | C | | 2865 | | | 2865 | | | 2863 | | | 2865 | |
| Total Wind | D | | 683 | | | 683 | | | 682 | | | 683 | |
| Total Wind | O | | 8144 | | | 8144 | | | 8134 | | | 8133 | |
| Total Wind | System | | 22272 | | | 22272 | | | 22267 | | | 22254 | |
| Total All TS | | | 49758 | | | 49758 | | | 49758 | | | 49756 | |

**Table 8.2c** Generation Results 2030

A focus on the wind energy is interesting, see table 8.3. values are in GWh.

In any year, the network is capable of delivering most of the available wind energy. The quality index, Wind Energy Not Generated (WENG) is calculated in the last column. This is the ratio on a yearly basis between the wind energy available, calculated in the unconstrained case, and the energy effectively delivered once the whole transmission system is included. It is worth noting that in any area the WENG is kept around 0.1% in the worst cases.

| 2020 | | Unconstrained | | Unconstrained | | Interconnections | | HV Grid | WENG (%) |
|---|---|---|---|---|---|---|---|---|---|
| Total Wind | A | 5707 | | 5707 | | 5708 | | 5707 | 0.0075% |
| Total Wind | B | 4857 | | 4857 | | 4858 | | 4850 | 0.1451% |
| Total Wind | C | 2858 | | 2858 | | 2859 | | 2857 | 0.0350% |
| Total Wind | D | 681 | | 681 | | 681 | | 681 | 0.0161% |
| Total Wind | O | 5701 | | 5701 | | 5697 | | 5694 | 0.1188% |
| Total Wind | System | 19805 | | 19805 | | 19803 | | 19790 | 0.0747% |

| 2025 | | Unconstrained | Unconstrained | Interconnections | HV Grid | WENG (%) |
|---|---|---|---|---|---|---|
| Total Wind | A | 5656 | 5656 | 5663 | 5656 | 0.0117% |
| Total Wind | B | 4819 | 4819 | 4821 | 4813 | 0.1349% |
| Total Wind | C | 2812 | 2812 | 2810 | 2812 | 0.0117% |
| Total Wind | D | 676 | 676 | 676 | 675 | 0.0326% |
| Total Wind | O | 8041 | 8041 | 8031 | 8032 | 0.1062% |
| Total Wind | System | 22004 | 22004 | 22000 | 21989 | 0.0716% |

| 2030 | | Unconstrained | | Unconstrained | | Interconnections | | HV Grid | WENG (%) |
|---|---|---|---|---|---|---|---|---|---|
| Total Wind | A | 5714 | | 5714 | | 5720 | | 5714 | 0.0126% |
| Total Wind | B | 4866 | | 4866 | | 4868 | | 4860 | 0.1290% |
| Total Wind | C | 2865 | | 2865 | | 2863 | | 2864 | 0.0084% |
| Total Wind | D | 683 | | 683 | | 682 | | 682 | 0.0483% |
| Total Wind | O | 8144 | | 8144 | | 8134 | | 8133 | 0.1357% |
| Total Wind | System | 22272 | | 22272 | | 22267 | | 22254 | 0.0791% |

**Table 8.3.** Wind Energy Delivered



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Finally, a focus on the offshore part, in particular the east Dublin looped connection through the Kish Banks generation platform.

| Year | Node 1 | Node 2 | Flow | | | | | Constraint Violation | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Average (MW) | % | 1 Sigma p.u. | Duration (Hours) | MAX (MW) | Duration (h) (Hours) | Cost (Euro/MW) |
| 2020 | Kish Bank | Carrickmines | 100 | 10.85 | 76 | 8740 | 937 | 0.74 | 48.17 |
| 2020 | Balgriffin | Kish Bank | 282 | 30.55 | 173 | 8706 | 891 | 0 | 0 |
| 2025 | Kish Bank | Carrickmines | 173 | 18.71 | 161 | 8738 | 1489 | 9.38 | 47.56 |
| 2025 | Balgriffin | Kish Bank | 366 | 39.59 | 237 | 8695 | 1443 | 92.69 | 24.86 |
| 2030 | Kish Bank | Carrickmines | 168 | 18.18 | 159 | 8738 | 1489 | 10.16 | 51.38 |
| 2030 | Balgriffin | Kish Bank | 372 | 40.3 | 247 | 8695 | 1443 | 131 | 23.11 |

**Table 8.4** Results on the Kish Bank looped connection

It is interesting to note that the connection of Balgriffin-Kish Bank circuit is loaded between 30 and 40% on a yearly basis. On average this is approximately double the typical loading on transmission circuits in Ireland and shows a high utilisation factor of the network.

This is of particular interest as the wind load factor of the Offshore Wind farm is below 30%. The extra load is due to the use of the Carrickmines-Kish Bank- Balgriffin circuits' route as part of the South to north flow across Dublin in particular Load/Generation combination scenarios. This has been also described in Figure 8.4.

Moreover, this has the effect of reducing the Kish-Carrickmines circuit loading; therefore the natural injection of power from Kish Banks generation is partially compensated by the South to North flows.

## 8.2.2 Reactive Planning Estimation

An offshore grid must be composed of subsea cables; due to the relative short distances and the meshed structure it is not straightforward either technically or economically to understand whether AC or DC technology is optimum for this purpose.

EirGrid/ERSE position was to start from an AC approach; consequently the reactive impact on the power system has to be considered carefully and in a large variety of scenarios. Voltage control will be a major issue because of:

- the large extension of the offshore grid
- the variability of the wind power resources and therefore of the infrastructure loading.

In some cases a technical limit could be reached which may suggest some offshore reinforcements need to be selected to be DC or embedded DC.



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This analysis is not part of the LTEP study and therefore was followed up with a comprehensive power system analysis investigation involving steady state voltage, dynamic transient stability and electromagnetic transient's investigations.

Analysis of one of these aspects, the steady state voltage has been performed. This analysis has been undertaken with the electric parameters of Table 8.4.

| | R [Ohm/km] | X [Ohm/km] | C [nF/km] | tgd p.u. | S [MVA] |
|---|---|---|---|---|---|
| Three Core 220 kV 1000 mm2 Cu | 0.057 | 0.09 | 200 | 1.00E-04 | 320 |
| Single Core 220 kV 1200 mm2 Cu | 0.046 | 0.07 | 198 | 1.00E-04 | 460 |
| Single Core 400 kV 1400 mm2 Cu | 0.043 | 0.07 | 216 | 1.00E-04 | 930 |

**Table 8.4.** Electrical parameters of transmission offshore alternatives

The analysis has investigated the previous Expansion Strategy Plan (ESP) for the previous BASECASE, MID5, and MID10 2030 scenarios, with circuits of an assumed 930 MVA capacity and to investigate this network utilising the cables or multiples of in Table 8.4 to provide this capacity.

Results of each scenario are shown in terms of total kilometres of circuit and Reactive Power produced at nominal voltage.

### 8.2.2.1 Reactive Requirements Basecase

In Figure 8.8 the extension of BASECASE ESP scenario is shown in term of kilometre of circuit for different alternatives.

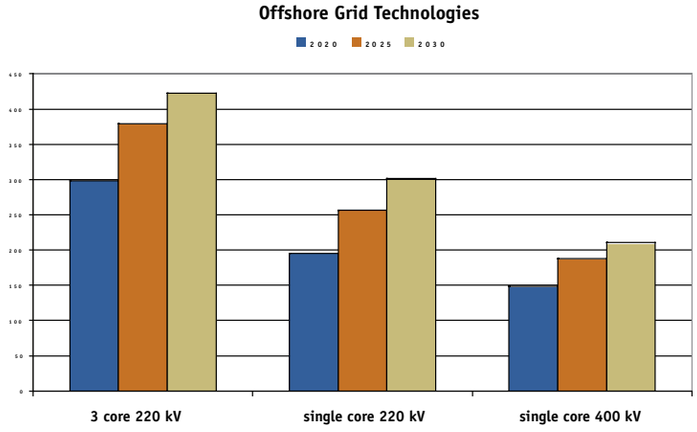


**Figure 8.8.** Kilometres of circuit for BASECASE



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In this scenario between 200 and 400 km is the variation in cable length as a result of moving between each cable type from Table 8.4

Base on this network, and estimation of the reactive power to be compensated is shown in Figure 8.9. Note that cable reactive power depends on the square of the voltage.

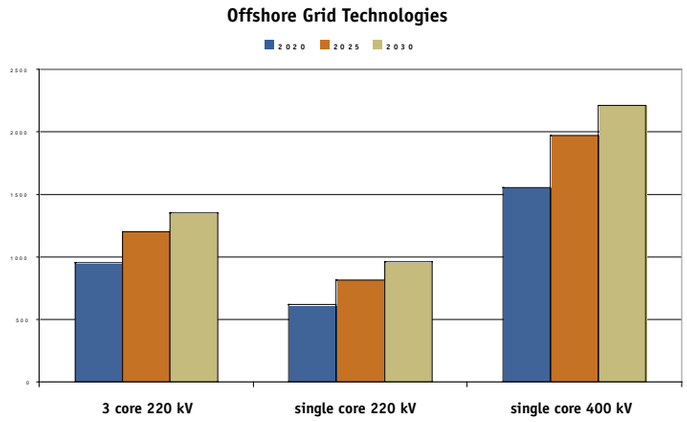


**Figure 8.9.** MVAr requirements of the circuits for BASECASE

Not surprisingly, the major impact is due to use of a 400 kV offshore strategy, as oppose to a 220kV as the 220 kV single core has the least reactive impact.

### 8.2.2.2 Reactive Requirements MID5

Figure 8.10 shows the MID5 ESP scenario results.

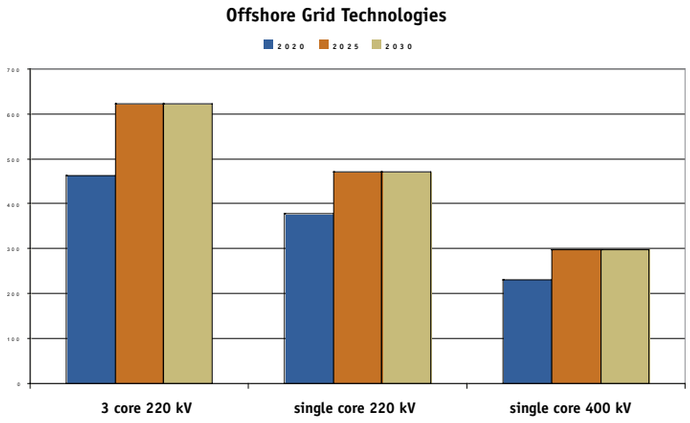


**Figure 8.10.** Kilometres of circuit for MID5



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In this scenario between 300 and 700 km is the variation as a result of moving between each cable type from Table 8.4. The increase is due to the increase of the installed wind power.

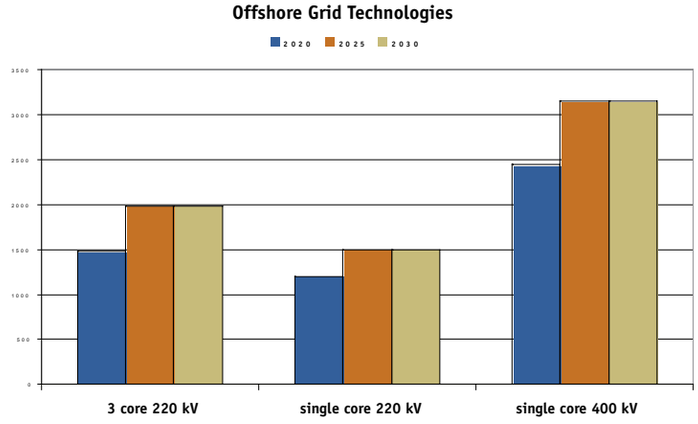


**Figure 8.11.** MVAr requirements of the circuits for MID5

In term of reactive impact single core 220 kV is slightly better than the three core alternative.

### 8.2.2.3 Reactive Requirements MID10

Due to a more dispersed wind offshore generation expansion, the requirements in this ESP scenario for the variation in cable type is the widest of those analysed. In 2030 it is expected between 600 and 1000 km, see Figure 8.12.

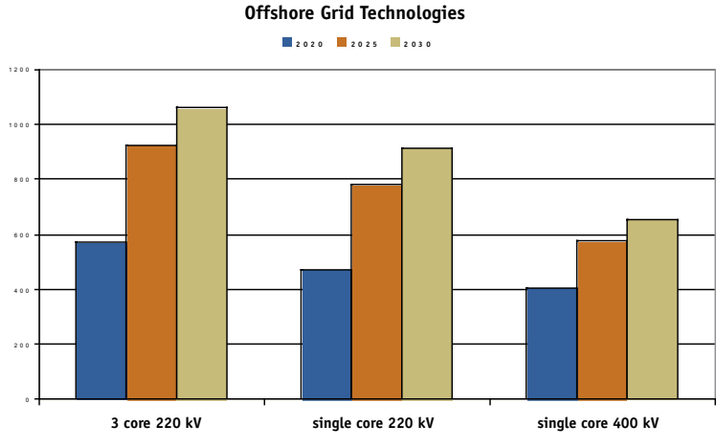


**Figure 8.12.** Kilometres of circuit for MID5



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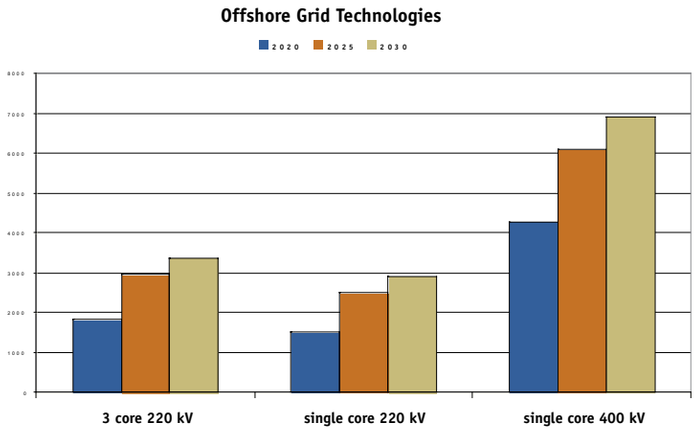


**Figure 8.13.** MVAr requirements of the circuits for MID5

As a consequence, a larger reactive impact is expected especially if a 400 kV offshore strategy is used.

This scenario shows the highest reactive impact, especially when developed using the 400 kV cables.

However the 220 kV alternatives are similar, with single core less marginal less than a three-core strategy.

## 8.2.3 AC Reactive Power Strategy Conclusion

To provide absolute certainty, the reactive compensation issue for the amount of AC cable in these scenarios would require a more detailed and robust examination study in order to verify that the ESP's could be sustainably connected from only the All Island transmission network.

However, based on the findings of the studies completed as part of this analysis and based on other utilities experience [TEPCO], [Singapore], it seems to be possible in principle to operate an underground transmission system with a reasonable extension.

For instance:

- Singapore:
  - 650 km of 220 kV Cable
  - 111 km of 400 kV Cable
- TEPCO:
  - 1700 km of 275 kV Cable
  - 80 km of 500 kV Cable



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Since no issues have been identified and the offshore expansion AC solutions for the All Island transmission network are well within other world experience of transmission system operation, a DC alternative does not appear to be necessary for any of the scenarios (BASECASE, MID5, and MID10).

Furthermore, considering the relative short distances between platforms and the shore, it is not considered to be economically viable for this application.

## 8.2.4 Harmonic Analysis

Following the steady state reactive planning analysis and setting up the suitable compensation strategy an Electromagnetic Transient analysis has been performed on a simplified ESP of the Irish Context, see Figure 8.14.

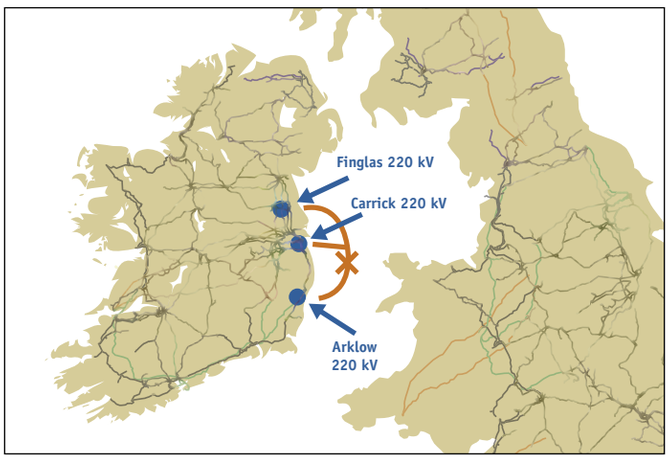


**Figure 8.14.** Example for EMT Analysis

The 220 kV Single Core Cable Technology is considered in the expansion. Three scenarios are considered:

- The Existing Grid without Offshore
- The Existing Grid with Offshore of Figure 8.14
- The previous scenario in N-1 Contingency on Arklow-Codling Connection.

A frequency scan was performed on the main 220 kV nodes of the area, aiming at finding the impact of the Offshore Grid and the potential for parallel resonances conditions in some of the assets.



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As thoroughly investigated in [5], severe conditions for operation are considered when the natural frequency approaches a low multiple of the Power Frequency, say 300 Hz and below. This is due to the potential Temporary Overvoltage's with high energy contents that might be triggered by some switching procedures that may introduce low harmonic orders stresses, i.e. transformer energisation.

The results are shown in figure 8.15.

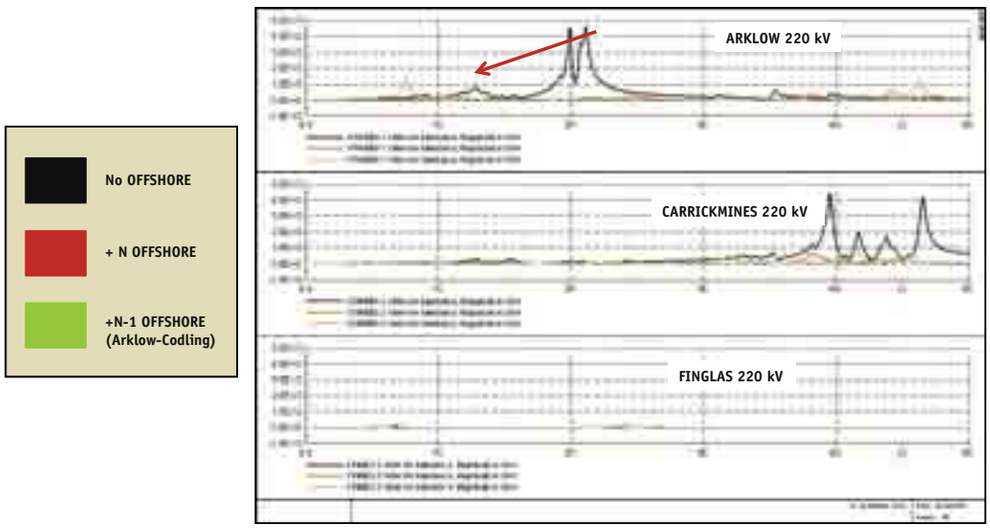


**Figure 8.15.** Results of Frequency Scan

With no offshore, Arklow and Carrickmines show parallel resonances at 1000 and 2000 Hz respectively. Finglas does not show any significant resonance within 3000 Hz. These values are well above critical frequencies.

When introducing the offshore grid, which is submarine cable based, the effect is twofold:

- The New Capacitive based grid lowers the natural system frequency
- The structure of the Grid, radial or meshed may increase or further decrease the natural frequency as a consequence of decreasing the short circuit impedance of the Onshore Grid nodes.

With reference to the red curve, it is worth noting that for Arklow and Carrickmines, the assumed offshore grid will strengthen the two nodes; this effect counteracts against the capacitance effect.

Particular care must be taken during outages. Considering the N-1 case of the Arklow-Codling connection, the cable in radially connected to Arklow, negating the strengthened effect at Arklow, creating a more onerous case to analyse.



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For this scenario Carrickmines and Finglas are still strengthened by the offshore network, whilst for other outages they are not. Therefore all outages should be considered.

Comparing the Green curves in Figure 8.15, it is worth noting a decreasing of the natural frequency in Arklow towards 300 Hz. The calculated 1000 Ohm impedance may not amplify the overvoltage significantly however, a time domain simulation of this scenario, which is out of the scope of this study, should be performed.

Similar effects may be observed in Finglas for the Balgriffin-Kish outage.

It should be noted that Carrickmines always benefits from a meshed offshore grid.



# 9 Irish Interconnection results

After initial analysis with candidate reinforcements from Ireland the same investigations were repeated for the MID5 scenario with a new candidate list of reinforcements. These included options to develop the offshore network into an interconnected network with other European countries notably Britain and France.

In order to do so the existing network model has to been extended to the neighbouring countries; in particular:

- The complete 400 kV and 275 kV 2010 Britain transmission network has been introduced using National Grid Web site data;
- The northern part of the RTE transmission network has been represented in terms of existing 400 kV grid as indicated in RTE web;
- The Belgium, Netherland, north of Germany, Denmark 400 kV transmission network has been considered according to information from web site documents;
- The Norwegian transmission network has been represented as equivalent nodes.

For computation reasons, the load and generation models for mainland European are equivalents; three equivalent load/generation nodes have been modelled to account for France, Netherlands and Germany.

The fundamental reason for modelling a wider northern European equivalent network is that exporting/importing power from/to Ireland will have a cascading impact on the need for grid expansion not only in Britain, but also the British interface with mainland Europe especially in the Channel and the Thames Estuary as well as the North Sea.

Therefore it is important for accuracy in the Ireland network expansion to realistically model transmission capacity available onshore in neighbouring countries considering, if any, grid expansion projects elsewhere in Europe.

The philosophy for the wider offshore candidate reinforcements is identical to Irish only analysis. Existing strategic network plans were used and supplemented with other conceivable potential reinforcement options.



In Figure 9.1 the list of candidates is geographically shown. About 1470 new reinforcements have been assumed over the Irish Sea and the North Sea for the purely AC scenario.

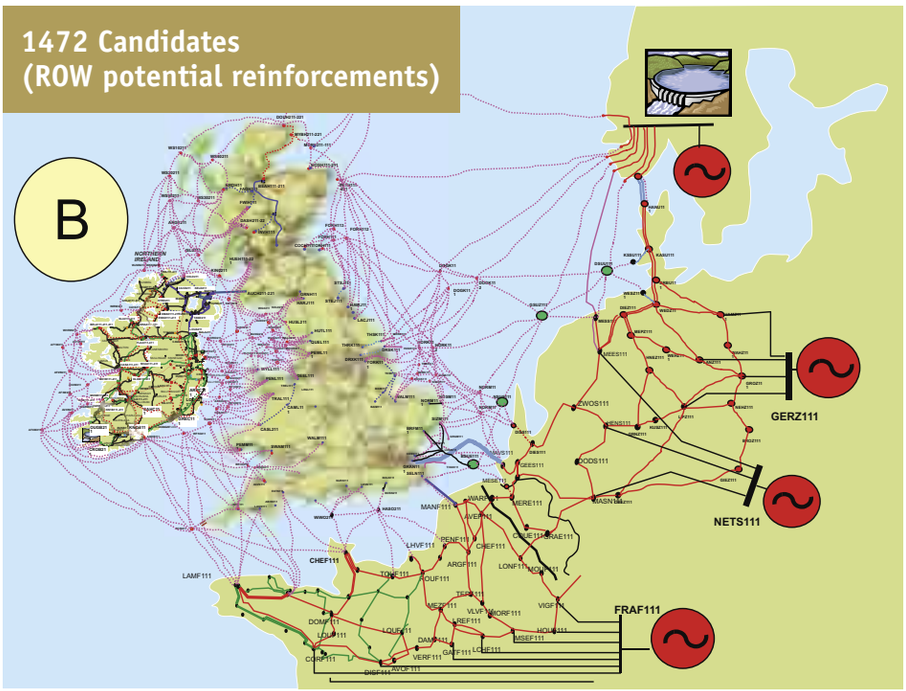


**Figure 9.1.** Geographical representation of candidate reinforcements

Although it is recognised that a full AC strategy cannot be technically fulfilled, due to long distances of some candidate connections and interconnections, the first examination used only AC candidate reinforcements. The rationale for an AC only first examination was a practical one due to the computation resources and modelling requirements of examining different technologies simultaneously.

However, this model gives indicative information about the overall interconnected system behaviour, particularly:

- Congested areas;
- Preferential exporting routes from Ireland to Britain and to Europe;
- Wind delivered and curtailed;
- A conservative value of Grid utilisation factor;
- The size of infrastructure expansion plan.



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## 9.1 Examined Sensitivities and Cases

Given the number of assumptions required in order to perform the analysis for the offshore network topologies some sensitivity analysis has been performed to identify the criticality of the individual assumptions on the overall results.

This is particularly pertinent given the uncertainties over a 20 year planning period.

The approach for this examination is to select individual key assumed parameters, which are varied to determine whether there is any variation in the resulting network topologies, the scale of any changes, and draw conclusions regarding the impact of changes in assumptions.

### 9.1.1 Use of Transmission Technology

According to the description in Chapter 6, different transmission technologies have been considered.

### 9.1.2 Generation Expansion Plans

The analysis examined variations on the previous Irish offshore generation network topographies, as a consequence of changing Irish generation expansion plans and those of adjacent transmission network operators, considered geographically close.

This analysis considered both Northern Ireland and Scotland's generation offshore expansion plan strategies which could interact with the Irish transmission network.

The MID5 scenario was utilised for this analysis given it represented the maximum generation potential at the existing applicants' sites totalling a 5 GW offshore potential off the East Coast of Ireland in five locations.

Sensitivities on the generation expansion strategies have been considered:

- Further increase of Eastern Offshore generation by 2 GW;
- Isles Project assumptions;
- Ocean Energy Deployment.

The focus of this sensitivity analysis is to provide EirGrid with information on whether there is a core network structure regardless of changes in generation expansion plans or whether the resulting network topographies are highly variable as generation targets change.



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### 9.1.2.1 Scenario MAX10 interconnection

Figure 9.2, shows the existing network with the assumed extra 5 future locations shown.




**Figure 9.2.** Geographical Location of extra 2 GW offshore

Future locations are marked 'WF10211' to 'WF50211'. These locations provide for uncertainties due to the location of potential extra offshore facilities that may arise following a future tranche of generation in the Gate process including extra offshore generation.

### 9.1.2.2 Isles Project Assumptions

In June 2010, the Scottish Government launched a comprehensive Offshore Grid study aiming at evaluating the Renewable Resource available in the area included by the West of Scotland, Northern Ireland and the Irish Sea [15]. Part of the scope is also to identify the suitable transmission technology to permit connections to be made which fully exploit the resources. The study boundaries extended to include a large proportion of the All Island network territorial waters.



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Figure 9.3, location and amount of extra potential offshore resources are shown for both Northern Ireland and Northwest of Scotland.

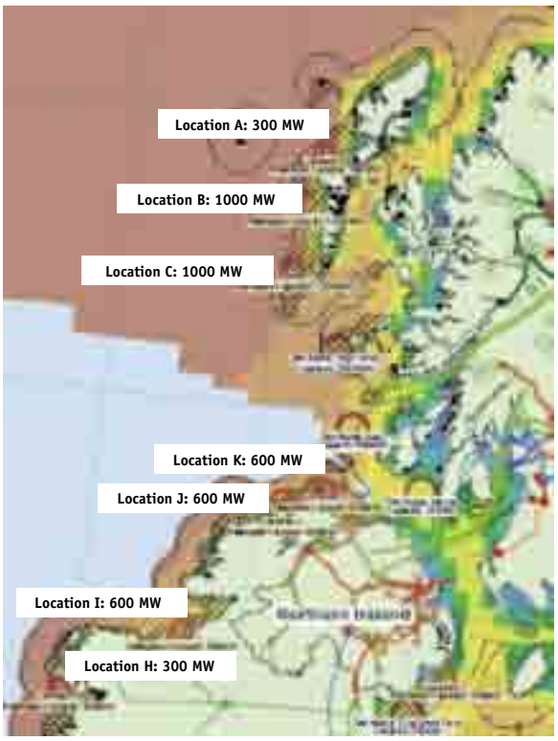


**Figure 9.3.** Extra offshore Resources in NW Scotland and Northern Ireland

### 9.1.2.3 Ocean Energy Deployment

Recent technological advances have put attention on all forms of ocean energy. In Ireland, wave energy has already been deployed in pilot test projects and a specific Renewable Energy Feed In Tariff (REFIT) was announced in 2008 for offshore generation.

Based on currently available information it is anticipated that the greatest resource for development for non-wind ocean energy is expected to be off the West Coast of Ireland (see Figure 9.4). This is in line with the findings of the offshore Strategic Environmental Assessment (SEA) performed for SEAI [16].

Although the governments Energy White Paper of 2007 set out a target of 500MW by 2020, a higher quantity can be reasonable expected over a longer period up to 2030. Using the profile of growth in onshore windfarms experienced from the early introduction of wind energy, a figure of 4GW of wave energy was predicted for 2030.



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Given the scale of generation being examined in the Irish Sea, 4GW is considered of sufficient size to trigger any potential changes in the general network topography rather than simply augmenting the existing network in Ireland.

Based on existing wave resources 4GWs falls well within development potential off the west coast of Ireland.

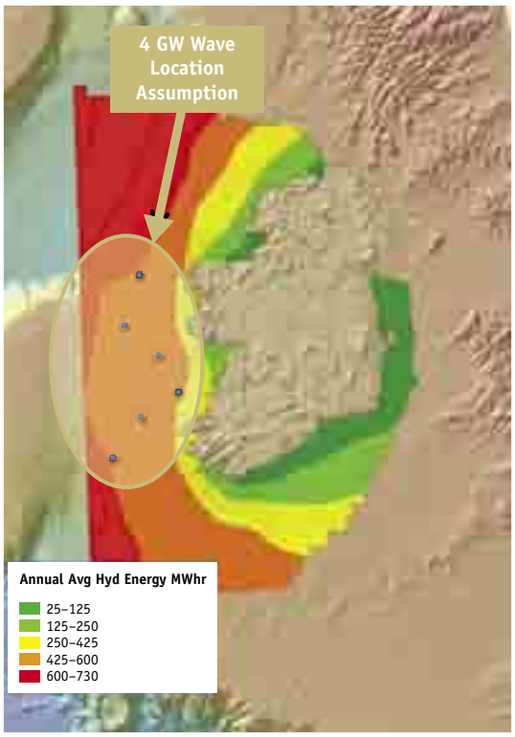


**Figure 9.4.** Wave offshore resources west coast of Ireland



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## 9.2 SENSITIVITY ANALYSIS SCENARIOS

Table 9.1 shows the Scenarios which have been examined in this analysis.

| | Tran.Altern | | | Wind Offshore | | Penalty Factor | Storage | PSTs | OCEAN | INTERMEDIATE |
|---|---|---|---|---|---|---|---|---|---|---|
| | Onshore | Offshore | ROI | NI | NW-SCO | | | | | STEPS |
| BASECASE | OHL | AC | 5 GW 5 Location | 0 | 2 GW | 10000 | NO | NO | NO | YES |
| VARIANT PF1 | | AC | 5 GW 5 Location | 0 | 2 GW | 0 | NO | NO | NO | YES |
| VARIANT PF2 | | AC | 5 GW 5 Location | 0 | 2 GW | REAL | NO | NO | NO | YES |
| BUSINESS AS USUAL | | AC | 0 | 0 | 2 GW | | NO | NO | NO | YES |
| VARIANT T1 | OHL | AC/DC | 5 GW 5 Location | 0 | 2 GW | REAL | NO | YES | NO | NO |
| VARIANT T2 | UGC | AC/DC | 5 GW 5 LOCATIONS | 0 | 2 GW | REAL | NO | YES | NO | NO |
| VARIANT WOFF1 | OHL | AC/DC | 7 GW 10 Location | 2.2 GW (ISLES) | 5.3 GW (ISLES) | REAL | NO | YES | NO | NO |
| VARIANT WOFF1-T2 | OHL | AC/DC | 7 GW 10 Location | 2.2 GW (ISLES) | 5.3 GW (ISLES) | REAL | NO | YES | YES | NO |

**Table 9.1.** Scenarios examined

The purpose of sensitivity analysis is to examine individual parameters effects on the Expansion Strategy Plans for offshore development.

Consequently every combination of parameters is not analysed but rather a smaller number of scenarios which adequately demonstrate the effect of changing the parameters.

The sequences of studies were selected to allow for understanding of the assumed impact of key parameters in order of their perceived significance. Following this examination order an appropriate (possibly revised) value for each parameter could be fixed in subsequent studies into the sensitivity of another parameter.

In particular, the penalty factor was revised to 'REAL' after the preliminary investigation, and offshore technology was revised to 'Mixed AC/DC', as some connections are not technically feasible with AC cable technology.

REAL identifies the scenario with penalty factors corresponding to the Renewable Feed-in Tariff (REFIT), available in each jurisdiction.

After initial investigations into the impact on the intermediate steps of development, it was found that an economy in the sensitivity analysis could be reasonably be made by only studying and comparing the ESP subset (i.e. 2030) for changes to the parameters. This is proposed to become a benchmark for the methodology and for future thorough investigation of other scenarios and cases.

### 9.2.1 List of candidates and subset

As explained in chapter 4, the first step in the process is to determine a subset of reinforcements for the Horizon year (2030) from the reinforcement options available, see Figure 9.5. This subset can be different depending on the sensitivities and cases.



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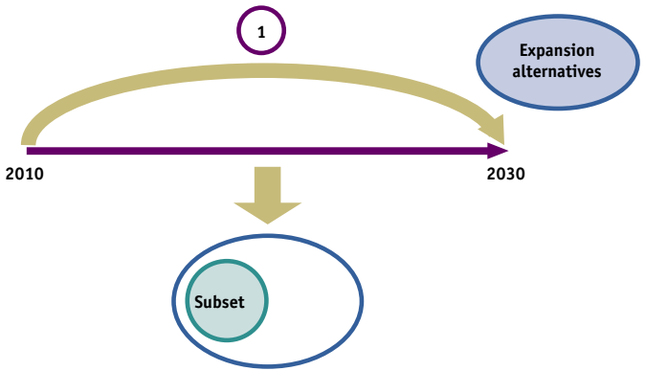


**Figure 9.5.** Definition of the Subset of Candidates

### 9.2.1.1 Max 10 Interconnection + Isles

Figure 9.6 subset results are shown. This scenario has been obtained using the Isle Project assumptions and the Extra 2GWs in the Irish Sea. Penalty factor for wind curtailment has been considered 10000 Euro/MWh.

This is the most general case to be considered and selects the largest number of candidate reinforcements in any of the sensitivity analysis. This ESP therefore is significant reduction of the candidate list but offers a high potential for further refinement. Therefore, the resulting subset in Figure 9.6 will be considered for all the cases except for the 'Wave Energy Scenario'. As a consequence of this approach the sensitivity scenarios can also be easily compared with each other.

Note no N-1 contingency has been applied in the North-Sea connections. The impact of doing so is expected to have negligible impact on the results in the network topography around the Island of Ireland.

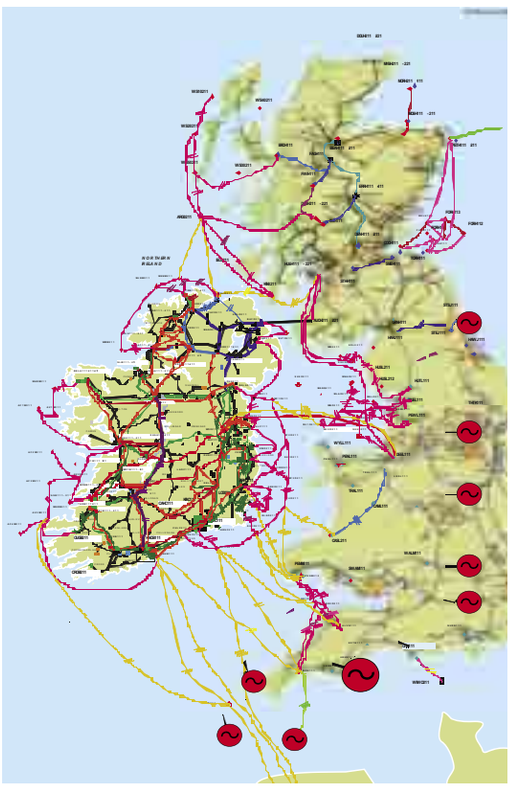

**Figure 9.6.** Subset of Elements MAX10+Isles



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### 9.2.1.2 MAX10 Interconnection plus Isles and Wave Energy

In this analysis a further step increase to the north of Ireland is applied with an additional 2GW of generation off the west coast of Scotland and 4GW of ocean energy off the west coast of Ireland on to the Max10 scenario shown in figure 9.7.

The solution refers to the case of 10000 Euro/MWh penalty factors, therefore no curtailment happens and all the assumed wind and wave energy are delivered.

With the 6GW increase in additional generation above the MAX10 scenario in 9.1.2.1, the network in the western side of Ireland is heavily developed with additional circuits, required to transmit the power produced.

The much greater change in geographical dispersion of the generation beyond the Irish Sea to the North of Ireland, provides a high probability for change to the network topography both onshore in the Irish All Island network and Britain, and also the offshore network in the Irish Sea

However the topography of the offshore network has not fundamentally changed, but instead additional circuits have once again mainly augmented the existing network increasing the size of the capacity to transmit power between nodes on the system.

It should be noted that the analysis commenced with the full list of candidate reinforcements available and no pre-selections.

This adds further conviction to the solutions robust nature, demonstrating the structure in the Irish Sea to be flexible to deal with a major step change in generation and its location. This supports the low probability of structural change to the network topography as a result of changes in the scale of offshore generation and also its geographical location.

The symbiotic nature of the onshore and offshore networks appears to become even stronger, with each network complementing and supporting each other reducing the overall need for additional assets by sharing their capabilities.

Reinforcement of the westerly side of the Irish onshore network to link generating sources of the north Irish coast line to interconnection with France permits a two way flow of power dependent on prevailing market prices and generation availability.

On the easterly side of the Irish onshore network from Waterford/Wexford to Louth a highly meshed onshore/offshore network has developed to transmit power in all directions not only north-south (or vice-versa) either onshore or offshore, but also east/west offshore (or vice-versa) for national or international consumption.



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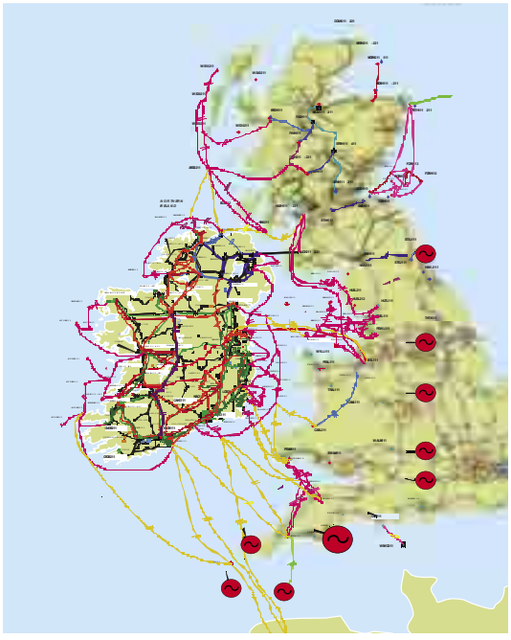

**Figure 9.7.** Subset of Elements MAX10+Isles+Wave Energy

## 9.3 INTERMEDIATE YEARS

Following the Subset definition, as explained in chapter 5, the expansion analysis is performed for each intermediate year, with the proper Load/Generation conditions. The existing network for each intermediate year is incrementally updated with the expansion results of the previous year, see Figure.9.8.

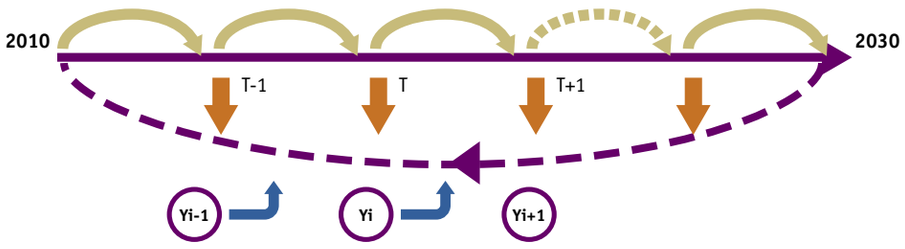


**Figure 9.8.** Intermediate Steps procedure

The purpose is to provide a timeline of the new reinforcements which are needed to meet the 2030 target.



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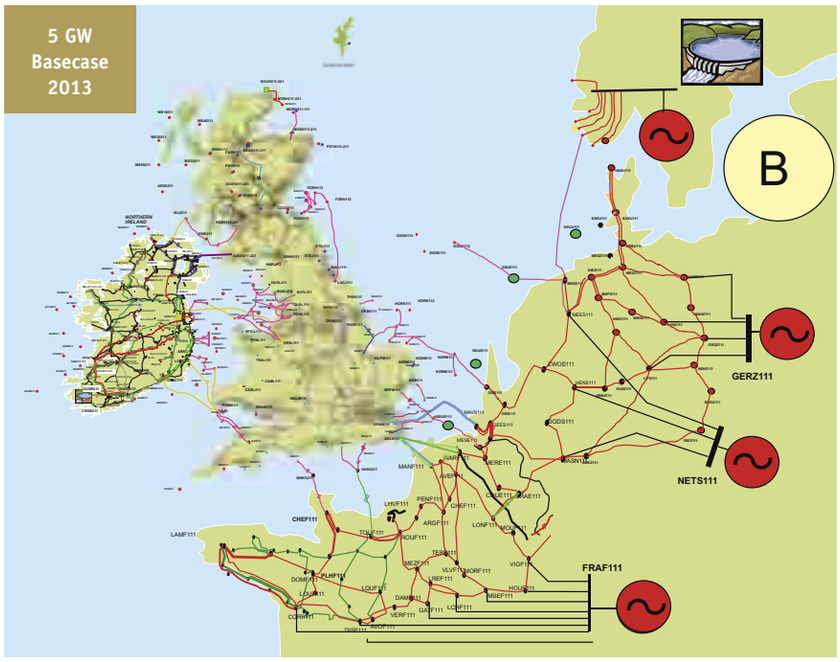
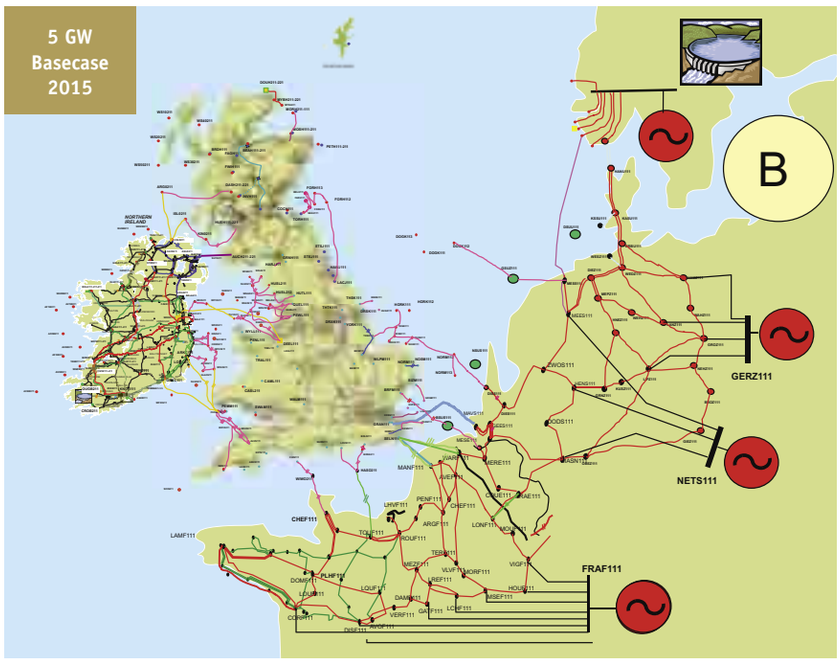
## 9.3.1 Scenario MID5 Interconnection

This scenario examines the Expansion Strategy Plan (ESP) for 5 offshore generation sites producing c.5GW of generation by 2030. Isles and Wave Energy are not included. Wind curtailment penalty is 10000 Euro/MWh.




**a) Year 2013**




**b) Year 2015**

**Figure 9.9.** Intermediate Steps solution of MID5 Interconnection Scenario



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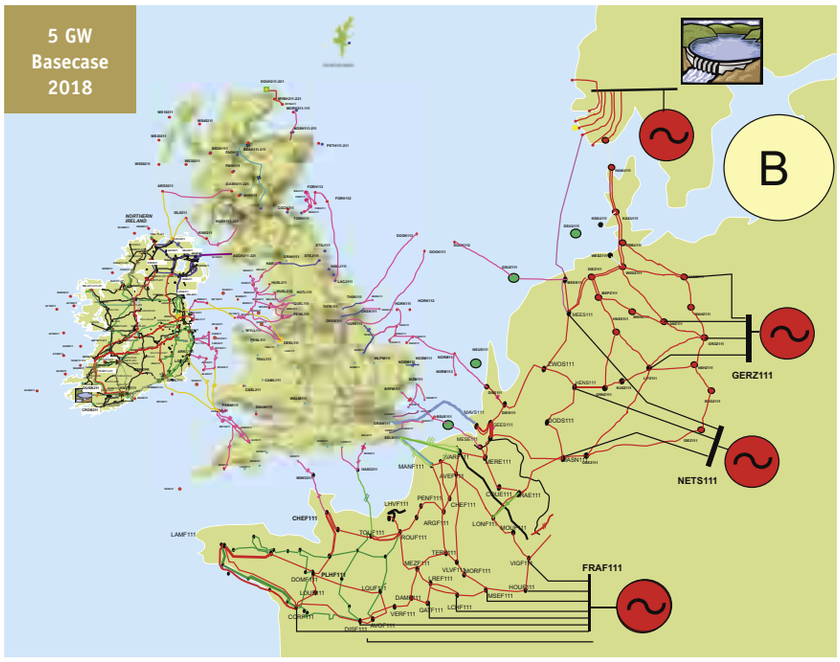
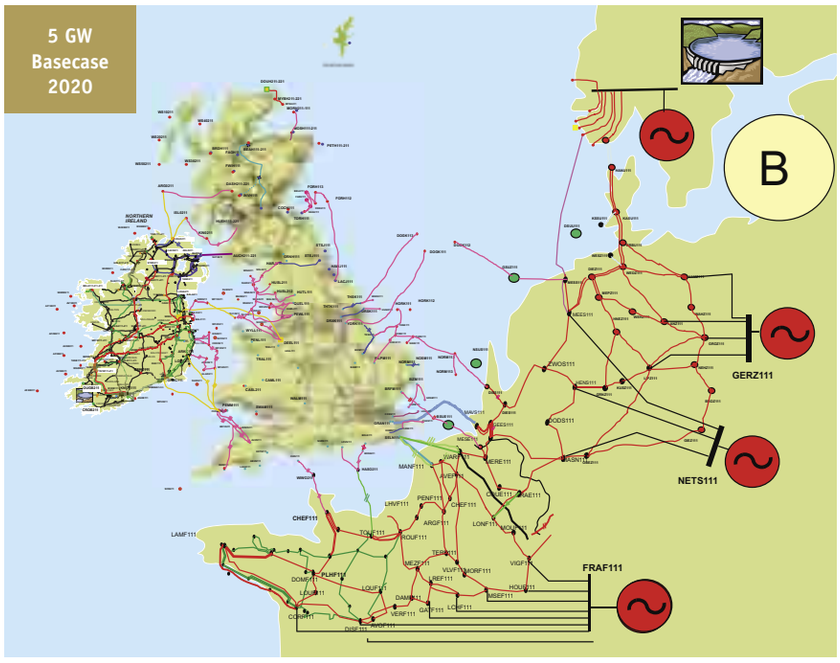



**c) Year 2018**




**d) Year 2020**

**Figure 9.9.** Intermediate Steps solution of MID5 Interconnection Scenario



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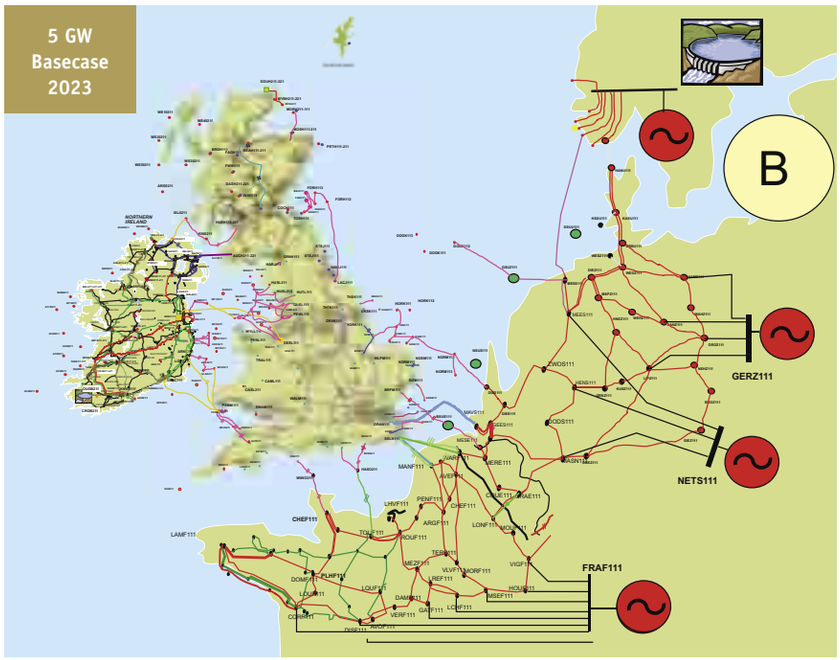
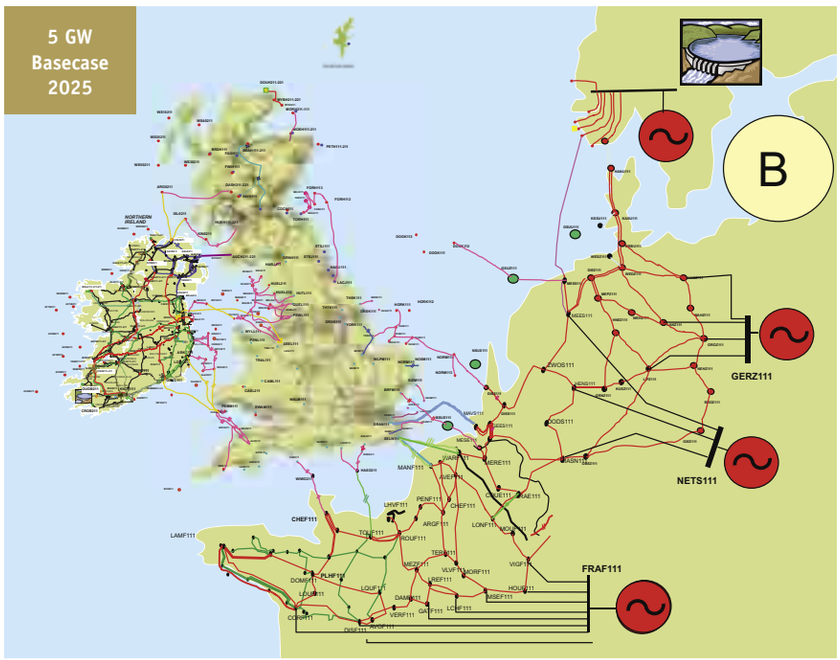



**e) Year 2023**




**f) Year 2025**

**Figure 9.9.** Intermediate Steps solution of MID5 Interconnection Scenario



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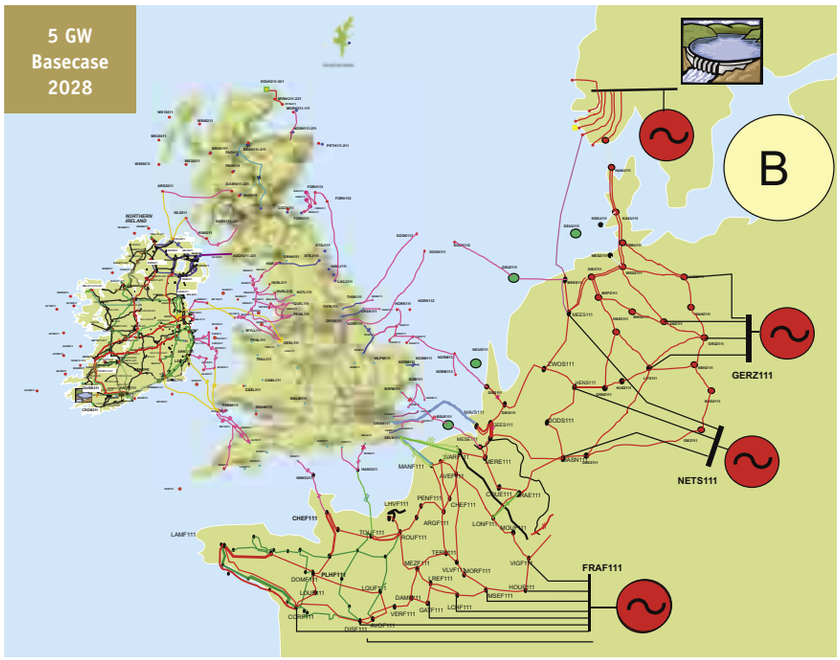
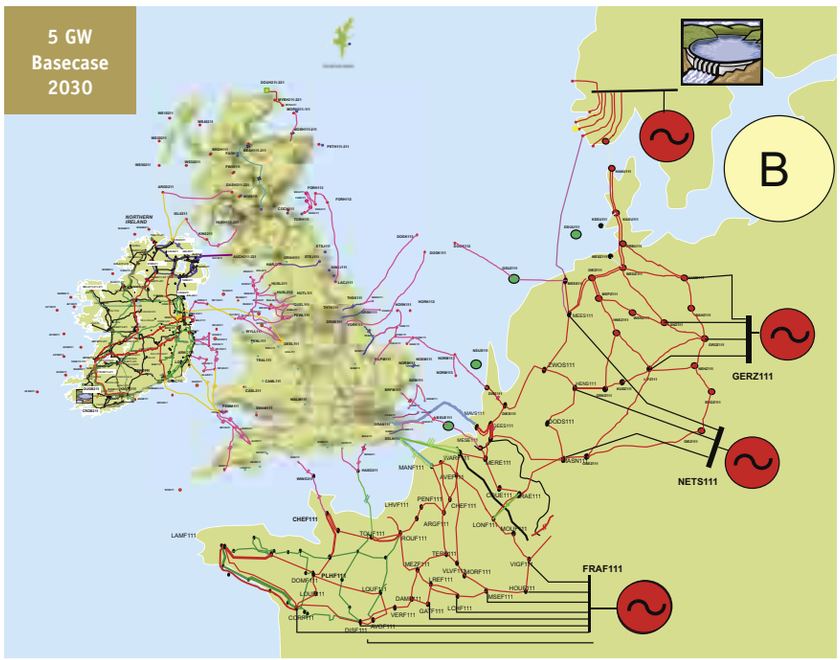



**g) Year 2028**




**h) Year 2030**

**Figure 9.9.** Intermediate Steps solution of MID5 Interconnection Scenario



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The results show a significantly different level of development in comparison to the MID5 Irish only results with significant interconnection being developed even in the earlier years.

It can be seen that many of these interconnectors are developed from offshore stations, reducing the length and consequently the cost of their development.

In many cases the same circuits selected in the Irish only network in 2020 (see chapter 8.1) to reinforce both offshore and also on shore are identical.

However, in many of these routes the number of circuits has been increased to allow for the higher levels of power transfer that exist with following the interconnection with other networks.

Over the study periods similarities are evident with the Irish only study which makes the networks comparable.





The shallow connection of three of the five windfarms is unchanged to the Irish only results (Codling, Arklow and Glasmore). Kish banks, change in connection is very marginal, both in distance and cost and is therefore comparable.

Only Oriel has a more pronounced change in connection point, how the appears to be unique to this study as other AC studies (Chapter 9.2.1.2) and Mixed AC/DC studies (Chapter 9.4) retain the same connection point found throughout Chapter 8.1.

The selected interconnections do however provide some changes in the needs of the network. The offshore reinforcement from the north to south of Dublin, is now not selected but comparable network loops are naturally made via Britain albeit with a longer path for power transfer. As with the shallow connections this appears to be scenario dependant with the higher generation scenario in Chapter 9.2.1.2 selecting an east Dublin offshore reinforcement.

Many of the onshore network reinforcements are also consistent

Differences in the network topography that exist in comparison to the Irish only context are mainly driven therefore by interconnection which enlarge the system horizon, and unlike the Irish only context all offshore generation points have been used to develop further offshore infrastructure. As a consequence offshore transmission stations should be designed suitable for expansion.

Another finding of the MID 5 interconnection study is the significant development of interconnectors both to Britain and France from the All Island network dispersed over the entire length of the east and south coast of Ireland. This implies not only desirable conditions for power exchange between more than one country but also that power transfer through each other's networks minimises network reinforcement requirements. Therefore strengthening of the Irish and British networks, for example, can be avoided by rerouting power through the other.

It is noteworthy that Interconnection with France is active after 2025. This is due to the combined effect of the full utilisation of transmission capacity on the British side, and the increasing offshore wind in Ireland and Britain.

Finally, a new North-South backbone has been also developed on the west side of Ireland from 2020. This allows the transfer of large amount of wind in Northern Ireland and of the Scottish Crown 3 Wind Farms to the South. The short distances to the shore are considered as an attractive alternative for energy transfer as onshore development throughout Ireland is considered possible.



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## 9.3.2 Sensitivity Results: Wind Curtailment Penalty Factor

A parameter required for the Expansion Strategy Plan (ESP) analysis is the penalty factor related to the Wind Energy Not Delivered (WEND). This reflects the market price, and notably the price paid for the wind under REFIT regardless of network constraints.

Refit tariff is set up in Ireland and Britain to:

- 60 Euro/MWh onshore
- 140 Euro/MWh offshore
- 220 Euro/MWh for waves
- 150 Euro/MWh for GB Offshore

In the sensitivity analysis the following penalty factors were considered:

- 10000 Euro/MWh everywhere
- 140, 60, 150 Euro/MWh respectively for ROI Offshore, ROI onshore and Britain Offshore, (220 Euro/MWh if wave exists) referred to as REAL subsequently in the report.
- 0 Euro/MWh everywhere

The effect of raising the penalty factor is to encourage expansion in order to avoid curtailments for any transfer of power, and the reverse if the penalty is lowered. For instance, with 10000 Euro/MWh, virtually any reinforcement will be preferable to curtailment and with 0 Euro/MWh the reverse. Therefore using both 10000 and 0 Euro/MWh should provide the full variation in network build in the ESP's.

Furthermore, the ROI offshore generation strategy is compared to using conventional Gas Turbine Units (BasU) to meet the increasing need for generation out to 2030.

### 9.3.2.1 Grid Expansion

Figure 9.10 shows the overall results in terms of km of new circuits and yearly investments, for different wind penalty factors and BasU

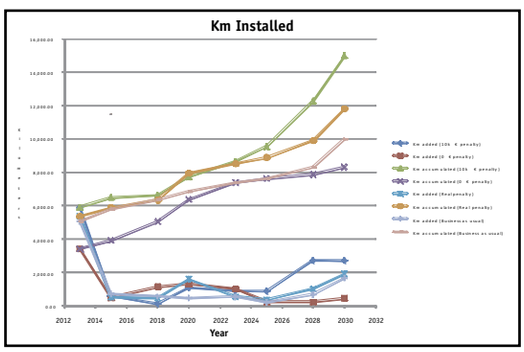


**Figure 9.10.** Km of Circuits



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Up to 2023, results are not much different. In terms of kilometres of new network build the 0 Euro/MWh penalty factor is only some 15-20% less developed than 10000 Euro/MWh case. This is interesting as it is when most of the proposed onshore generation is deployed, with small infrastructure costs mainly onshore. However the onshore network increasingly needs interconnections with Britain to fully delivered available renewable power. These needs interact with the Generation Mix of Britain and Ireland. Results suggest that there are potential synergies between the two systems anyway which may be exploited by further interconnection.

This is evident from the 2013 results, where for any penalty factor it is worth to introduce at list 3000 km of new circuits.

The effect of the penalty factor is only to delay reinforcements between 2013 and 2023.

It is noteworthy that at this stage interconnecting Britain is relatively cheap for short distances. Furthermore, the need for interconnection is coupled with the connection of offshore windfarms.

It is possible to recognise a threefold synergy in this process:

- Increase market competitiveness (exploitation of generation mix);
- Avoid wind curtailment penalty factor ;
- Reduce production costs.

From 2023 onwards the penalty factor has a bigger impact. In particular from this year the offshore has been assumed to rapidly increase due to a full deployment of the supply chain.

Furthermore, Britain's wind strategy has a major impact on the overall generation mix leaving Irelands wind market resources with more competition.

Therefore, part of the energy produced by Irish renewables need a different path to be delivered, that is to Europe through France. This requires large investments in extremely long HVDC links, i.e. 300-400 km.

At this stage less synergies are present and the benefit of enhancing interconnections only depends on the penalty factor related to the curtailment of wind and the improvement on the production costs overall.

With a 0 Euro/MWh penalty factor, expansion to Britain effectively ceases with only a few hundred kilometres built mainly on the British side.

At this stage for Ireland, no further interconnection with France is justified and the new offshore wind basically uses the existing offshore infrastructure built up to 2023, supplanting onshore wind which is curtailed instead.

It is noteworthy that wind curtailment occurs in the Western part of the country.



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The 0 Euro/MWh penalty factor is an extreme theoretical case which does not correspond to market agreements. Wind is entitled to get at least the market price in the future that is the 60 Euro/MWh. For the time being, the REFIT of offshore, onshore is the reference. This is reflected in the REAL case.

The REAL expansion remains very close to the 10000 Euro/MWh case. Interestingly, in the preliminary phase up to 2023, an even larger expansion occurs in 2020. This is the computational effect of the discretisation process in deciding reinforcements.

In particular, the REAL case expansion is different from 10000 Euro/MWh and for the 2020 intermediate steps the two cases have an initial different working point. The larger expansion in the REAL case of 2020 is an attempt to 'rebalance' the system assets of 2018. Longer term (2030) as would be expected the REAL justifiable network expansion is only 85% of the 10000 Euro/MWh case.

The main effect of the penalty factor is a delay to network development. In fact, a similar circuit expansion of the REAL case compared with 10000 Euro/MWh case is obtained but postponed from 2028 to 2030.

It is not surprising that the most beneficial candidate reinforcements are consistently used regardless of the scenario being examined. In the main for each scenario a core reinforcement strategy is supplemented by an accumulation of beneficial offshore projects when the energy not delivered and the improvement on the production costs exceed a certain threshold. The scale of the scenario determines how many of these additional beneficial offshore projects are justifiable.

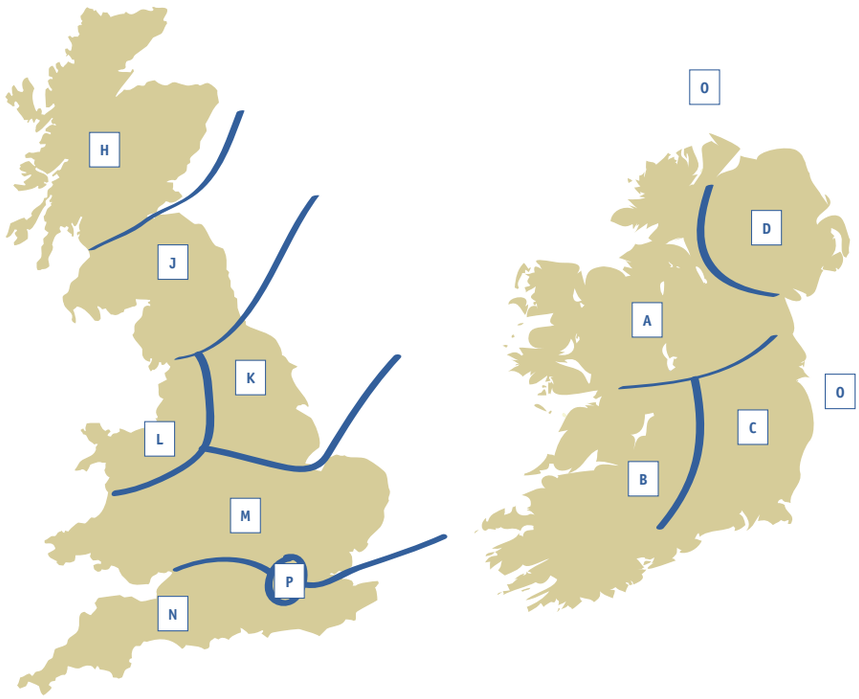
Therefore in many scenarios a candidate reinforcement present in other scenarios would be ultimately justifiable as time progresses.

The step change due to large cost and capacity of some candidate reinforcements, i.e. interconnection with France as well as an Irish 400 kV backbone are driven only for the delivery of renewables. Their scale limits the number required, and also provides a capacity surplus for the long term, reducing major changes in network topography as generation increases.



### 9.3.2.2 Wind Curtailments

Results are shown separately for Britain and All Island including NW Scotland Offshore (NWSCO). The division of both Britain and Ireland into areas used in the graphs in this chapter is shown in figure 9.11.



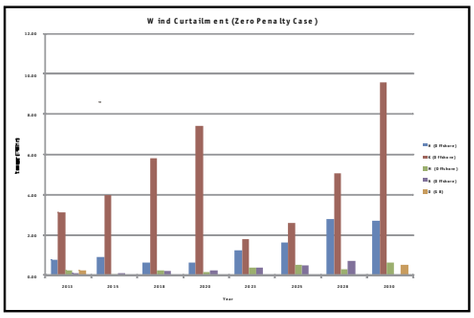

a) Great Britain b) All Island and NW of Scotland

**Figure 9.11.** Areas used in wind curtailment analysis

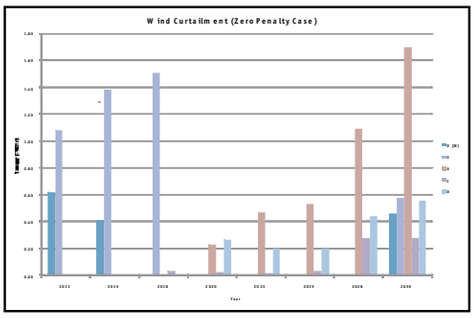


The analysis has showed no curtailment of wind with a 10000 Euro/MWh penalty.

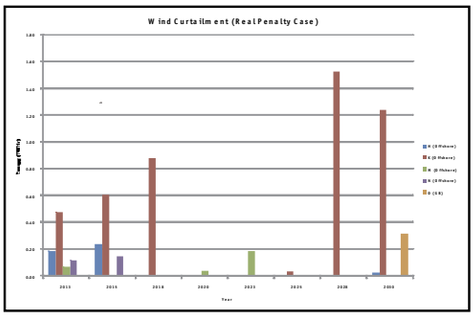
In Figure 9.12a, b, c, and d Curtailments are shown for Britain in terms of yearly TWh not delivered for 0 Euro/MWh and REAL scenarios respectively.



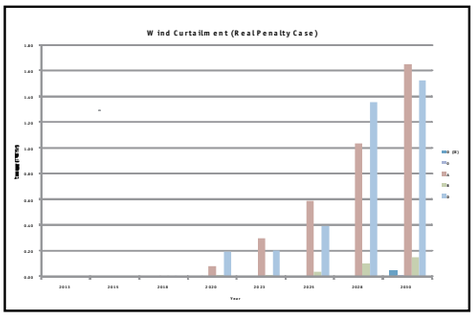

a) United Kingdom




b) Ireland and NW of Scotland




c) Britain




d) Ireland and NW of Scotland

**Figure 9.12.** Wind Curtailed (TWh)

For Britain, in the 0 Euro/MWh case, the major curtailment occurs in area K, which consist of large amount of wind further Off the East Coast of England (i.e. Dogger Bank). This means that the connection of generation and hence the network required:

- is expensive;
- cannot provide enough synergies with interconnectors;
- does not sufficiently reduce energy costs to be justifiable;

However, this is an extreme case which does not constitute the present regulatory arrangement.



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Moving to the REAL scenario, where a penalty is introduced if the wind is curtailed, the amount of curtailment is reduced 7 fold.

For All Island and NWSCO generation in the 0 Euro/MWh case the behaviour is more complex.

In the early stages before 2020, the major curtailments occur in the Irish Sea and NWSCO. However from 2020 onwards, a gradual increase of curtailment onshore in Ireland is seen, in particular in the North (Area A and D). Minor curtailment is recorded by 2030 in NWSCO and the Irish Sea.

Earlier, curtailments are due to the minor amount of offshore generation available, so that the decision is to avoid network expansion until a major increase in generation drives network expansion.

It should be noted that, compared to the Irish Sea Wind, NWSCO curtailments are prolonged before 2020, because of their location which does not provide interconnection synergies.

From 2020, onshore generation is curtailed to accommodate the new offshore installations in particular the NWSCO generation. This generation flows easily to Northern Ireland and Ireland congesting the capacity of the network to the West of the country.

When moving to the REAL case, in particular for the North West of Ireland, the final results are approximately the same with only some improvement in congestion in the intermediate step years.

As previously discussed after 2020, the wind in Ireland is sufficient to require significant additional export capability driving interconnections to France, as interconnection capacity to Britain is saturated.

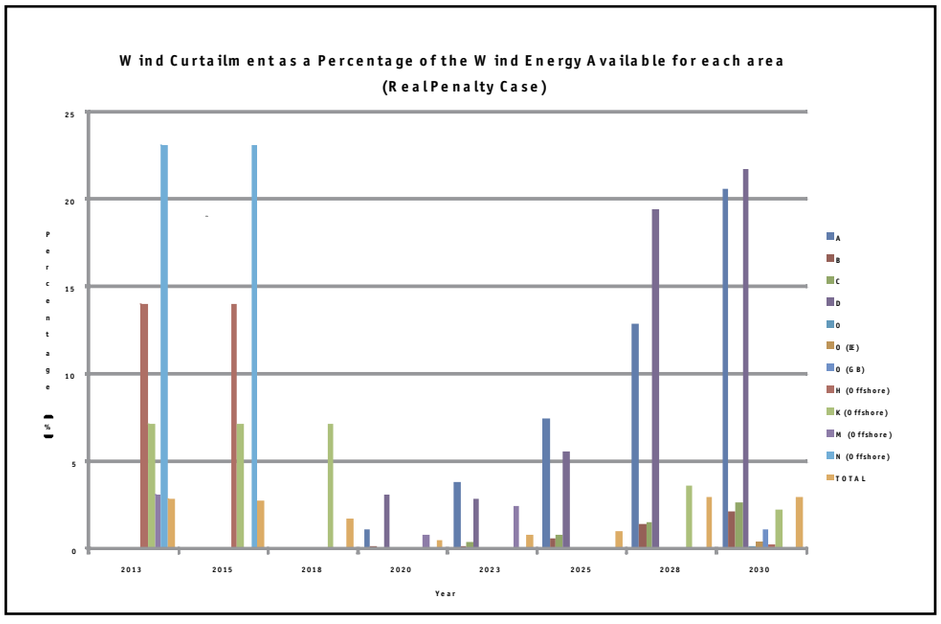
This extra renewables would require large investments onshore as well as offshore so that it is preferable to curtail instead, starting from the most remote areas, which is NW ROI.

In the REAL Scenario, also the NI renewables suffers large curtailments. Despite the more favourable position of this generation to make use of the network to the east, the renewables are replaced by the NWSCO generation because of its higher penalty factor.





In Figure 9.13, the same results discussed above are shown as a % of the Yearly Energy available.



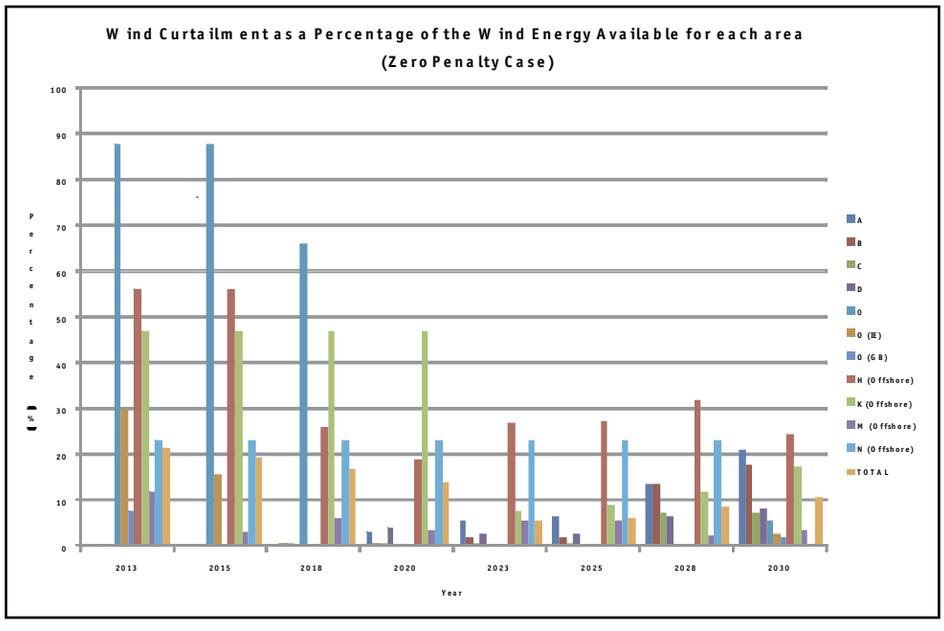




**Figure 9.13.** Yearly Energy Wind Curtailment



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The 0 Euro/MWh penalty case shows the highest cost is the NWSCO generation in the early years, with 57% in North East of Scotland (Area H) and the next highest at 47% off the East Cost (Area K).

By the horizon year some of the renewable generation is accommodated with curtailment decreasing within 30% (i.e. NESCO (H), NWSCO (0), NW ROI (A), and North Sea (K)). Overall the Wind Energy curtailment is around 11%.

It is noteworthy that in the extreme case, the Irish Sea Offshore, both in Ireland and Britain only suffers minor curtailments in 2030.

In the REAL scenario, curtailments are reduced. In the final stages only the curtailments in NW and North of Ireland onshore exceed 20%.

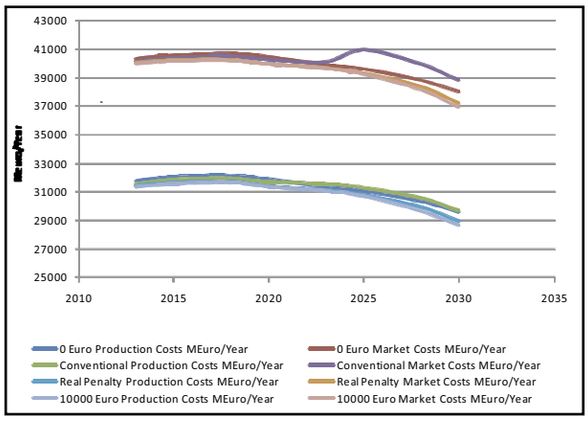
Overall, the Wind Energy curtailment in the system is about 3%

## 9.3.2.3 Production and Market Costs

Both production and market costs have been analysed below to provide both prospective of the energy costs and markets cost to ensure continuing proportionality for the changing time periods and scenarios.

In order to account also for the Market Economic impact, costs are also estimated using the Market Clearing Price in each scenario assuming an overall Regional Market arrangement without cross-border surcharges.

REFIT and penalties, if any, are not taken into account in the cost estimation.




**a) Whole system**



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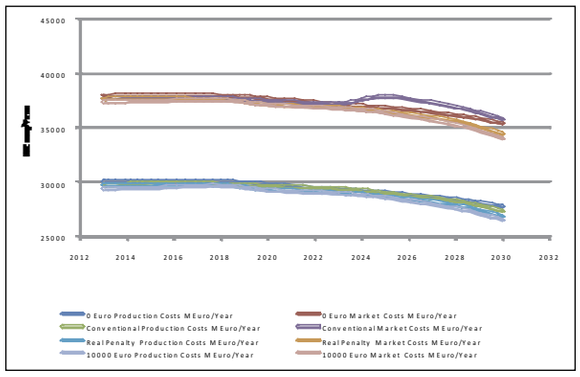
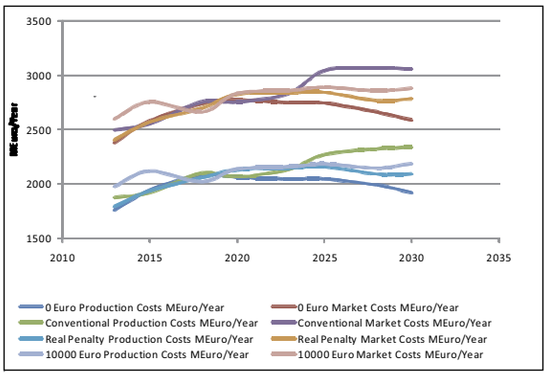



**b) Britain**




**c) All Ireland**

**Figure 9.14.** Yearly Production and Market Costs

Production and Market Costs behaves similarly with a 20-30% difference.

The impact of the additional offshore renewable energy up to 2030 on the whole European system gradually decreases energy cost by 5 to 7% despite increasing load demand, which is 2000-4000 MEuro/year.



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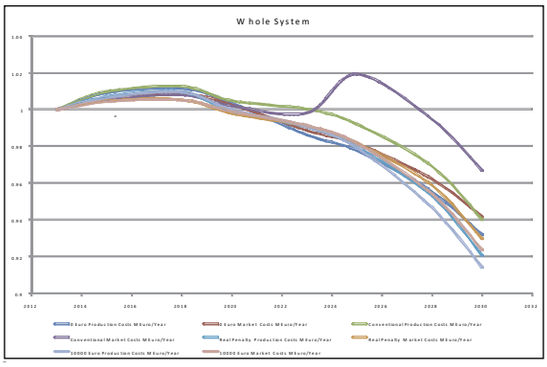
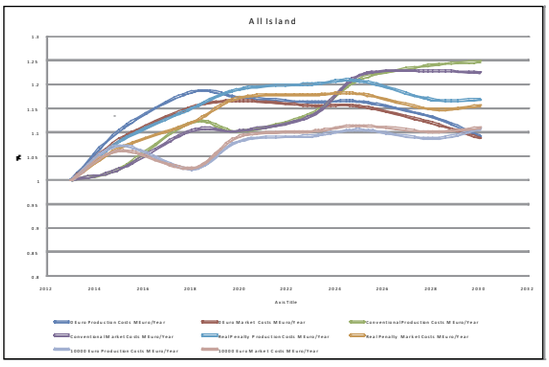
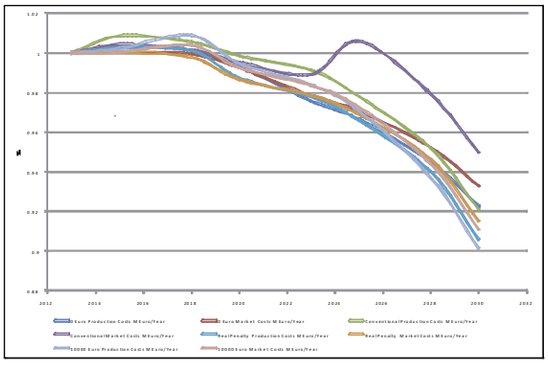
In Figure 9.15, the Costs are shown as percentage of the initial Costs.




**a) Whole System**




**b) All Ireland**



**c) Britain and Europe**

**Figure 9.15.** Yearly Production and Market Costs in %



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However differences can be appreciated in the break-down.

For Britain and Europe combined the costs decrease up to 11% by 2030.

For Ireland an overall increase in production costs is shown for any scenario. This is the effect of the interconnection between Ireland with Britain and the rest of Europe. However, the amount and the dynamics depend very much on the scenario.

The conventional scenario, with no offshore generation developed, sees a constant increase in energy costs in Ireland ultimately increasing costs by 25% over the period up to 2030, in particular, in 2013-2015; this is due to the available cheap imports from Britain not being able to be supplied in later years as the offshore network has not been put in place. After 2020 the missing offshore network will cause the conventional generation to operate with a partial further 10% increase from 2020 to 2025.

However the initial energy costs of 1.0 PU for both strategies are not identical and therefore even a 25% rise in the conventional costs is still below the renewable energy strategy costs by 2030.

The 10000 Euro/MWh scenario shows the minimum increase in production costs at 10% in 2030. In this case the constant development of the interconnections, simultaneously with wind development allows shared benefits to the neighbouring countries over the whole planning period.

The 0 Euro/MWh scenario in the early stages suffers from a lack of network development with an increase to costs, however the lack of interconnection in this scenario artificially distorts the wider European market in the long term as Ireland cannot export to neighbouring countries. From 2023 a gradual cost decrease is observed in Ireland and the scenario offers the lowest production costs in 2030 with a 9% increase. Inversely however, the costs to Europe as a whole are broadly comparable to the conventional scenario, economically showing no benefit from much higher renewable fuel resources.

The REAL scenario behaves like the 0 Euro/MWh in the early stages of development. However, from 2020 it evolves like 10000 Euro/MWh with a higher cost because of some wind curtailed.

### 9.3.2.4 Utilisation of the System

An important parameter of the study is the annual average system network assets loading.

Firstly, this can immediately provide a measure or quality of the suitability and efficiency of the study methodology. A cost effective network development approach should provide a high utilisation factor of the infrastructure.



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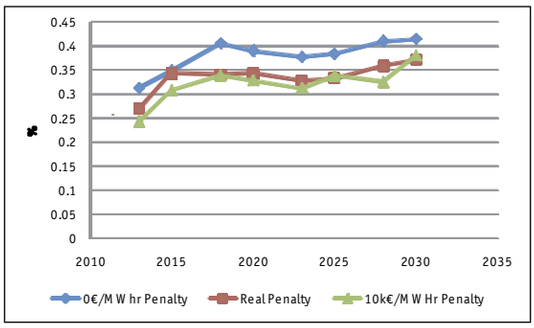
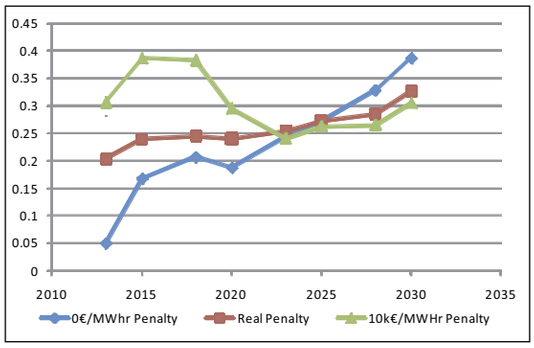
Secondly, the parameter allows comparison between different technology applications. As discussed above, a 'smart device' should in principle allow network asset to be adapted for many scenarios without the need for wide spread reinforcements.

Finally, it provides an understanding of the interaction between networks and the synergies between onshore, offshore and interconnectors.

The average yearly loading of the system is shown in Figure 9.16 for Rest of Europe, Ireland Offshore, Ireland Onshore, and Ireland Interconnectors.




**a) Rest of Europe**




**b) Ireland Offshore**



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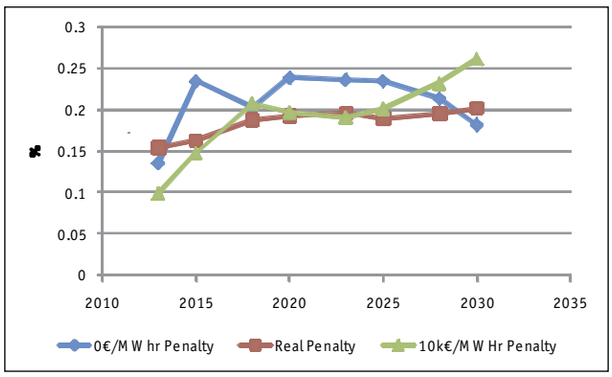
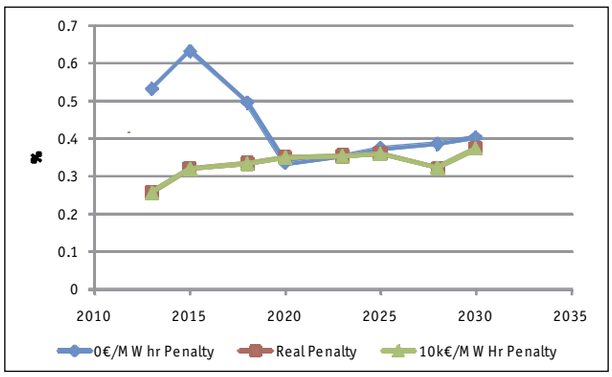



**c) Ireland Onshore**




**d) Ireland Interconnectors**

**Figure 9.16.** Annual average network loading (%)

For the Rest of Europe, Figure 9.16.a, results show an average loading between 25 and 40%. An increase is observed over the planning period.

This is due to the gradual deployment of the wind strategy coupled with the computational discretisation effect of introducing transmission infrastructure (on-off). In the early stages this causes some infrastructure to be put in place for small amounts of wind, in particular for high penalty Wind Curtailment coefficients.

By 2030 the grid offshore gets a meshed shape, with a better utilisation of the capacity for multiple purposes.

However, the Irish context is more complex.



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### 9.3.2.4.1 Irish only Onshore Grid

The onshore grid loading, see Figure 9.16.c, show a stable increase in the 10000 Euro/MWh scenario. This is probably due to the full deployment and utilisation of the wind energy and export trends by 2030. Overall, the full onshore network is enhanced to accommodate this generation including the resulting high power flows from NW Ireland and NWSCO.

In the other scenarios, NW Ireland and NWSCO are not fully utilised and therefore the network loading is less. In particular for 0 Euro/MWh scenario, the impact of not enhancing interconnection and hence export of energy resulting in the loading of the onshore network levelling out with even a decrease by 2030 as offshore Irish Sea generation is more commonly chosen to produce power.

### 9.3.2.4.2 Irish Only Offshore Grid

The offshore Irish Sea network, see Figure 9.16.c (interconnectors excluded), is strongly scenario dependent. In early stages of development, few links are in place both in 0 and 10000 Euro/MWh the difference in loading is due to the network structure with a mostly radial and meshed network respectively.

As the structure evolves, i.e. by Year 2023, network loading converges to similar values. Towards 2030, the reverse is true, with much more loading for the 0 Euro/MWh, compared to 10000 Euro/MWh scenario, which develops further interconnections with Europe (France).

The REAL case is a perfect compromise of the two strategies.



### 9.3.2.4.3 Irish Only Interconnectors

The loading of the Interconnectors, see Figure 9.16.d, show differences present from an early stage for 0 Euro/MWh scenario which is affected by the scarce number of interconnectors, i.e. 1 in 2015. By 2020, values stabilise around 30-35% for all scenarios.

Figure 9.17. shows the results for the different Scenarios

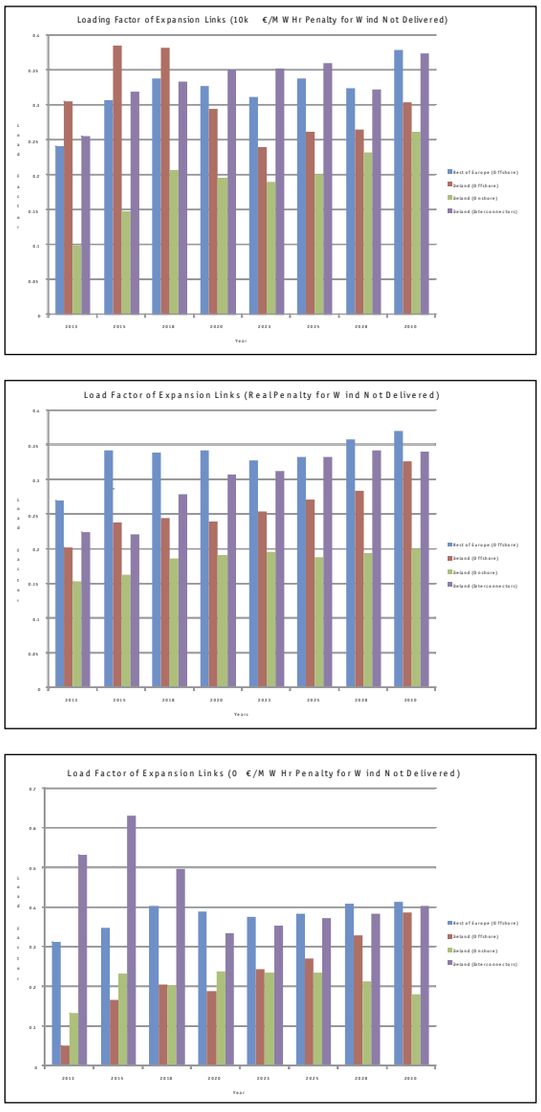


**Figure 9.17.** Yearly System Loading



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It can be noticed that, neglecting the early stages, the offshore grid has a much higher loaded network 25-35%, compared to onshore at 20-25%. This is because of the loading of the existing network which at around 20% disproportionately contributes to the average loading.

The Interconnectors are loaded around 35-40%. This does not appear high. However it is the effect of the lack of power flow control device in the AC model; a much higher value is expected with the use of 'smart' technology devices.

The high value of Rest of Europe is simply due to the lack of N-1 contingency analysis on most of this Grid.

A yearly average of 30 to 35% is obtained, with 50 to 60 % in periods of high to medium wind in Ireland. However in low wind period values are still around 20%. This demonstrates that the network is getting added benefit by using the interconnections driven by increased renewables. A radial development approach by comparison would only load the offshore network 9-10%, at minimum wind periods.

Focusing on interconnections, during high wind periods, are shown in Figure 9.18 and 9.19

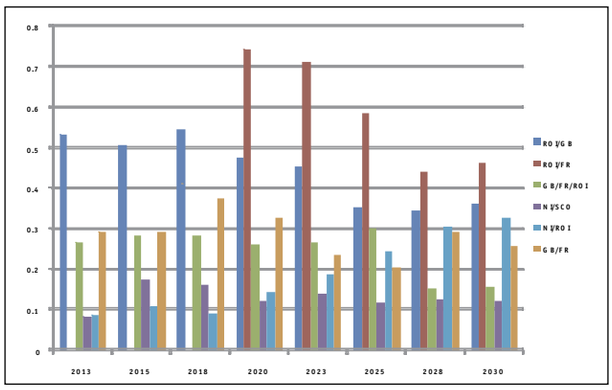


**Figure 9.18.** Yearly Interconnection Loading (10000 Euro/MWh Case)

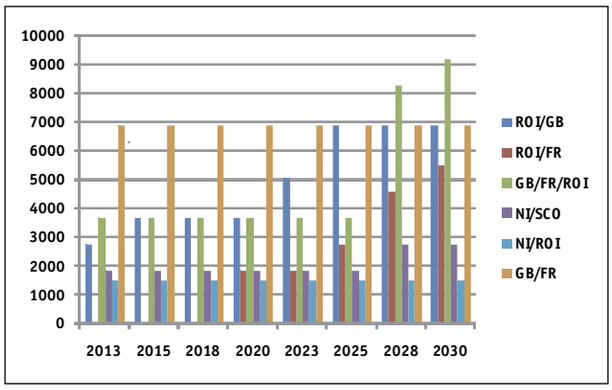


**Figure 9.19.** Expansion of Interconnection Capacity in MVA (10000 Euro/MWh Scenario)



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Before 2020, only interconnection between Ireland and Britain is enhanced. This is mainly the consequence of using offshore generation stations as a lower cost interconnector method between the two countries.

From 2020 onwards, Interconnection with France is also developed to 5.5 GW up to 2030.

Interconnection from Ireland to Britain rises to 7 GW over the same period.

Interconnection between the eastern side of Britain and France is stable at 7 GW since throughout the analysis, whilst showing the need for a continuing expansion of interconnection from the south of Britain to 9 GW up to 2030.

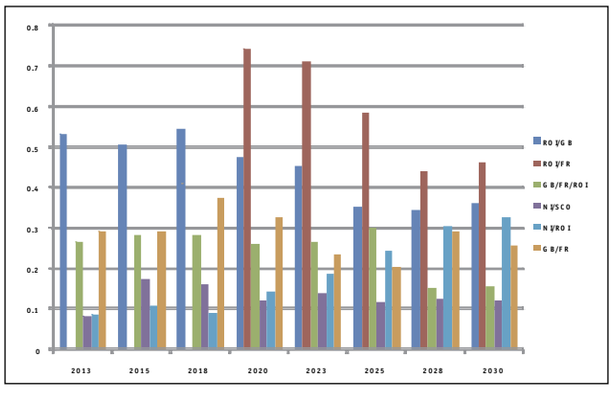
Part of this interconnection from the south of Britain is due to Ireland which transmits power on candidate reinforcements through Cornwall and on to France.

### 9.3.2.5 Island of Ireland Focus

This chapter focuses on results related to Island of Ireland. Results are also broken-down for Onshore, Offshore and Interconnections between the Island of Ireland (referred to as Ireland subsequently) and neighbouring countries.

#### 9.3.2.5.1 Grid Expansion

In Figure 9.20 the expansion of the network over the planning period is shown.




**a)**



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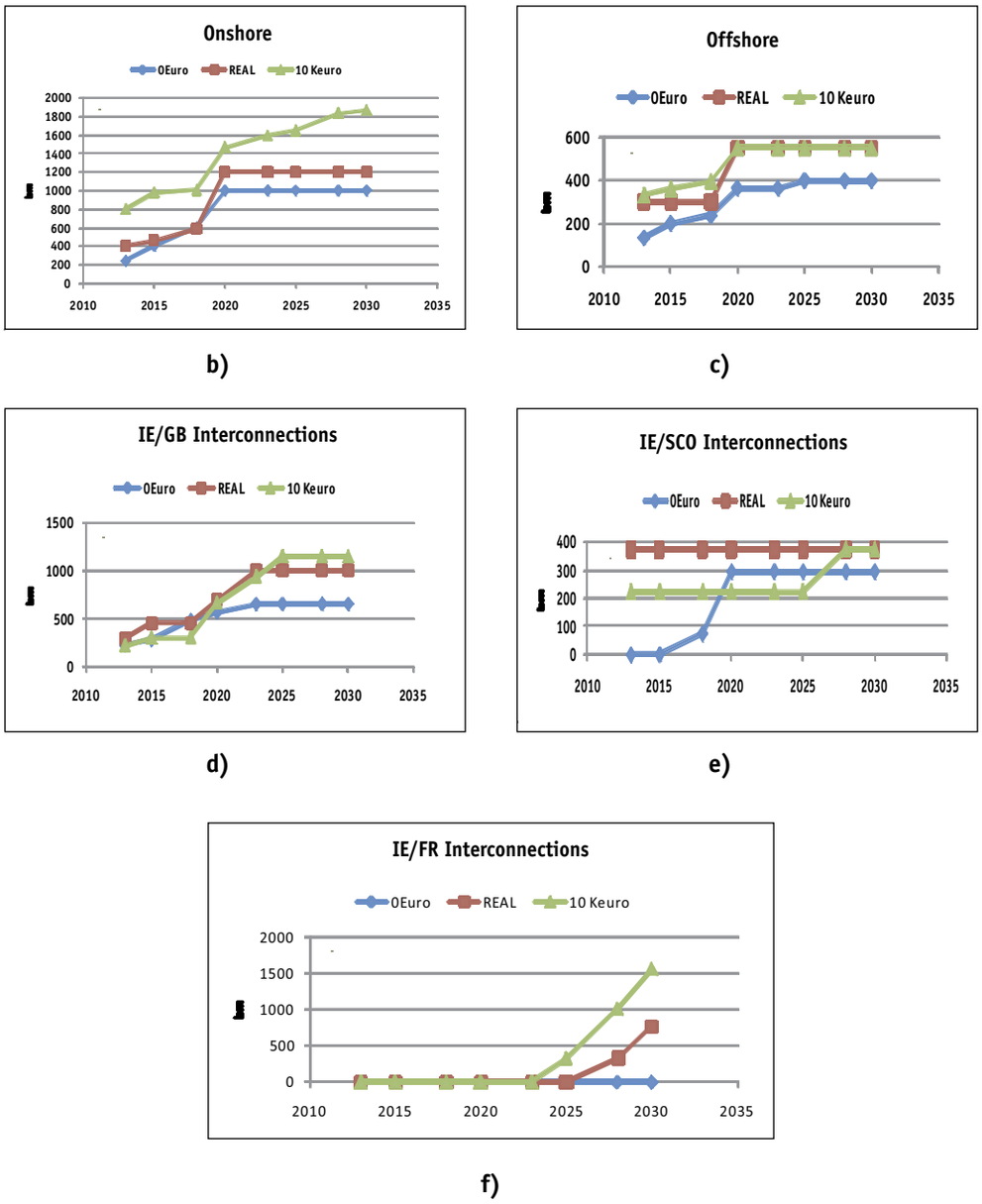


**Figure 9.20.** Grid Expansion: Ireland Focus



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From Figure 9.20.a, the total expansion is similar for any penalty cost until 2020. This is due to the synergies in the Irish Sea between offshore connections and interconnections. In 2020 between 2200 and 2800 km of circuit have been selected even in the Low Wind Penalty case.

From 2020 to 2030, the Penalty factor becomes important due to increasing difficulties to deploy wind resources in remote areas. In order to fulfil these requirements large investments are required with high penalty factors (REAL and 10000 Euro/MWh). It is worth noting that no interconnection with France is developed in the 0 Euro/MWh case.

In general the penalty factor has the effect of postponing grid investments.

Figure 9.20.(a-f) demonstrates the previously mentioned sequence of development of interconnection with both connections to Britain (GB and SCO) developed first then levelling out, whilst interconnection to France develops later and steadily out to 2030.

### 9.3.2.5.2 Wind Curtailments

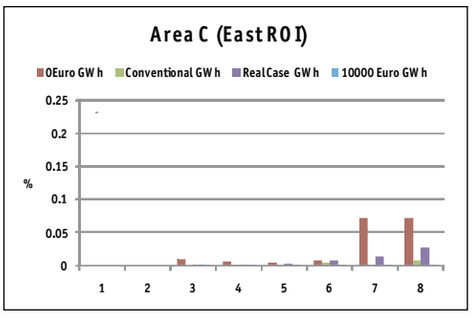
Wind curtailments results are shown in terms of percentage (%) of the wind energy available, see Figure 9.21.

The results show that the onshore wind, until 2020 (4) has no curtailment for any of the scenarios. The only generation affected by curtailment is offshore for the extreme 0 Euro/MWh case in the early development stages.

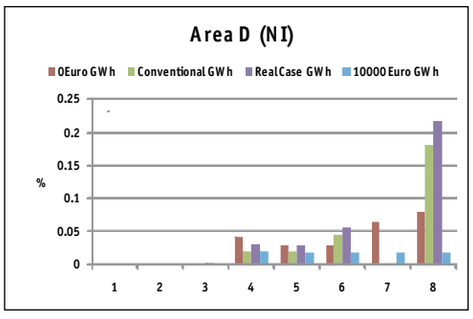
After 2020, when the onshore is fully deployed at c.7 GW in Ireland, the offshore generation become more and more relevant.

As already discussed economically, only the 10000 Euro/MWh penalty make the network expansion cost effective to cater for full Onshore Offshore deployment, shown as the blue bar in the Figure 9.21.

In the REAL case, shown as the violet bar in the Figure 9.21, a substitution effect occurs between extra offshore, and onshore in particular, remote area A and D onshore wind is replaced by NW SCO Offshore Wind, shown in Figure 9.21 a, d and f .




a)




b)



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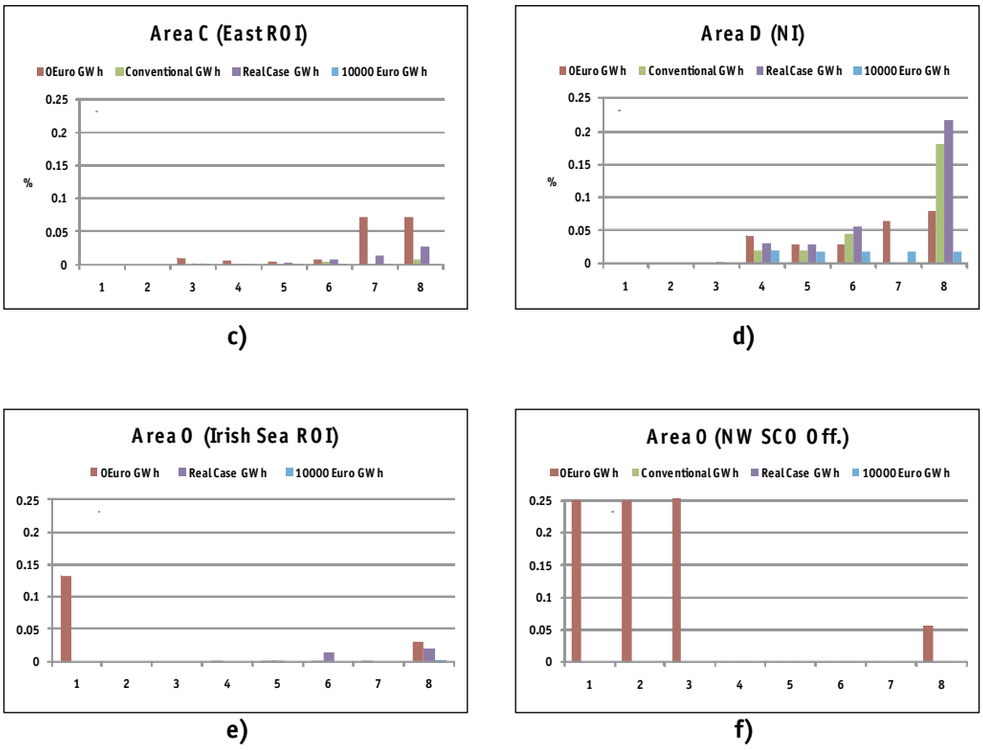


**Figure 9.21.** Wind curtailments in Ireland

Comparing curtailment with the conventional scenario where no new offshore generation is added confirms that the offshore Scottish wind is in competition with the Irish onshore wind.

In remote areas A and D, for the 0 Euro/MWh scenario appear better than REAL. This is because, competition is equalised by applying the same penalty factor for all wind resources.

A key message can be extracted from Figure 9.21.e. for any of the investigated scenarios no curtailment occurs for the Irish offshore generation. This indicates the relatively attractive location of the Irish generation considered in the analysis.



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## 9.4 THE MIXED AC/DC TRANSMISSION MODEL

As mentioned earlier, the model which has been discussed previously above has been a pure AC model, with all candidate reinforcements AC technology. The DCLF approach 'prevents' the issues related to use of long length of AC cable; however this must be taken into account in the process of building the list of candidates for the ESP analysis.

Although the previous results can be considered as preliminary indications of advantages and challenges of the renewable generation deployment strategy on and offshore in the Irish Sea, the model needs to be suitably enhanced and integrated to account for the wide range of technology options that must be considered in the scenario.

For long distances, HVDC options has been using since the 50s with first connections in Scandinavia. Several interconnections have been in operation for more than 30 years and make HVDC a valuable and proven reliable alternative. Recent advancements provide the TSO with further HVDC options that offer interesting features. These allow their use to not be limited to long interconnections but also as a potential application in meshed HVDC networks.

Consequently, after considering the first preliminary results it has been identified as necessary to develop a DC model to be integrated in the ESP tool. A model description can be found in the Appendix 4.

### 9.4.1 Transmission Alternatives

A thorough description has been performed in chapter 6 with a description of the different options available. In appendix 1 an analysis has been undertaken of the AC technology in order to identify the technical limits in terms of maximum length.

How the AC model has been modified in order to incorporate the HVDC transmission technology is summarised below.

Onshore, the future grid has been assumed to be overhead line primarily at 400 kV. Furthermore, in parallel on some existing routes, a DC overhead based option has also been introduced connected to major 400 kV existing substations. This is in order to provide a potential for development of an 'Overlay DC Grid' concept that may be suitable for high power transfer duties as an alternative to the need to expand several AC circuit on existing line routes.

In order to restrict the number of technological changes to candidate reinforcements and thereby computational combinations considered in ESPs, some economically and technically based reductions in the potential choices have been made, as follows:

- The Expansion Offshore with AC 400 kV XLPE only for distances < 80-90 km
- HVDC LCC technology only for point to point onshore applications
- HVDC VSC technology for other offshore connections for any distance.



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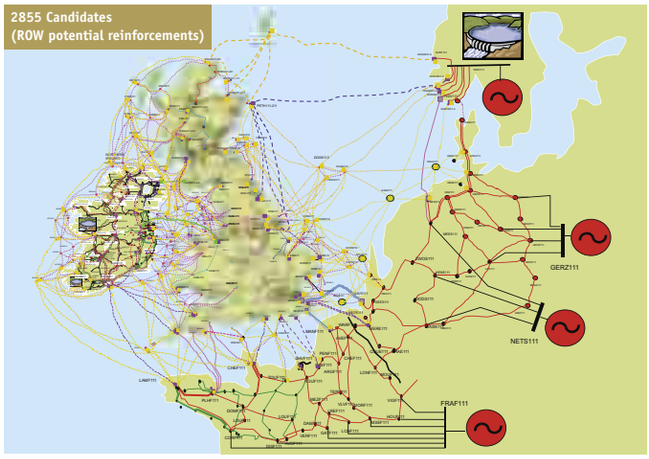
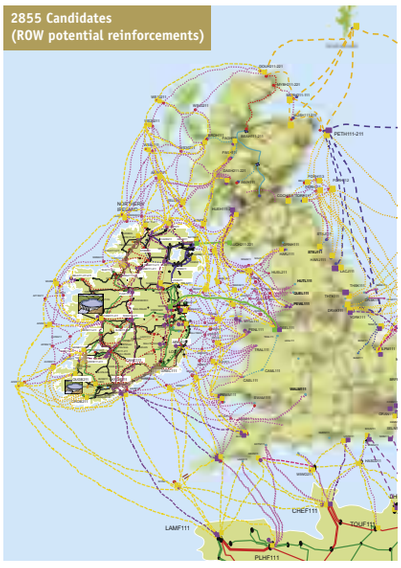
This approach has provided a large set of HVDC-VSC alternatives for the offshore connections in the Irish Sea, within the distances in the range of AC application, which could also be economic effective.

Figure 9.22. shows the candidate reinforcements for the technological study, with the DC technological reinforcements (Purple for LCC and Yellow for VSC technology).




**a) General scheme for the study**




**b) Irish Sea Zoom**

**Figure 9.22.** Mixed AC/HVDC meshed candidate grid



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### 9.4.2 HVDC Advantage and Challenges

Compared to the AC model, HVDC technology can provide the network flexibility to control the power flows through the DC links. The controllability may provide enhanced performance to the network and it is of particular interest to verify performance potential at the expansion planning stage.

Indeed with purely AC reinforcements the electrical parameters of the routes, existing and the candidate reinforcements could provide a markedly over sized ESP.

For instance, a long link to France would represent a very high impedance path as an AC circuit that would impede power transfer through it. Therefore, some extra reinforcements may be decided in order to sufficiently lowered the impedance path and let the power to flow.

Furthermore, the variability of some generation resources create multiple power flow patterns, which without power flow control devices may result in an overdesigned network.

The HVDC model, introduced with the ESPAUT Optimisation procedure, provides this further ability to control power flow for different scenarios, being mostly independent from the physical impedance path.

If it is optimum to do so, a circuit can be loaded to the maximum capacity for any scenario, avoiding extra reinforcements. It is noteworthy that the circuit itself can be much more economic than the corresponding AC model, see Appendix 1.

Compared to the pure AC model, the solution is expected more cost effective overall.

However, multiple HVDC units pose an issue related to coordination of their control, which is out of the scope of this study but that are intrinsically assumed in the optimisation algorithm.

### 9.4.3 Scenarios and Subset

Given the previous results, the new Basecase is considered the REAL Scenario approach using the new list of candidate reinforcements.

For any generation scenario a new subset is calculated. As MAX10 Interconnection is a particular case of MAX10+Isles it is omitted.

### 9.4.4 MAX10 Interconnection+ISLES

#### 9.4.4.1 Case A

Figure 9.23, shows the subset ESP for the same results. This case has been obtained using the Isle Project assumptions and 7GWs in the Irish Sea at the previously discussed 10 sites. Penalty factor for wind curtailment has been considered 10000 Euro/MWh.



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The ESP comprises a number of large HVDC circuits as both LCC and VSC technologies. It is particularly interesting that there are some parallel DC and AC paths selected for those distances where both technologies are technically viable. This implies that the ESP has selected the higher cost DC technological solution because its power flow capability minimises the need for further network reinforcement (or better use of lower cost generation).

Onshore, an HVDC line is selected on the eastern side of Ireland from Cavan to Great Island with an interface station to the existing 400kV network in Laois, central Ireland.

A DC backbone offshore in the Irish Sea is also selected from NW SCO down to Cornwall with a deviation to Holyhead. The backbone is also heavily meshed with a number of AC offshore links from the eastern side of Ireland.

Two pure AC links are also selected to interconnect from Dublin area, Ireland to North Wales in Britain. These links although selected as AC technology undoubtedly because of their lower capital cost may prove to be technically challenging or undesirable.




**Figure 9.23.** Max10+Isles scenario subset

An interesting mixed technological solution is found to connect Oriel and WF1 windfarms; an AC circuit connects Oriel to the shore and to WF1, providing N-1 security. WF1 uses an HVDC circuit to inject power into the DC Irish Sea backbone; however an AC cable is also selected from WF1 to connect to the Isle of Man, where a major LCC HVDC station transfers the power either to North of England or to Deeside.



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This is evidence that in a dynamic evolution of an Offshore Grid concept, a simple early stage radial AC connection from the shore to Oriel windfarm may be at later stage part of a major Interconnector allowing Oriel wind power to flow as well as power exchange between Ireland and Britain for market trading.

On the British side of the Irish Sea most of the connections are AC except for some long distances HVDC-VSC that are not only for the purpose of connecting this generation.

It is noteworthy that also the 'West Bootstrap' conceived by NGC [14] has been selected with NO intermediate connections, directly from Hunterstown to Deeside. It is a 2 GW connection aiming at transferring part of NWSCO Offshore southwards.

### 9.4.4.2 Case B: Sensitivity on Irish Onshore Transmission

Case B differs from the previous case, with additional candidate reinforcements in the west of Ireland either double circuit AC 400 kV or HVDC LCC technology. Furthermore, HVDC VSC candidate reinforcement from NWSCO extending to Letterkenny has been added.

The resulting ESP is shown in Figure 9.24.

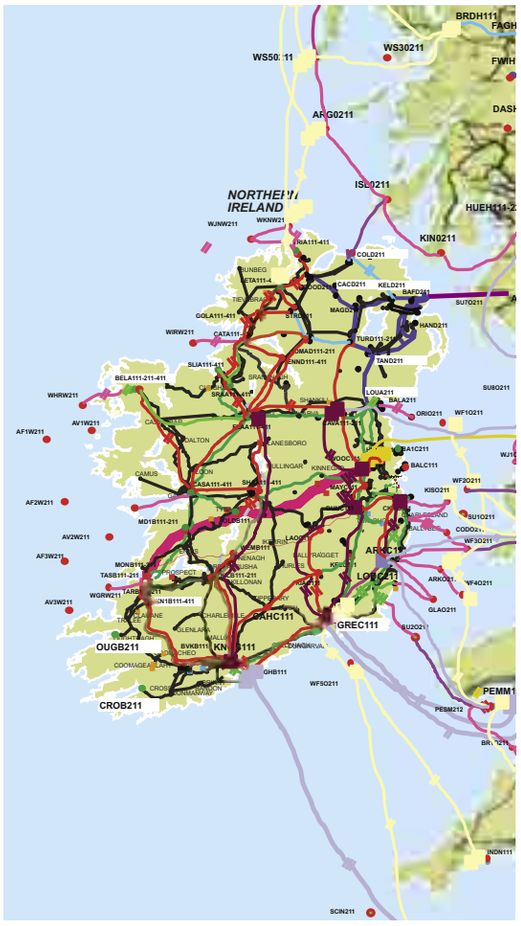


**Figure 9.24.**
Max10+Isles scenario subset



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The additional candidate reinforcements have been selected increasing transmission capacity in the west of Ireland in the ESP. It is worth noting that the power transfer from the NWSCO has now moved westwards; in particular:

- A backbone HVDC-VSC is chosen to connect the NWSCO wind Offshore to Letterkenny;
- to transfer power from Letterkenny in the north of Ireland to the export node of Knockraha in the south, a western backbone onshore is created;
- As a consequence the offshore HVDC-VSC backbone in the Irish Sea has now been limited to the central and southern part;
- The interconnection with Unterstown have been reduced to single AC connections for N-1 purposes;
- The 'British West Bootstrap' is reduced to 1 GW.

## 9.4.5 MAX10 Interconnection+ISLES+Wave Energy

To examine the effect to the ESP of developing an offshore network for renewable generation off the west coast of Ireland, 4GWs of offshore generation is included in this scenario. The resulting ESP is shown in Figure 9.25.

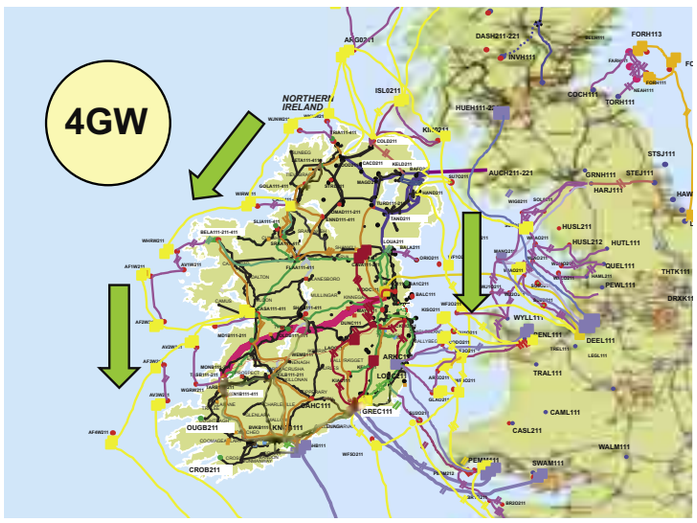


**Figure 9.25.** Max10+Isles+Wave Subset

The inclusion of the additional offshore generation makes it more cost effective to add some more DC circuits offshore in the west, partially avoiding the need for 400 kV circuits and a DC backbone inland.



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It is worth noting that this happens despite the assumption that onshore 400 kV and HVDC are low cost overhead circuits.

A mixed AC/DC grid structure is proposed which can be considered split into two parts:

- A North West offshore network finishing in Cashla station, using both AC and DC offshore networks. Power flowing south at this point splits with part wheeling eastwards to Cavan. The remaining is transfer from Cashla to Cork.
- A South West Offshore Grid, starting from Cashla using both AC and DC offshore networks to both the south west of Ireland but mainly using DC technology for large transfer from the offshore network directly to France.





# 10 Conclusions

The results show that the more cost-effective way to deliver the wind is by a meshed network not by radial connections. A meshed network provides higher reliability and a much better utilisation of the infrastructure.

The topology of the offshore grid looks very similar for the majority of scenarios analysed. Changes from one solution to the other are in the number of circuits between nodes, which translates into different transfer capacities between points and/or areas.

The offshore grid can be developed gradually striving to optimise both the long and medium term perspective whilst satisfying the requirements for the intermediate years. The offshore transmission stations should be designed with the potential for future expansion.

The offshore grid can even be optimised further by using smart grid devices. This would enhance its flexibility and reduce its scale. For part B (further interconnection with Europe), a mixed solution with both AC and DC circuits proves to be the more profitable. Due to the large distances and the length needed, it also makes a lot of sense that a part of the offshore grid would be better in the form of DC links.

The topology is quite interesting, as it shows the HVDC links used as “main roads” whereas the AC links are used as secondary roads. This reduces the amount of offshore infrastructure by several kilometres compared to the just AC links solutions.

The offshore grid and the onshore network are symbiotic, as the optimisation process finds ways to connect a huge amount of generation offshore without allowing major constraints onshore. In fact, the circuits offshore also help to relieve loaded onshore links. This is not surprising, because scenarios of very low energy wind input were considered and weighted properly in the optimisation process.

Many reinforcements onshore suggested by the optimisation process for the medium/long term perspective were already identified and proposed by the EirGrid planning department in previous studies, and included in Grid 25. This shows the robustness of the onshore strategy planned by EirGrid, showing that plans are robust to substantial changes in the generation portfolio and the intrinsic change of dispatches this causes.

The sensitivity performed by changing the value of the penalty for wind energy not delivered (cost of wind curtailment) revealed that the impact was not as big as intuition suggests. The costs for the new infrastructure with the 10k€/MWh was twice as high as with the 0k€/MWh. Using the real value for the penalty, the cost of the investment was in the vicinity of 80% of the infrastructure chosen for the 10k€/MWh.

The topologies of the networks found in those three cases are very similar. A noticeable effect is the rate of delivery of the new infrastructure offshore. For instance a link that was chosen for the year 2020 in the case of the 10k€/MWh may be postponed until 2030 in the 0€/MWh case.

In this same sensitivity, the energy not delivered due to wind curtailment with the real penalty was more than three times higher than in the zero penalty case.



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# 12 Appendix 1: Maximum length of ac cables

The electrical parameters of transmission equipment affect their use in transmission systems. In case of AC cables, electromagnetic phenomena must be thoroughly investigated as they can limit the maximum length.

There are many criteria that a project must fulfil, which also affect the maximum length that an AC cable project can be before technical issues arise.

Aside from the technical driven problems other development issues can arise which must also be resolved.

A description can be found in [16].

Three significant technical issues that impact on the critical length of a cable can be singled-out:

- Steady state stability
- Charging Currents
- Voltage difference

## 12.1 ELECTRICAL PARAMETERS

In Table A.1.1, power frequency direct sequence electrical parameters are shown for alternative types of transmission cable used in the study.

| | R | X | Tgd | C | S nom |
|---|---|---|---|---|---|
| Type | O hm /km | (O hm /km) | (p.u.) | (nF /km) | M V A |
| Three core 220 kV 1000 mm2 Cu | 0.057 | 0.11 | 1.00E -04 | 200 | 311 |
| Single core 220 kV 1200 mm2 Cu | 0.046 | 0.07 | 1.00E -04 | 198 | 460 |
| Single core 400 kV 1400 mm2 Cu | 0.043 | 0.07 | 1.00E -04 | 216 | 930 |
| Buried cable 380 kV 2500 mm2 Flat 700 mm | 0.0105 | 0.223 | 1.00E-05 | 240 | 1500 |
| Buried Cable 220 kV 1600 mm2 Flat 350 mm | 0.025 | 0.152 | 1.00E-05 | 240 | 600 |
| Overhead 380 kV | 0.03 | 0.28 | 0 | 13 | 1500 |

**Table A.1.1** Electrical parameters of Transmission Alternatives

With reference to Figure A.1.1, critical length calculation has been performed with some cables and OHL, used in the study.

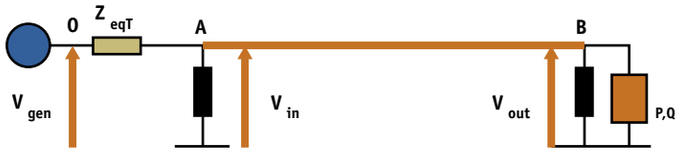


**Figure A1.1** Reference for critical length calculation



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For operational steady state stability, an angle difference of 10 degrees is considered acceptable by EirGrid, based on the existing constraint of 450 MW on Dunstown-Moneypoint line, which is 208.5 km long.

The potential size of reactors used for compensation is based on allowing for an N-1 of one of these reactors in No load conditions and maintaining voltages within compliant limits.

For calculation in Normal operation, the compensation ratio has been assumed to be the optimal level to provide the longest length of cable that can accepted. It is assumed that the link is compensated split, with 50% of the required compensation at each end.

The maximum permissible voltage difference between the reference voltage and highest variation along the cable is assumed to be 5%.

In this study both criteria, charging current and the voltage difference, are taken into account and the most constraining element will define the maximum length that can be accepted.

## 12.2 THREE-CORE 220 KV

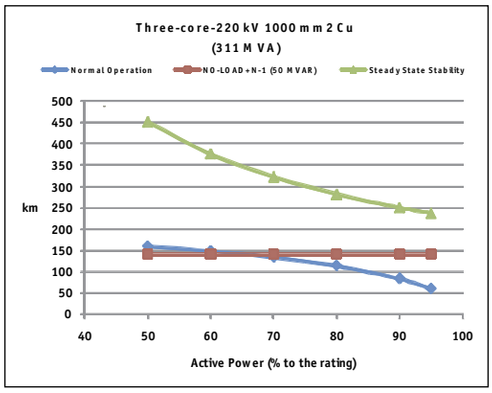


**Figure A1.2.** Critical Lengths

As can be seen in Figure A1.2, the steady state stability (shown in green) is never a constraint for the cable. The charging current in NO-load (in red) or operation (in blue) is limitations that define the feasible length of cable to be no more than 140 km.

However to make efficient use of the transmission capacity of the cable the maximum length must be restricted to 80-90 km.



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## 12.3 SINGLE-CORE 220 KV

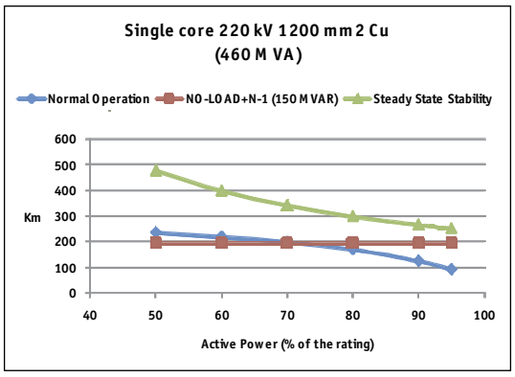


**Figure A1.3.** Critical Lengths

As can be seen in Figure A1.3, the steady state stability (shown in green) is never a constraint for the cable. The charging current in NO-load (in red) or operation (in blue) are limitations that define the feasible length of cable to be no more than 100-150 km allowing for efficient use of the transmission capacity of the cable.

## 12.4 SINGLE-CORE 400 KV

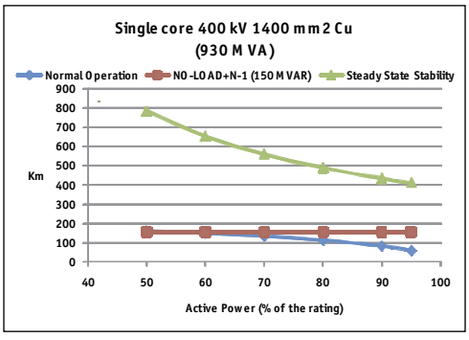


**Figure A1.4.** Critical Lengths

As can be seen in Figure A1.4, again the steady state stability (shown in green) is never a constraint for the cable. However the higher reactive compensation that is needed at 400kV restricts the cable length to c.90km to permit efficient use of transmission capacity (i.e. active power at c.90%) when in normal operation (in blue).



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## 12.5 BURIED 400 KV 2500 MM²

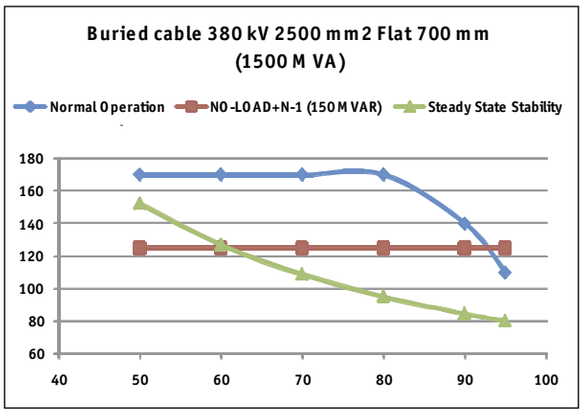


**Figure A1.5.** Critical Lengths

As can be seen in Figure A1.5, the relationship between steady state stability, NO-load and operational limitations are markedly different.

The underground cable has some differences in direct sequence parameter compared to the submarine. In particular the longitudinal reactance is at least 2-2.5 times greater, which makes the steady state stability, drop proportionately.

It should be noted that this cable parameters are directly relates to the installation of the cable to match OHL line capacity, which is with a very large interaxial distance between phases.

In this case the steady state stability (shown in green) is the most important constraint limiting the cable length to c.80km allowing for efficient use of the transmission capacity of the cable (c.90% active power).

Due to stability limit, such an alternative is constraint to around 80 km for 90% transmission efficiency.



## 12.6 BURIED 220 KV 1600 MM²

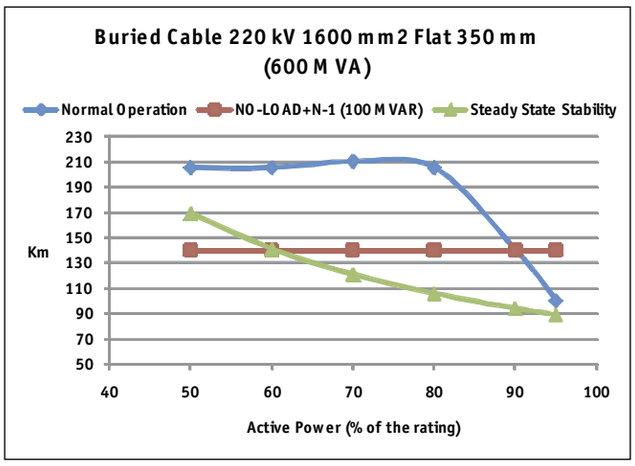


**Figure A1.6** Critical Lengths

As can be seen in Figure A1.6, a similar behaviour between the limiting factors is found for the equivalent 220 kV cable.

Once again the steady state stability of the cable constrains to maximum length to c.100 km to permit an efficient transmission capacity. In this case however normal operation of the cable is almost as restrictive approaching c.95% transmission cable capacity efficiency for the same length.



# 13 Appendix 2: Calculation of AC/DC Break-even points for offshore infrastructure

The offshore grid candidate reinforcement's options allow for a mixed use of AC or DC technology in the network Expansion Strategic Plans (ESPs).

Selection of a mixed AC/DC ESP is mainly due to the geographic distance that a circuit is to cover which prevents AC technology to be used. However, areas where either technology could and has been selected have also been found. The main reason why DC technology has been selected regardless of its assumed higher capital cost is because of the potential advantages of controlling power flows to minimise further network reinforcement elsewhere on the network.

Furthermore, in a meshed structure, an ESP may share HVDC units for several purposes therefore reducing the actual break-even distance between AC and DC technologies.

If we considered a lifetime cost AC technology is the more economic for relative short length. When considering DC two factors affect the economic comparison with AC:

The large investments in HVDC units and the operation costs

The reducing number of cables, 2 instead of three, for the same power and the reduced longitudinal losses.

When the cable length is increased the latter factor will help compensate for the first and a break-even distance can be calculated, where the overall lifetime costs are equivalent.

In this chapter, a break-even distance between AC and both DC technologies is considered, taking into account a Power Transfer of 1 GW between two points, as shown in figure A2.1.

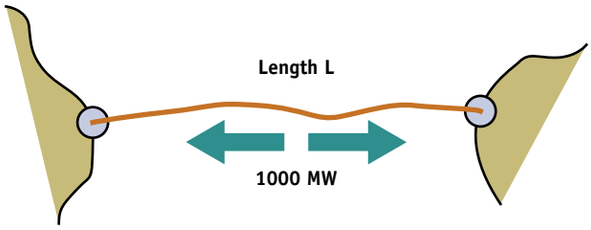


**Figure A2.1.** 1GW point to point connection

Cost references have been taken from [14], for both conventional LCC and VSC type HVDC convertor units, and for DC cables. For AC cables, a reference three-core cable has been considered from [14] and [17]; other alternatives have been calculated using alternatively sourced information to provide a cost ratio to the three-core reference cable.



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## 13.1 DC CONVERTER LOSSES

When calculating break-even distances, it is of particular importance to include converter losses in detail. This is because they are a source of heavy power losses, in particular at present for the VSC type and greatly influence the solution.

Furthermore, it has to be underlined that converter losses may be divided into two parts:

- Voltage dependant losses
- Current dependant losses

With reference to figure A2.2, an example is considered based on the HVDC-VSC units designed for the EWIC Project [18].

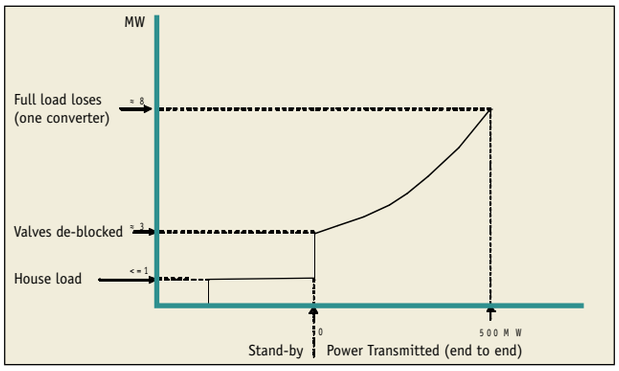


**Figure A2.2.** Converter Losses in EWIC

In Table A2.1, the assumptions used for the calculation of Converters losses are shown.

It worthy of note that conventional LCC Converters are much more efficient that the VSC types. However, recent advancements in the technology by manufacturers are leading their future predictions for VSC technology to become close to 1% in the near future.

| | VSC | LCC |
|---|---|---|
| Total | 1.60% | 0.70% |
| No-Load+Deblock | 0.60% | 0.20% |
| Current Dependant | 1.00% | 0.50% |

**Table A2.1.** Assumptions for Converters Losses Calculation



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## 13.2 AC AND DC CABLE LOSSES

| DC cables | R | X | Tgd | C | Snom |
|---|---|---|---|---|---|
| Type | Ohm/km | (Ohm/km) | (p.u.) | (nF/km) | MW |
| XLPE 1800 mm2 Cu 320 kV | **0.0101** | na | na | na | 1000 |
| PPL 2000 mm2 Cu 500 kV | **0.009** | na | na | na | 1000 |

**Table A2.2.** DC cable parameters used for Losses Calculation

In Table A2.2 and Table A1.2, DC and AC cable resistance are shown respectively, for the calculation of losses.

It should be noted at present that to construct a 1GW DC cable circuit requires a dual cable circuit bundled. Therefore the DC Resistance is lower than the equivalent AC resistance, due to the number of cables, the lack of skin effect and the induced current in the sheath.

These advantages however are partially reduced by the high losses in the DC converter units, in particular for VSC type.

For an AC cable, shunt and longitudinal losses have been considered as well as the losses associated in the compensation devices. An 80% compensation ratio has been assumed.

## 13.3 INVESTMENTS, OPERATING COSTS

For the break-even calculation, a life-cycle cost is considered for the five alternatives. Table A2.3, shows the economic parameters which have been used to distribute investments costs on a yearly basis[4]. For AC cables investments the compensation devices are also included based on 33% variable and 66% shunt.

Operating costs, i.e. losses are calculated assuming a 40% load factor for AC and an 80% for DC.

| **cost of losses** | 70 | Euro/MWh |
|---|---|---|
| | | |
| years | 50 | anni |
| discount rate | 5.63 | % |
| annuity | 0.0647 | % |

**Table A2.3.** Economic Parameters from CER



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## 13.4 RESULTS

In figure A2.3, the results are considered in terms of yearly costs of a cable circuit with a rating of 1GW.

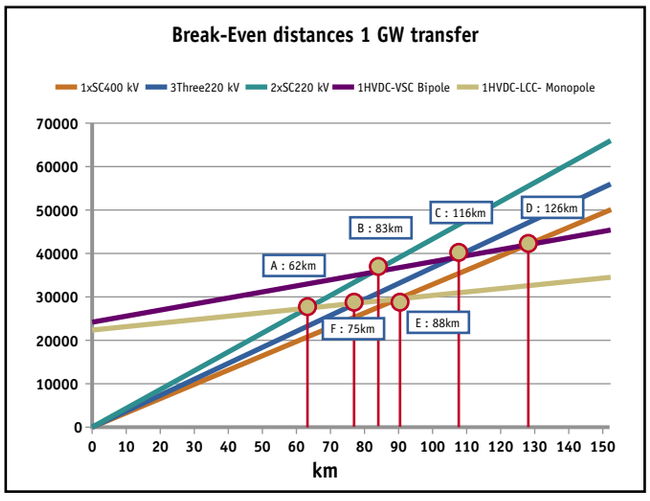


**Figure A2.3.** Break-Even distances

As previously discussed the losses have been calculated using a 40% yearly load factor for AC and an 80% for HVDC. Therefore, the comparison is not consistent with HVDC, but the assumption is justified by the HVDC control capabilities that allow a better use of infrastructures in any of the considered Load/Generation scenarios.

From figure A2.3, AC technology demonstrates its cost effectiveness for distances within 60-90 km. In particular, for a 1 GW power transfer, the 400 kV benefits from lower installation costs. However this is the realistic maximum distance for this technology, as for longer distances, transmission power transfer efficiency decreases, see figure A1.4.

Conventional HVDC is the best for longer distances, having a break-even point with 400 kV AC, at about 88 km in this test case. From this distance onwards, it is the most cost effective for point-to-point connections.

A multiple circuit three-core cable is also an AC effective solution, with 75 km break-even with DC-LCC; it can be used for longer lengths, i.e. 100 km with an acceptable transmission efficiency.



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Single core 220 kV does not offer great performance for this test scenario. It suffers from an overall high investment cost. However it might be of interest in the case of upgrading AC to DC scenarios as the 220 kV voltage, may be possible to be converted to support 320 kV DC.

VSC technology appears the least attractive. Indeed many alternatives, may offer better performance, covering the whole range of point-to-point application.

VSC suffers from high operation costs, losses, both for the HVDC convertor units and for power transmission, due to a lower operating voltage compared to LCC.

However, VSC technology is not yet at a mature stage and improvements will be available in the near future. In particular HVDC losses are expected to reduce further to less than 1% overall.

Furthermore, not all technical considerations are considered in this analysis. VSC for instance has been selected in many cases because of its ability to connect between weak systems, which prevent LCC technology being selected. For this reason it is the most suitable technology for an HVDC offshore meshed grid concept.

VSC also has a smaller footprint due to reduced filtering requirements.



# 14 Appendix 3: Examples of Smart planning

The concept of "Smart Planning" is developed in the framework of the Expansion Strategy Plan as a technological aid to the development of the network to reduce the intrinsic 'Discretisation Effect' in the decision making process of the new infrastructure. This has some advantage in long term as it allows the risk associated with making large capital investments to be reduced, by postponed part of it, allowing the overall transmission system to make best use of the existing network over the period of dynamic evolution of the network, until such time that a need for further reinforcement becomes clearer. In particular, the concept addresses the issue of infrastructure utilisation over a long period, i.e. 20 years, in the Offshore Grid space.

At this time a decision as to whether to 'recycle' AC infrastructure into DC can be made.

This is of major importance as a move to a full DC solution has associated high investment costs which may not be justified in the early stages of network development.

Initial investigation with cable manufacturers, has confirmed that this may be technically possible provided the connection is planned for this purpose from its inception.

## 14.1 AC TO DC ADVANTAGES

In terms of advantages, the upgrading of AC infrastructure to DC has been already identified for the Spain-Morocco Interconnection Project [19]. In the first phase, a 700 MW AC Oil fluid filled cable has been installed with a vision for a total of four phases of development. The cable circuit design has been performed to allow for it to be ultimately used DC, in a quadrupole HVDC configuration. The final stage will have upgraded the transfer to 2000 MW.

When transforming an AC cable to DC, the increase in transmission performance is due to:

1) An increasing operating voltage, DC can be close to the AC peak, that is 1.41 time the AC operating voltage
1) An increasing in ampacity, DC avoids induced currents in the sheath and therefore reduces losses and increases ampacity.
2) A reduced number of conductors, from three to two for one circuit.

Overall, if we considered a single three-phase AC circuit, the gain would be:

i. 40% because of 1 above
ii. 50% because of 2 above
iii. 50% reliability on the cable

In the case of two AC circuits, the 50% reliability, can be substituted with an extra circuit (i.e. 3 single poles DC circuits) giving a further 50% gain to the transmission capacity.



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## 14.2 SUBMARINE CABLE AND AC/HVDC TECHNOLOGY

The aforementioned advantages can be exploited using Oil filled and XLPE cable. MI PPL cable is not suitable for this multipurpose use.

Therefore, in this report, the 'Smart Planning', concept is addressed to Submarine Cable scenarios which involve XLPE cables.

The transformation from an AC to DC circuit should therefore be considered as HVDC-VSC technology.

## 14.3 EXAMPLE OF APPLICATION

This example of an application is demonstrated from a portion of the subset solution shown in figure A3.1, where a Mixed AC/DC grid has been proposed as solution of the ESP optimisation process.

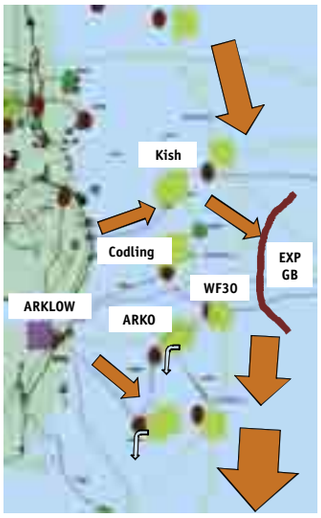


**Figure A3.1.** Irish Sea Mixed AC/DC

The focus of the discussion is the ARKLOW-ARKO-WF3-EXP_GB pathway, a network development synergy between connecting to Wind farm, ARKO and a Future WF3 and Interconnecting Ireland and Britain.

We assume there are 4 stages of wind offshore expansion, and corresponding potential solution for their connection in a dynamic evolving grid. This is shown in Figure A3.2.



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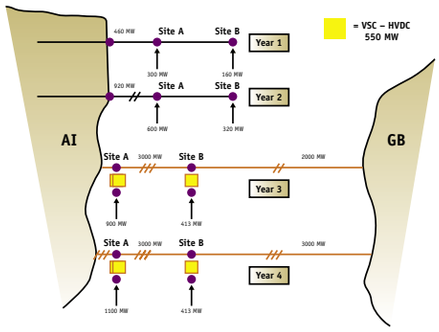
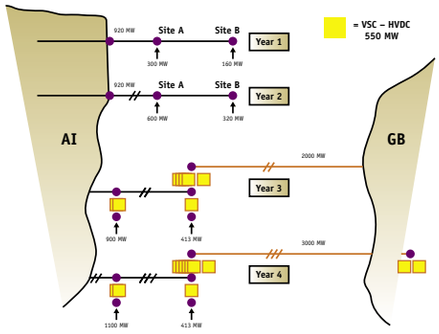
Three solutions are proposed in order to reach the following objectives in the final year:

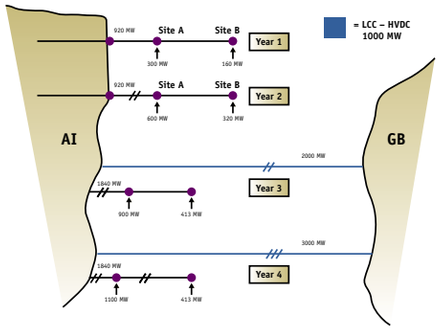
1) Connection of Offshore Wind Farms
2) A final Interconnection capacity of 3000 MW




**a) AC to DC-VSC scenario**




**a) AC 400 kV and DC-VSC Off to GB**




**c) AC 400 kV and DC-LCC AI to GB**

**Figure A3.2.** Dynamic Expansion Alternatives



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In the estimation of the total costs, capital costs as well as losses are considered according to data described in the report for any type of technology. Load factor has been assumed 80% in this case for simplicity, and not the typical AC technology load factor due to the use of power control to make better use of the capacity and still maintain the network within acceptable limits post contingency.

In Figure A3.2 Scenario a), the flexibility of conversion to DC-VSC network is assumed. It is considered at year 3 (stage), where from a double AC a triple DC is obtained with a 3.2 times capacity gain. Initial AC is 220 kV.

In Figure A3.2 Scenario b), AC technology is retained over the 4 stages as 400 kV. DC technology is implemented at year 3 (stage) directly from the last offshore wind farm to Britain.

In Figure A3.2 Scenario c), a more traditional approach is selected, considering a radial connection to Ireland for offshore generation and an onshore point-to-point link from AI to GB interconnector. 2 GW are assumed by year 3 and an extra 1 GW by year 4.

In the base case, geographic distances are as shown in fig.A.3.3

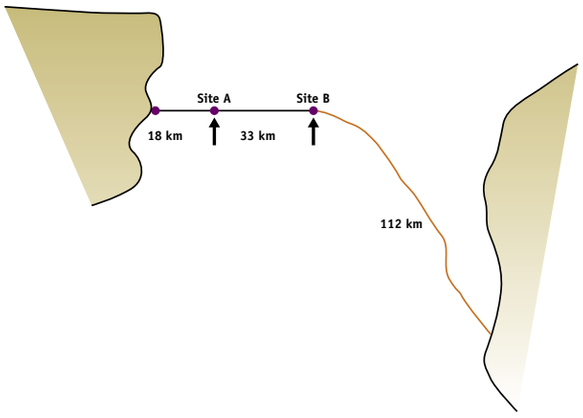


**Figure A3.3.** Geographical Distances

Sensitivity analysis has been performed, by changing the distance of Site A from the shore; from 18 to 72 km. the other intermediate distances remain unchanged.



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Cash flow base case is shown in table A3.1

| | | AC to DC-VSC | | AC 400kV+VSC | | AC 400kV+ LCC | |
|---|---|---|---|---|---|---|---|
| | | invest | operation | invest | operation | invest | operation |
| years | | (keuro) | keuro/y | | | | |
| 0 | 2013 | 165240 | 1377.231 | 256062.2 | 1632.927 | 197294.9 | 1632.92652 |
| 1 | | | 1377.231 | | 1632.927 | | 1632.92652 |
| 2 | | | 1377.231 | | 1632.927 | | 1632.92652 |
| 3 | | | 1377.231 | | 1632.927 | | 1632.92652 |
| 4 | 2017 | 58320 | 1863.312 | 0 | 1632.927 | 0 | 1632.92652 |
| 5 | | | 1863.312 | | 1632.927 | | 1632.92652 |
| 6 | | | 1863.312 | | 1632.927 | | 1632.92652 |
| 7 | | | 1863.312 | | 1632.927 | | 1632.92652 |
| 8 | 2021 | 1307165 | 23341.75 | 1320586 | 27066.64 | 1041229 | 16034.532 |
| 9 | | | 23341.75 | | 27066.64 | | 16034.532 |
| 10 | | | 23341.75 | | 27066.64 | | 16034.532 |
| 11 | | | 23341.75 | | 27066.64 | | 16034.532 |
| 12 | 2025 | 447552 | 30375.78 | 788324.2 | 40599.96 | 520614.3 | 22418.8715 |
| 13 | | | 30375.78 | | 40599.96 | | 22418.8715 |
| 14 | | | 30375.78 | | 40599.96 | | 22418.8715 |
| 15 | | | 30375.78 | | 40599.96 | | 22418.8715 |

**Table A3.1.** Basecase Cash Flow.

For evaluation of the alternatives the Net Present Value Method is assumed with a discount rate of 5.63% (in line with regulated rate of return in Ireland).

| AC to DC-VSC | | AC 400kV+VSC | | AC 400kV+ LCC | |
|---|---|---|---|---|---|
| invest | operation | invest | operation | invest | operation |
| (keuro) | keuro/y | (keuro) | keuro/y | (keuro) | keuro/y |
| 165240 | 1377 | 256062 | 1633 | 197295 | 1633 |
| 0 | 1304 | 0 | 1546 | 0 | 1546 |
| 0 | 1234 | 0 | 1463 | 0 | 1463 |
| 0 | 1169 | 0 | 1385 | 0 | 1385 |
| 46846 | 1497 | 0 | 1312 | 0 | 1312 |
| 0 | 1417 | 0 | 1242 | 0 | 1242 |
| 0 | 1341 | 0 | 1176 | 0 | 1176 |
| 0 | 1270 | 0 | 1113 | 0 | 1113 |
| 843397 | 15060 | 852057 | 17464 | 671812 | 10346 |
| 0 | 14258 | 0 | 16533 | 0 | 9794 |
| 0 | 13498 | 0 | 15652 | 0 | 9272 |
| 0 | 12778 | 0 | 14817 | 0 | 8778 |
| 231951 | 15743 | 408562 | 21042 | 269817 | 11619 |
| 0 | 14904 | 0 | 19920 | 0 | 11000 |
| 0 | 14109 | 0 | 18858 | 0 | 10413 |
| 0 | 13357 | 0 | 17853 | 0 | 9858 |
| 0 | | 0 | | | |
| 1287434 | 124316 | 1516681 | 153009 | 1138924 | 91950 |
| Grand Totals PWV | 1411749.657 | | 1669689.195 | | 1230873.722 |

**Table A3.2.** Net Present Value: Basecase



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From Table A3.2, it can be seen the strategy C, is the most economic viable over the planning period. The benefit of LCC technology and the relative long distances of the overall point to point interconnection at 160 km make this technology the most efficient.

The AC to DC strategy shows, a 13% cost increase and strategy B a 30%. The phased introduction from AC and DC and hence cost are not sufficient in this case to mitigate the disadvantages of investing in a VSC solution and the associated losses.

Economic sensitivity analysis has been performed, aimed at verifying the effect of strategic offshore development options. HVDC units are source of large losses, especially VSC; however, when transmitting power this is partially mitigated by the greater efficiency of a DC link compared to AC.

By increasing the distance of site A from the Irish shore, it is expected the difference in NPV cost between the alternatives will be reduced, particularly for LCC (alternative C) which is much more affected by the radial AC connections of wind farm Offshore over the whole planning period.

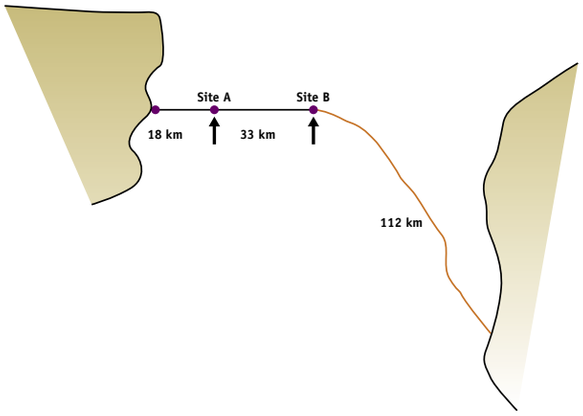


**Table A3.3.** Net Present Value: Sensitivity analysis of position of site A

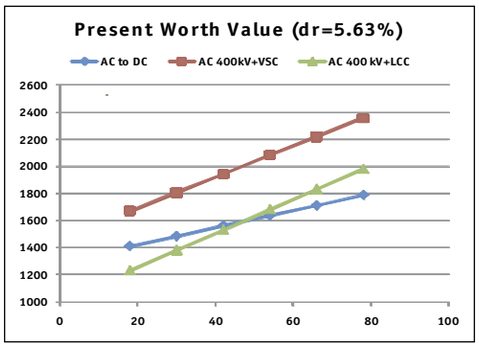


**Figure A3.4.** NPV sensitivity



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From figure A3.4, a break-even distance is obtained for site A, at about 48 km, where alternative A and C are economical equivalent.

It is interesting to note that the NPV cost of DC-VSC becomes a lower cost alternative at a much shorter cable length than the distances calculated in 14.3, based on the same 15 year period to progress through the four stages of development. This is because there are more synergies exploited in these scenarios with a more complex system which allows the costs a single solution to resolve more than the one problem.

The use of LCC (alternative C), is less likely to be able to provide network development synergies as the connection of the windfarms and interconnection are not provided by shared assets but are split into two distinct network assets.

In comparison, a conversion from AC to DC (alternative A) provides flexible and can be further developed from either site A or B or both in future, creating a meshed DC topology, unlike LCC (alternative C) has a more rigid structure which oblige to reinforce from the AI and GB shores.

The use of an AC and VSC (alternative B), is the more expensive for any length. Indeed in this simple comparison of a combined DC and AC technology in interconnected offshore networks, it is the worst performer over all stages of development. This is because the drawbacks of both technologies are combined in this mixed solution both in term of economical efficiency, ability to perform multiple network duties and the efficiency of transmission.

In the evaluation, reliability of the network plus losses is not accurately modelled. An examination using a more detailed system modelling approach would be needed.

However, with reference to figure A3.2, it can be seen that in LCC (alternative C), the offshore network power flow, is compelled to flow back to AI for the whole planning period, whatever the market conditions between AI and GB. Alternatively alternative A and C, from this perspective, are more flexible, allowing the power to be transfer to AI and GB from half a way. This can provide further efficiency to the operating costs.



# 15 Appendix 4: HVDC Models for Expansion Planning in MIXED AC/DC meshed Transmission Systems

## 15.1 INTRODUCTION

The increasing complexity and scale of the transmission network, the market driven interest in transferring power over long distances, and need for power flow control as a consequence of the increasing penetration variable generation sources, has been a driver factor for the need of DC circuits not just as point to point connections but also in a more complex meshed, multi-terminal structure. These must somehow be integrated with the existing and/or future AC network.

Therefore it is of paramount importance to develop tools able to manage this mixed AC/DC nature which is part of the concept of the future 'Smart' Transmission system.

The new HVDC model used as part of this analysis inside an AC grid using the DCLF approach is discussed below. The model was also conceived in order to benefit from Mixed Integer Programming (MIP) procedure for expansion planning (ESP) studies.

## 15.2 HVDC SYSTEMS IN THE ESP STUDIES

### 15.2.1 Nodal Current Injection Approach for DC Grids

The DC equation is written assuming:

- $N_d$ node numbers,
- $M_d$ branches,
- $R_{i,j}$ line, cable, transformers, HVDC, etc.., (the resistance of the branch connecting node i-th, with node j-th).

The following equation can be found:

$$I_{i,j} = \frac{V_i - V_j}{R_{i,j}}$$

Where $V_i$ and $V_j$ are DC voltage at nodes I and j respectively.

The balance at each node is the following:

$$\sum_{j \in \alpha i} \frac{V_i - V_j}{R_{i,j}} = 0 \quad i = \{1,2,\ldots,N_d\} \quad (1)$$



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Where $\alpha$ is the subset of nodes connected to the i-th

In case of some known flows on branches, imposed for instance by a suitable control or system requirement, the equation becomes:

$$\sum_{j \in \alpha i} \frac{V_i - V_j}{R_{i,j}} = 0 \quad i = \{1,2,\ldots,N_d\} \quad (1)$$

The solution of such a system of equations describes the full DC grid in steady state conditions with no approximation.

### 15.2.2 The linear DCLF Approach for AC Grids

In this case, similar equations can be written for the AC grid, assuming however that no losses are present and that voltage is similar to the nominal value in each node

Assuming:

- *N* number of AC nodes
- *M* number of AC branches,
- $X_{i,j}$ the longitudinal reactance between node i-th and j-th
- $T_{i,j}$ the active power flow on this branch from I to j, is given by::

$$T_{i,j} = \frac{V_i V_j K_{i,j} (\vartheta_i - \vartheta_j)}{X_{i,j}}$$

Where, are the absolute value of Voltages, the phase angles, at node I and j and the transformer ratio between node I and j respectively.

For any node a balance equation of active power can be written as follows:

$$\sum_{j \in \beta i} \frac{V_i V_j K_{i,j} (\vartheta_i - \vartheta_j)}{X_{i,j}} = 0 \quad i = \{1,2,\ldots,N\} \quad (2)$$

In case some of the flows are known in some branches:

$$\sum_{j \in \beta i} \frac{V_i V_j K_{i,j} (\vartheta_i - \vartheta_j)}{X_{i,j}} = J_0 \quad i = \{1,2,\ldots,N\}$$

Therefore the formula above will give the active power flow ($J_o$) in any AC grid asset for steady state conditions.



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### 15.2.3 AC/DC Similarities

When comparing (1) with (2), the DC solution has some similarities with AC, in particular with the following assumptions.

1) Voltage level is unique in DC, $U_{nom}$, therefore, $K_{i,j}$ will be considered equal to 1 for all the branches
2) It is assigned the nominal voltage in DC as $V_i = \sqrt{U_{nom}}$ .
3) The longitudinal reactance are substituted by corresponding resistances
4) The power injection in the nodes is replaced by current injections.

Therefore by using four assumptions above, a tool able to solve an AC grid can also solve a DC grid.

Due to these assumptions, results must also be considered accordingly:

1) Flows on DC links are currents
2) Phase angles in DC nodes are the Voltages in p.u.

### 15.2.4 Linear Approximation of AC/DC Interface Constraint

A mixed AC/DC system can be represented as two different subsystems, suitable interfaced through HVDC units in some nodes. The equations (outlined below), link the AC and DC circuit parameters.

*c)AC/DC interface*

The AC/DC system are interfaced somewhere with HVDC devices. As AC is described with only active power flow equations, it is a simple assumption to use active power flows to define constraints between AC and DC equipment. In particular, considering for the moment an ideal HVDC, it is assumed there that AC and DC active power will be equal.

For any i, j index associated with AC/DC interface, the following can be written:

Where

$$P_i = U_j \cdot \mathrm{I}_j \qquad (3)$$

$P_i$ = Active Power on the AC grid injected into the i-th converter;

$U_j$ = DC Voltage

$\mathrm{I}_j$ = DC Currents

As $U_j, \mathrm{I}_j$ are DC variables, they are related with a non-linear equation, see (3).



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Therefore, the mixed AC/DC system can be fully described in the interrelated parameters by introducing some NON linear constraints into the model, in particular due to the premise of equality of active power transfer through the AC/DC interfaces.

Using equation (3) for sake of simplicity with the index subscripts removed:

$$P = U \cdot I$$

Where $P, U, I$ are, the AC Active Power, the DC nodal Voltage and Current respectively, the equation can be written, as first order approximation as follows around a $(U_0, I_0)$ solution:

$$P = U \cdot I \cong U_0 I_0 + U_0 \cdot (I - I_0) + I_0 \cdot (U - U_0)$$

With reference to figure A4.1, dividing the DC voltage and DC current in small intervals k-th:

$$P_i = U_i \cdot I_i \cong U_{0i} I_{0i} + U_{0i} \cdot (I_i - I_{0i}) + I_{0i} \cdot (U_i - U_{0i}); \qquad i = \{1,2,\ldots,k\}$$

Where:

$U_i, I_i$ DC variables defined in the i-th interval with ends

$U_{0i}, I_{0i}$ the coordinates of a suitable working point internal to the i-th interval.

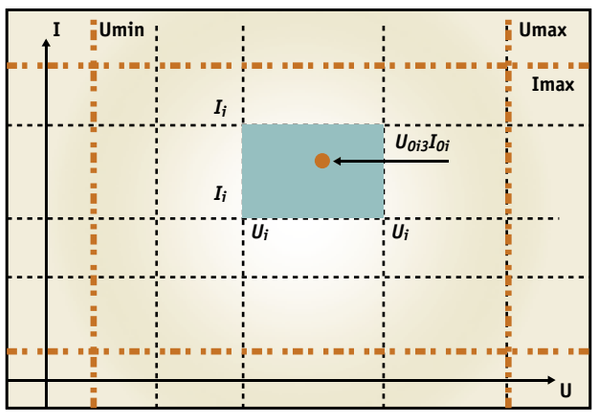


**Figure A4.1.** HVDC linearisation



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By assigning a value to P, on the AC side, an i-th interval must be chosen for the HVDC, which guarantee the fulfilment of the equation 3. The solution can be found, by evaluated P on the DC side for every subset of intervals, identified by the binary variable subset $(AP_i \quad i=\{1,2,..,k\})$, of the continuous variables $(P_i, F_i, IF_i, UF_i \quad i = \{1,2,\ldots,k\})$ and writing constraints where and interfacing AC/DC unit is located, as follows:

a) $F_i = U_{0i} I_{0i} + U_{0i} \cdot (IF_i - I_{0i}) + I_{0i} \cdot (UF_i - U_{0i}); \qquad i = \{1,2,\ldots,k\}$

b) $P_i = U_{0i} I_{0i} + U_{0i} \cdot (I_i - I_{0i}) + I_{0i} \cdot (U_i - U_{0i}); \qquad i = \{1,2,\ldots,k\}$

c) $P_{ac} - \sum_{i=1}^{k} P_i + \sum_{i=1}^{k} F_i + \sigma - \mu - \sum_{i=1}^{k} (U_{0i} \cdot I_{0i} \cdot AP_i) = 0;$

d) Only one linearization must be considered the feasible solution:

$$\sum_{i=1}^{k} AP_i = 1$$

## 15.3 PHASE SHIFTER TRANSFORMER (PST)

### 15.3.1 Simplified PST Model

A simple way to model a PST in a DCLF is to introduce a new independent variable which is able to modify the nodal phase angle.

As a consequence the active power through a link can be written in a more general format as (Variable definition same as 15.1 and 15.2 above):

$$T_{i,j} = \frac{V_i V_j K_{i,j} (\vartheta_i - \vartheta_j + \Delta\varphi)}{X_{i,j}}$$

Where the $\Delta\varphi$ represents the PST regulating angle capability.

The effect of the PST is like a modification of the physical reactance of the branch, see (4), so that in principal a desired power flow through the branch can be obtained by suitably adjusting the angle

$$X^*_{i,j} = X_{i,j} \frac{(\vartheta_i - \vartheta_j)}{(\vartheta_i - \vartheta_j + \Delta\varphi)} \qquad (4)$$

The criteria for the set up of the control angle may be introduced in a formula for general OPF problems.



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## 15.3.2 Candidate PSTs in a ESP tool for HVDC approximation

The HVDC model described in 15.2.4 is a detailed approach which overcomes the non-linearity by a suitable discretisation of the HVDC working characteristics. This discretisation then is solved by applying the MIP type of problem for the selection of the most profitable infrastructure. However, a single HVDC introduces many binary variables, i.e. 30-50 for reliable modelling, which may not be viable for large problems.

Therefore, in the chapter it is shown how a 'suitable PST' could in principle fulfil the job. In particular the PST can account for the power flow controlling feature that may have important consequences in the implementation of a reinforcement infrastructure strategy.

The idea is therefore to represent the AC/DC interface with an AC PST device whose power flows may be controlled by the PST device itself.

With reference to figure A4.3, an example is described where the two systems, AC and DC are connected through a device which makes the phase angles independent on both sides.

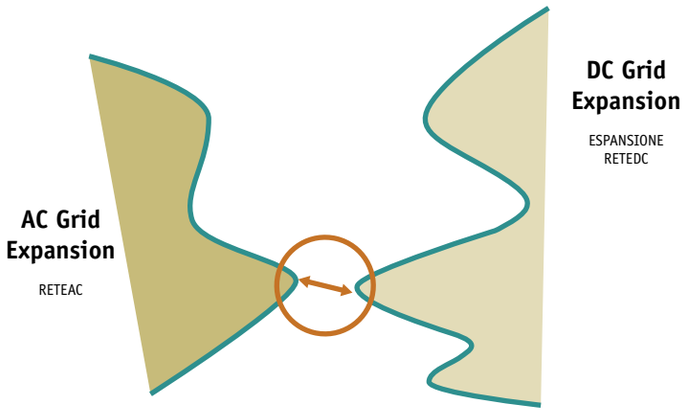


**Figure A4.2.** HVDC-PST

This model is an approximation which neglects losses in line with the approximation of the AC grid.



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## 15.4 THE MIXED AC/DC MODEL FOR ESPAUT

To summarise the aforementioned model developments, a MIXED AC/DC grid model can be represented in the ESPAUT tools, by using a fully equivalent AC linearised model where for the DC system the following equivalences have been account for:

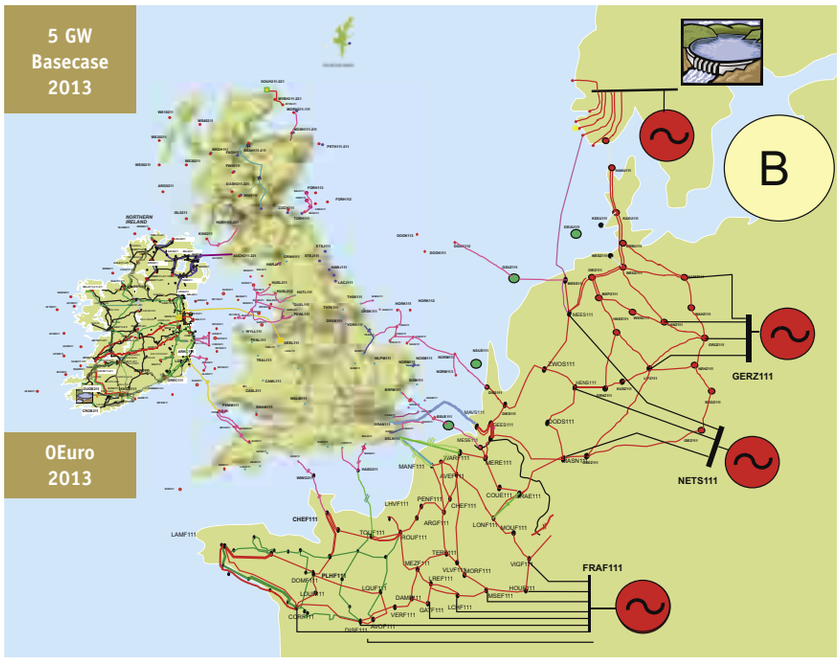
- Longitudinal 50 Hz reactance's are replaced by DC resistances
- The nominal DC voltage in kV is replaced by its square root value

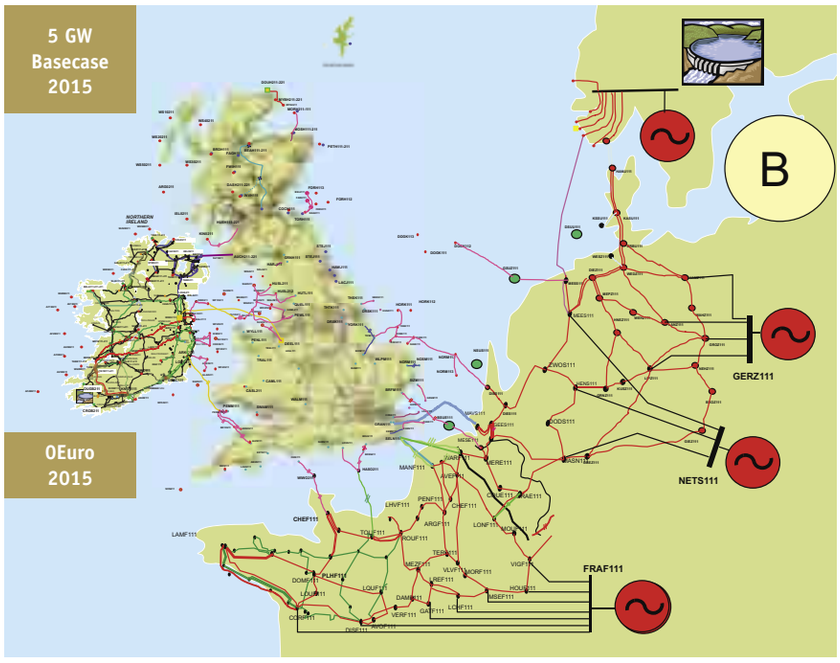
Finally the results of the DC side have the following correspondences:

- For DC nodes, phase angles are the DC voltages in p.u. of the nominal.
- For the DC branches, the power flows represent the currents in kA



# 16 Appendix 5: Pure AC Model Senstivity Results



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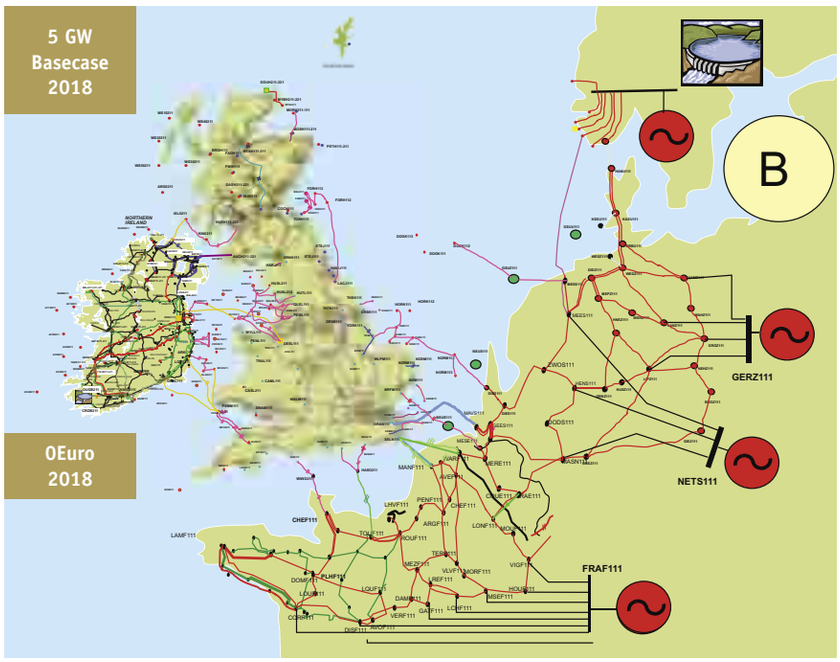


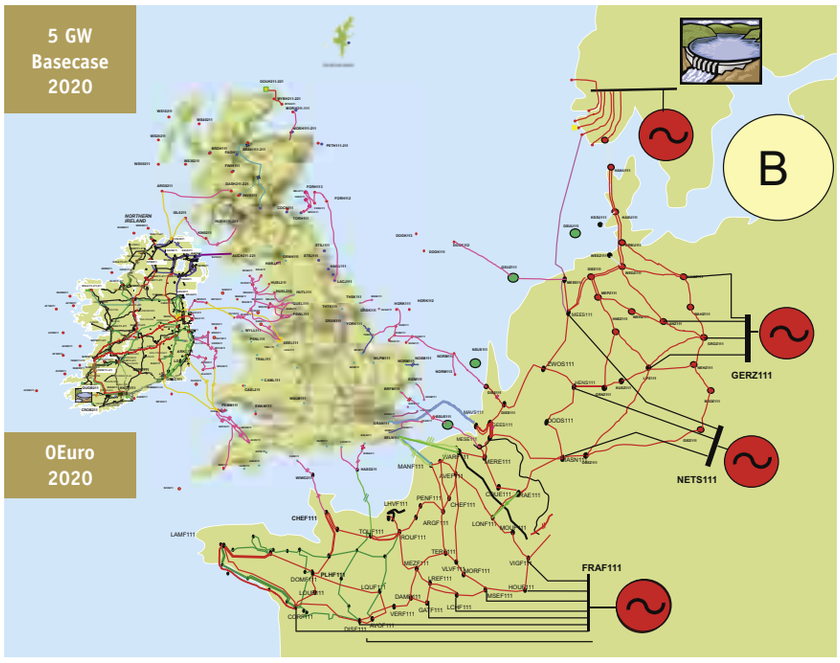




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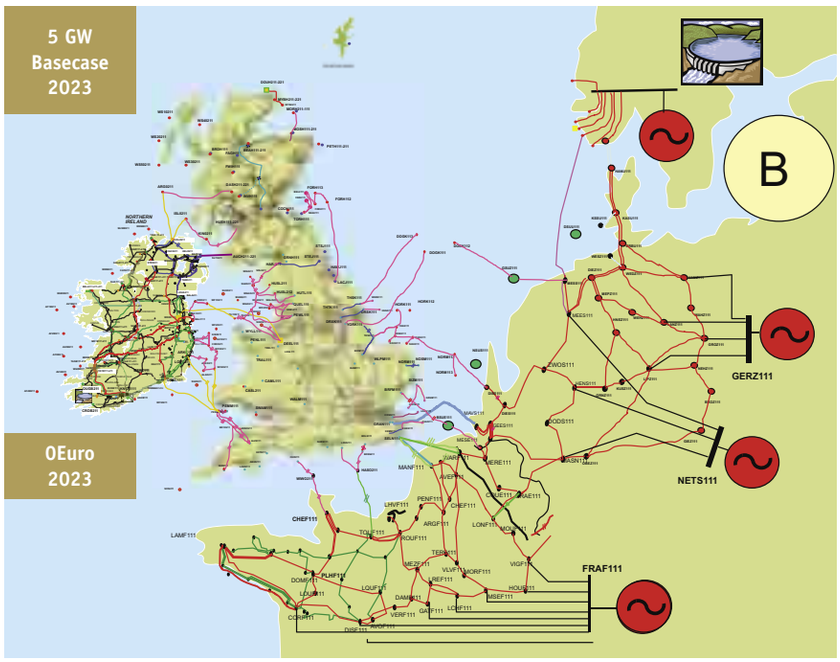


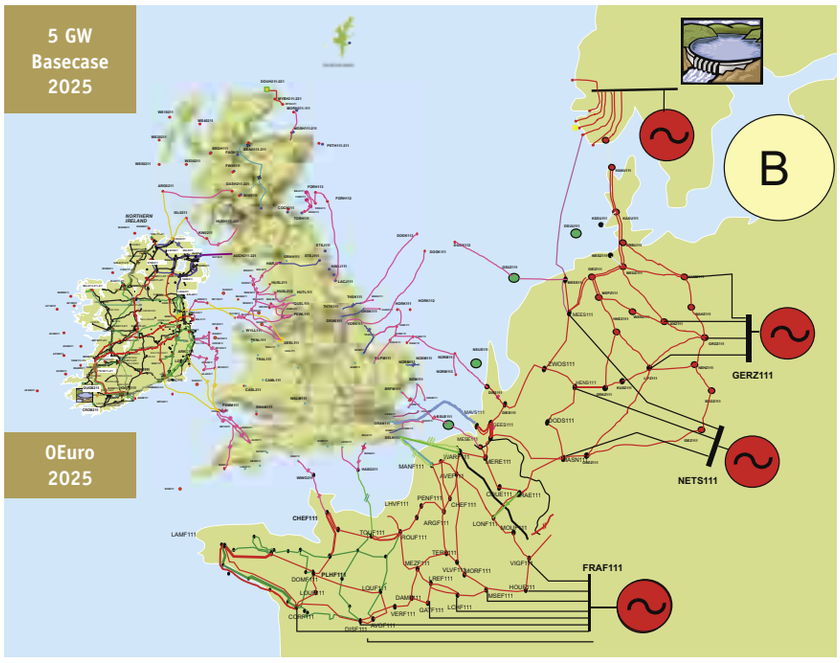




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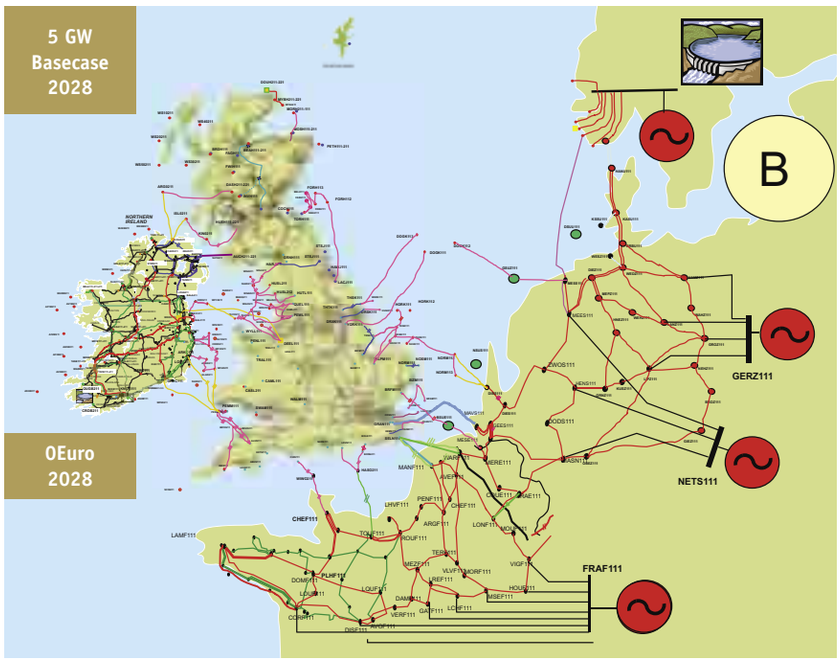


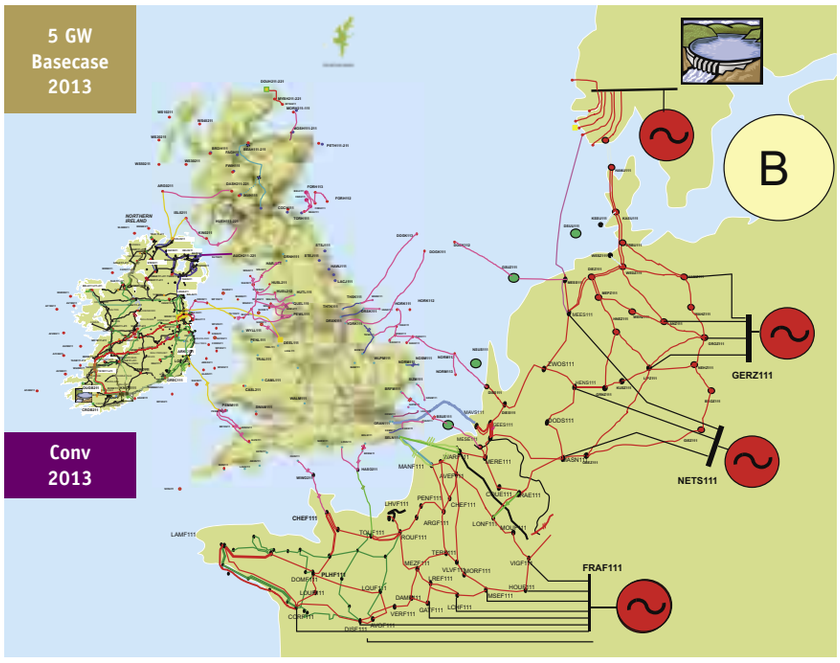




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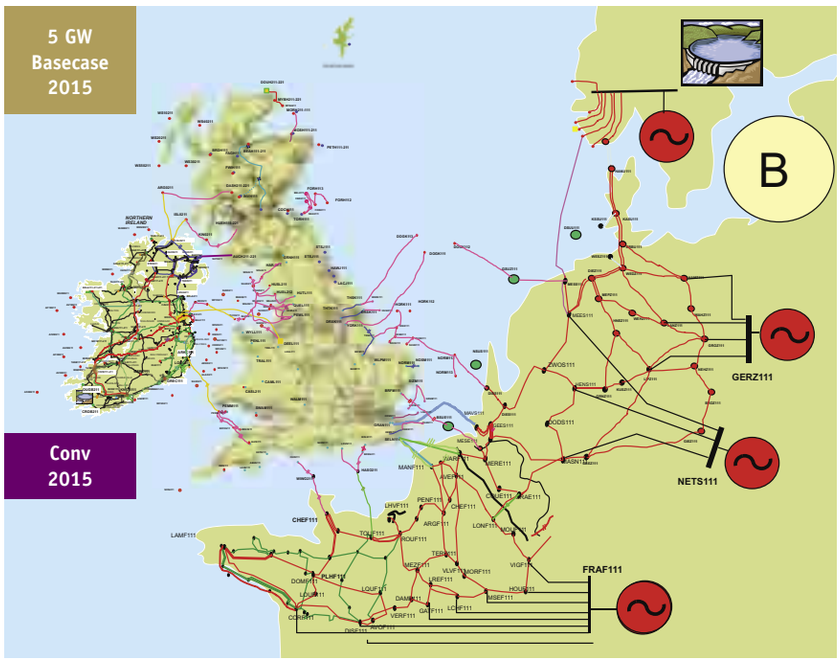


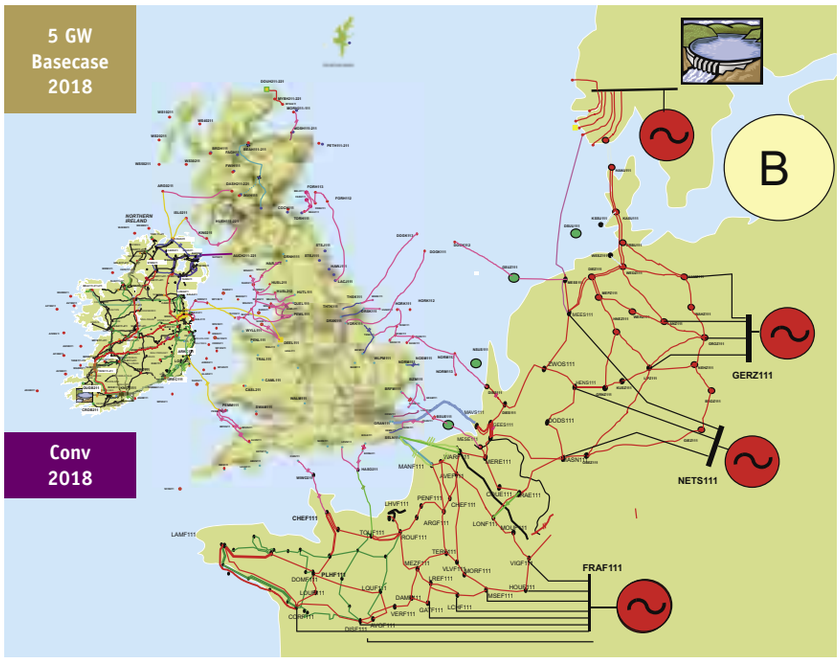




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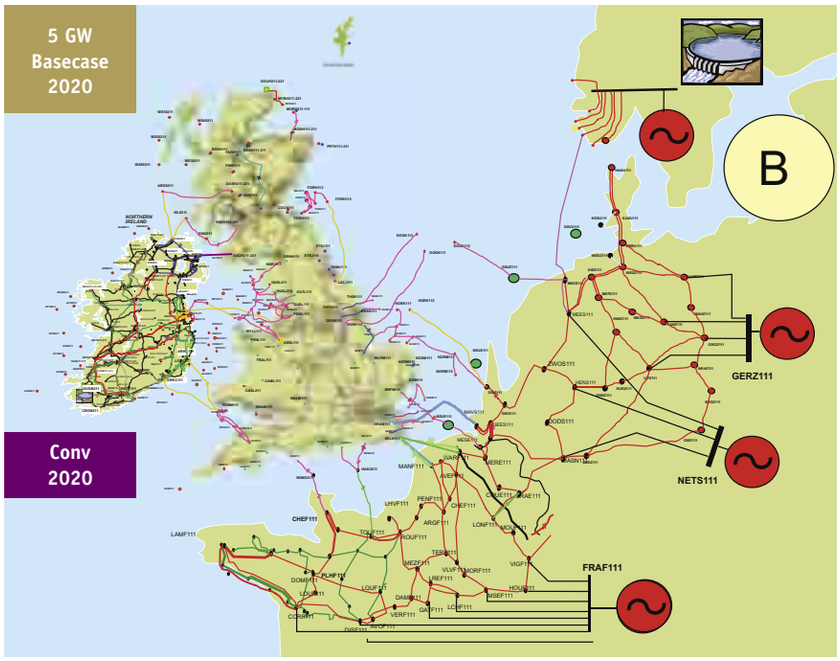


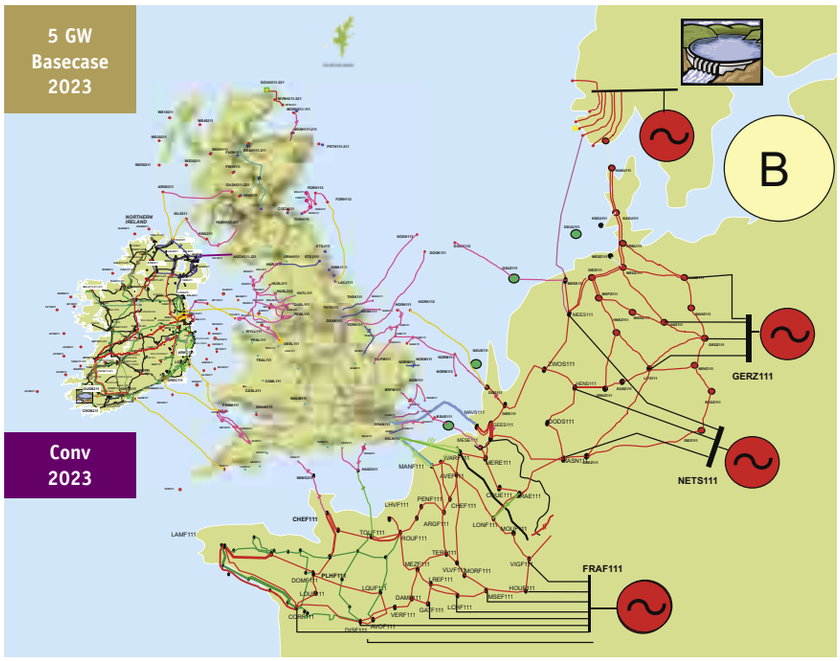




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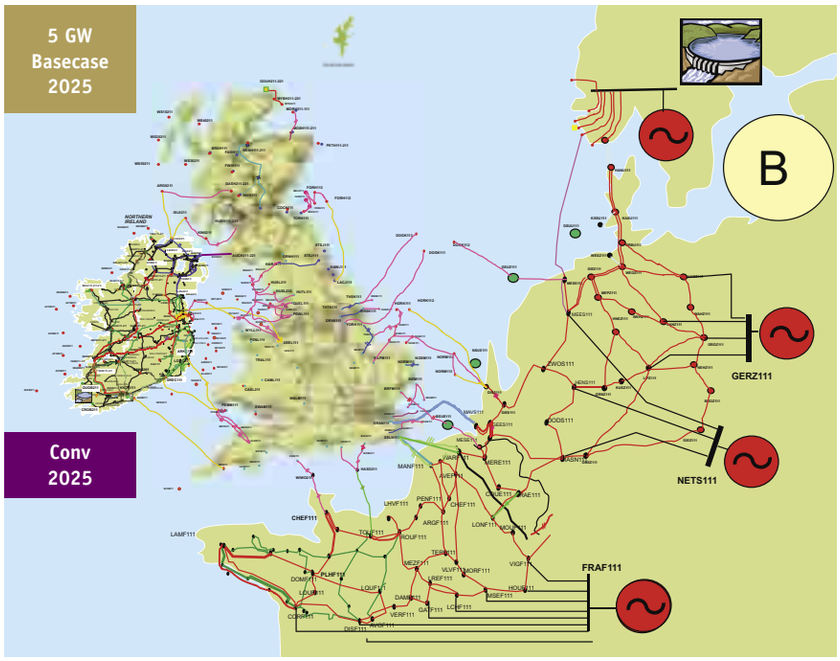


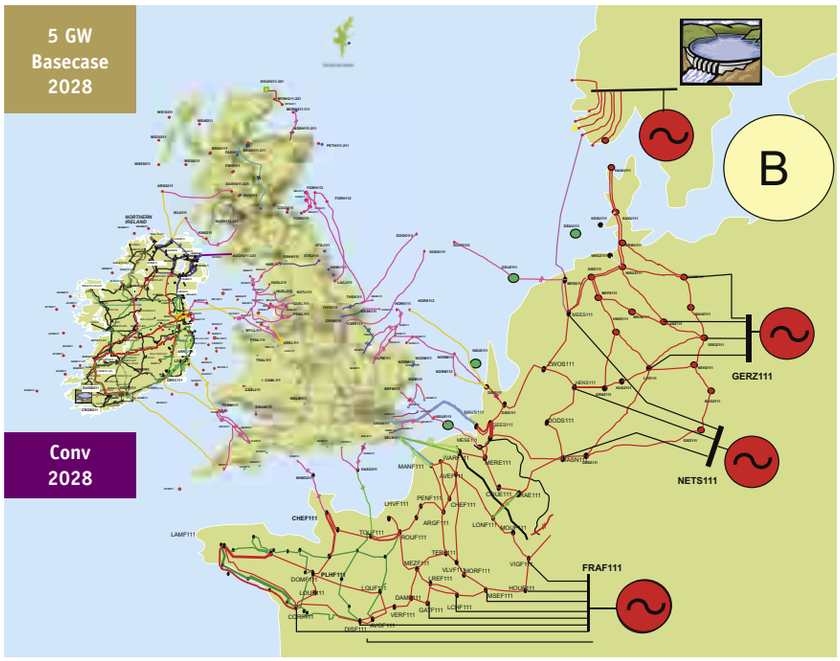




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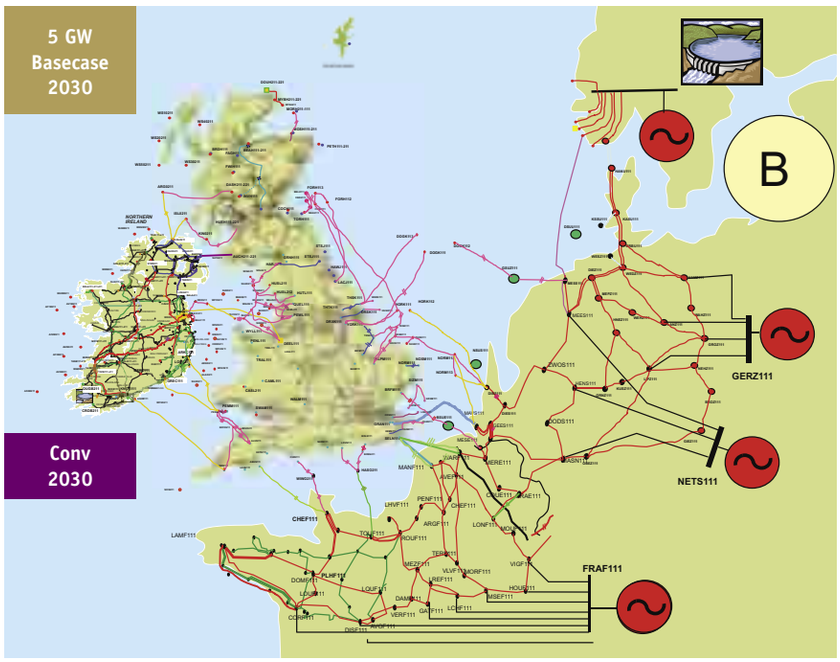


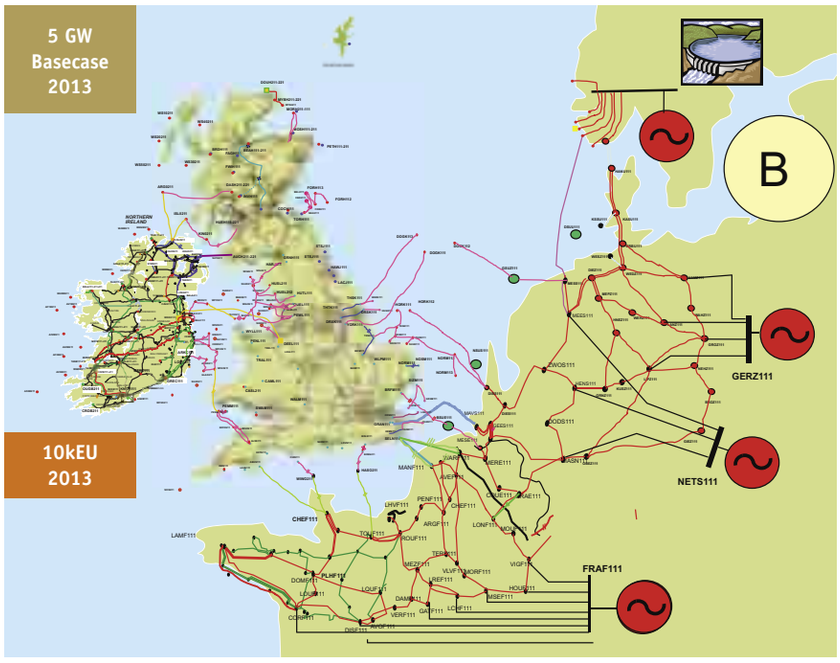




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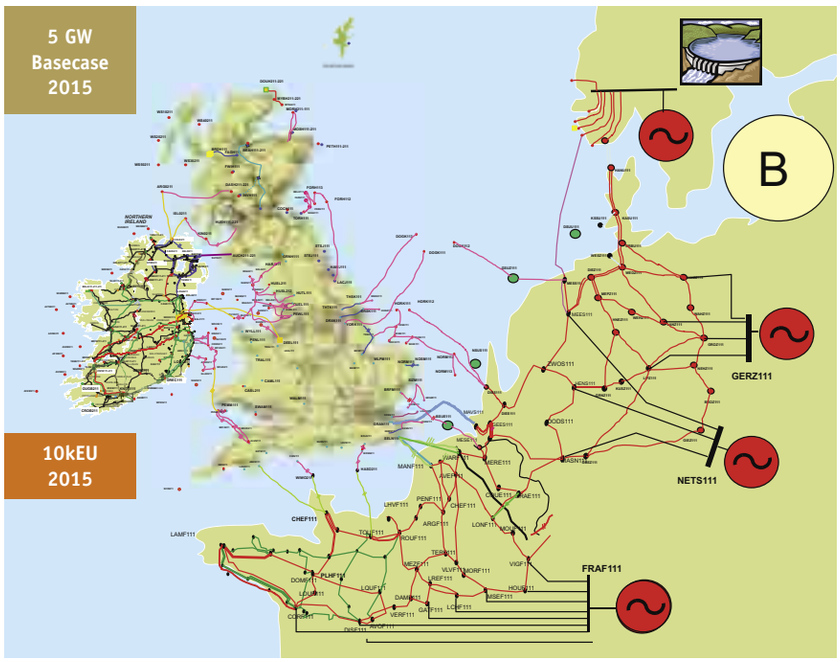


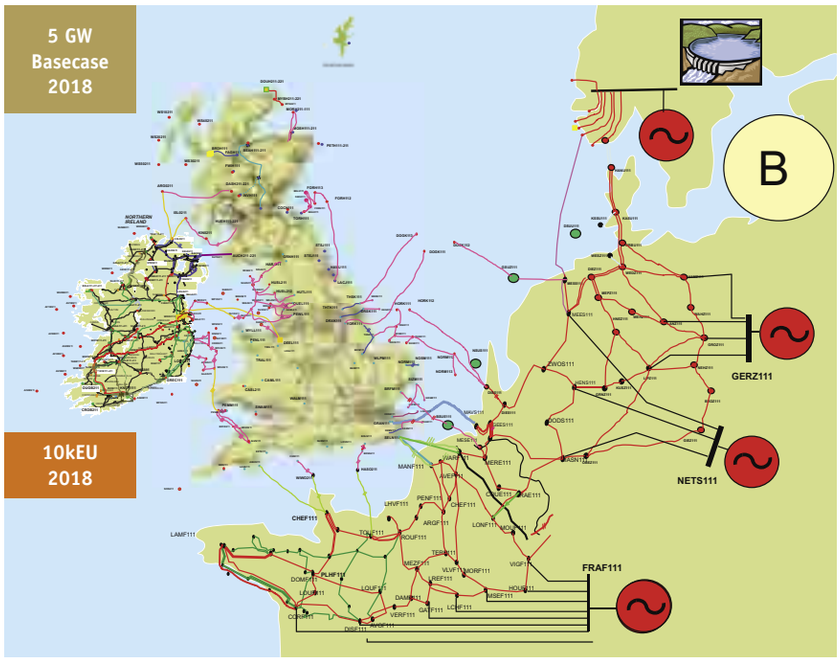




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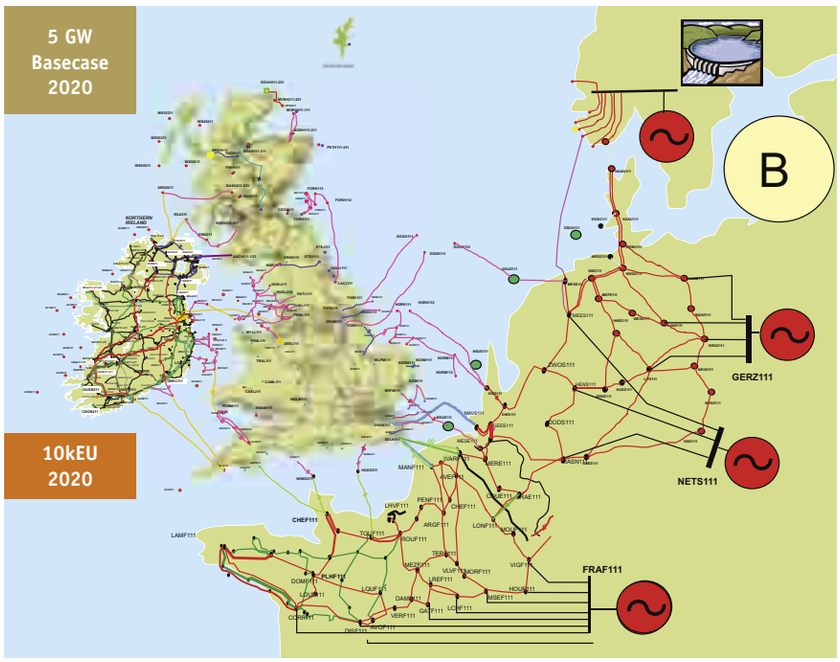


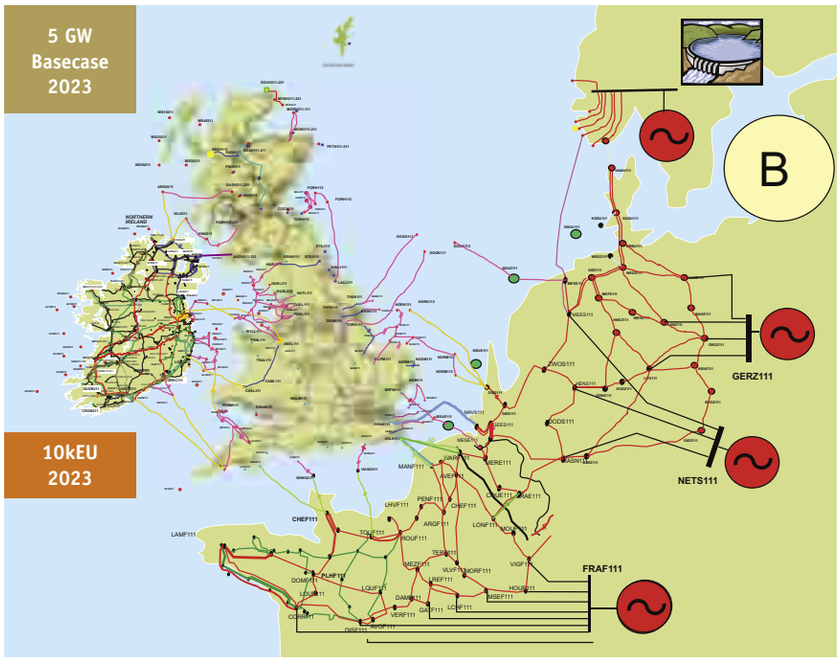




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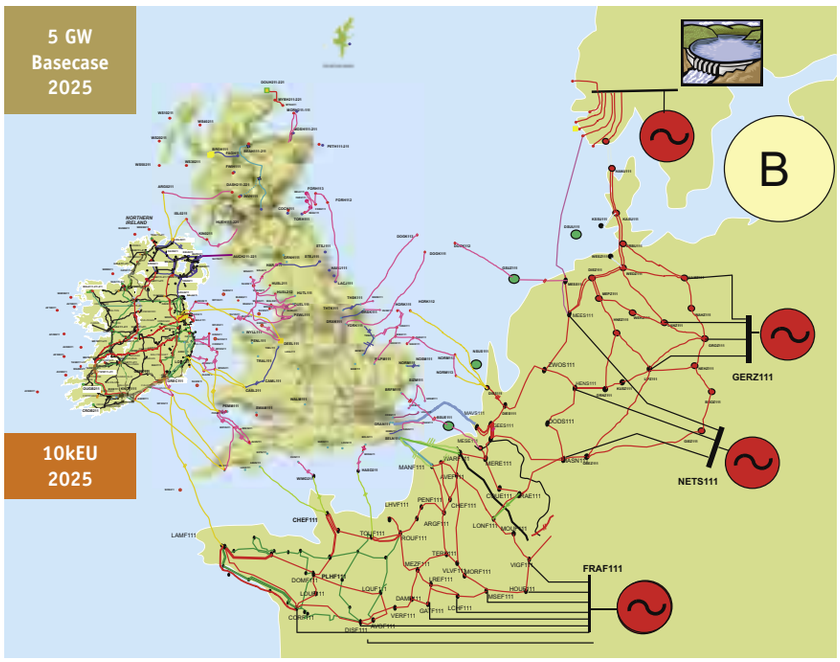


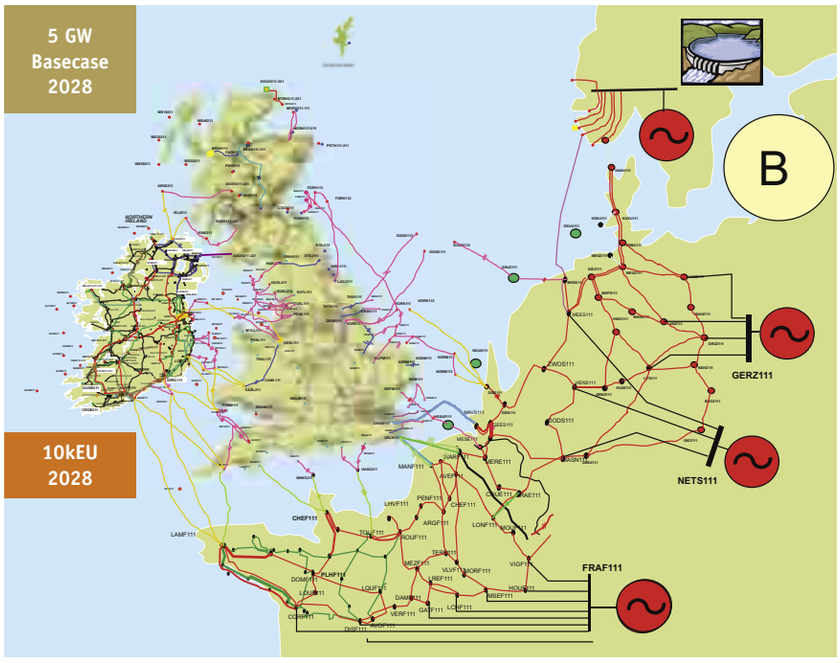




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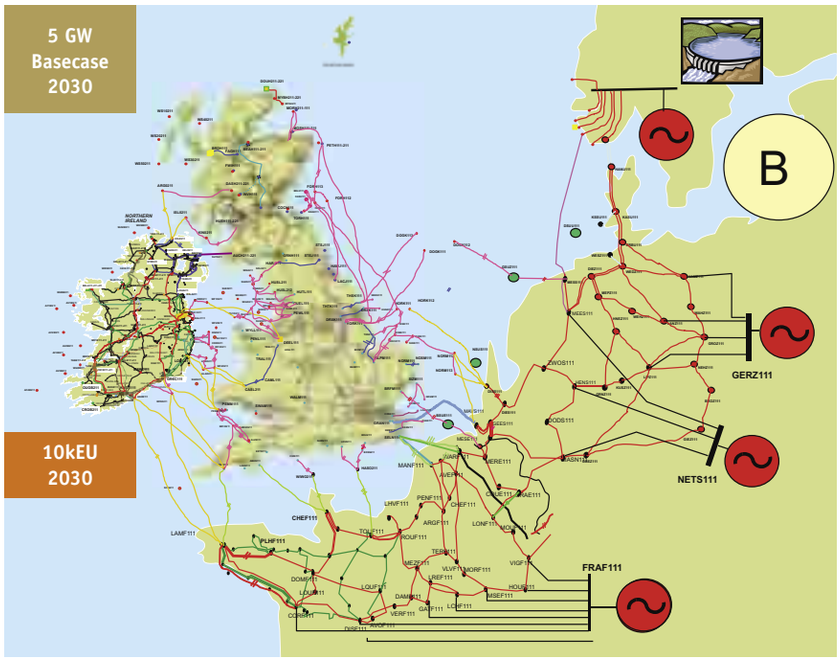
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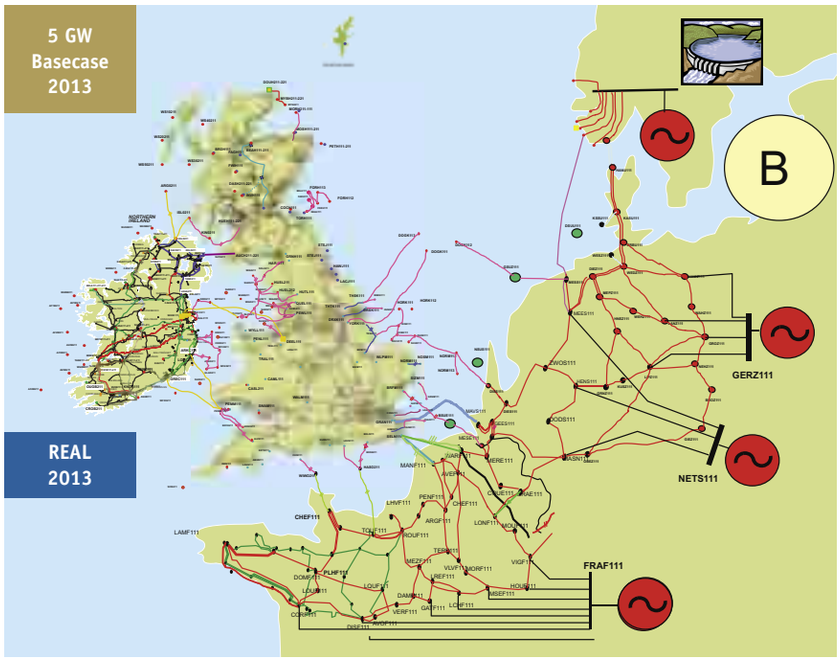


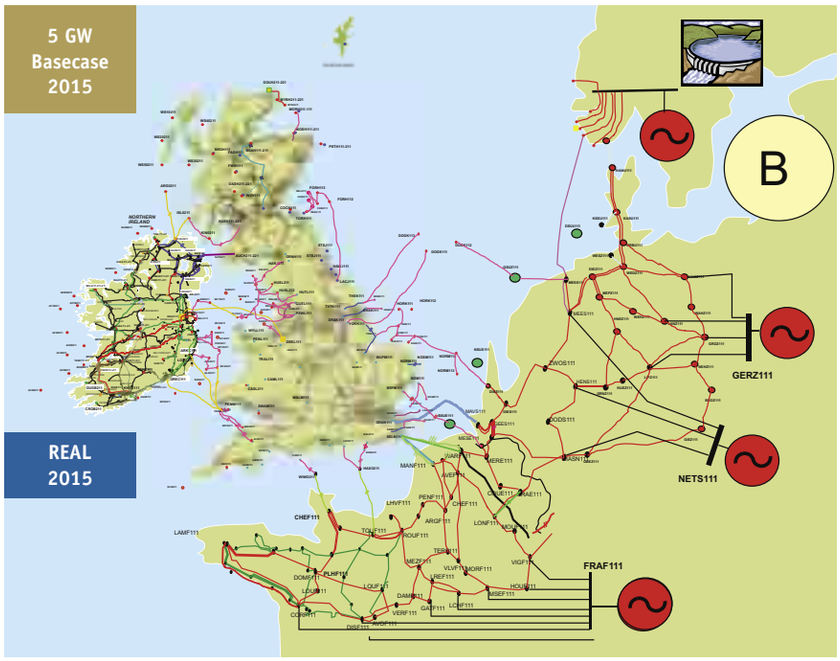




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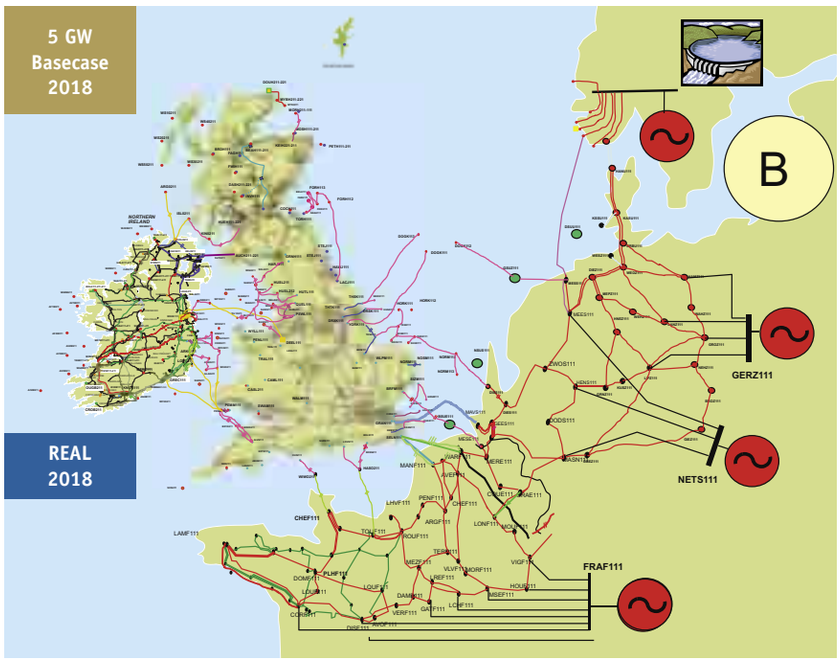


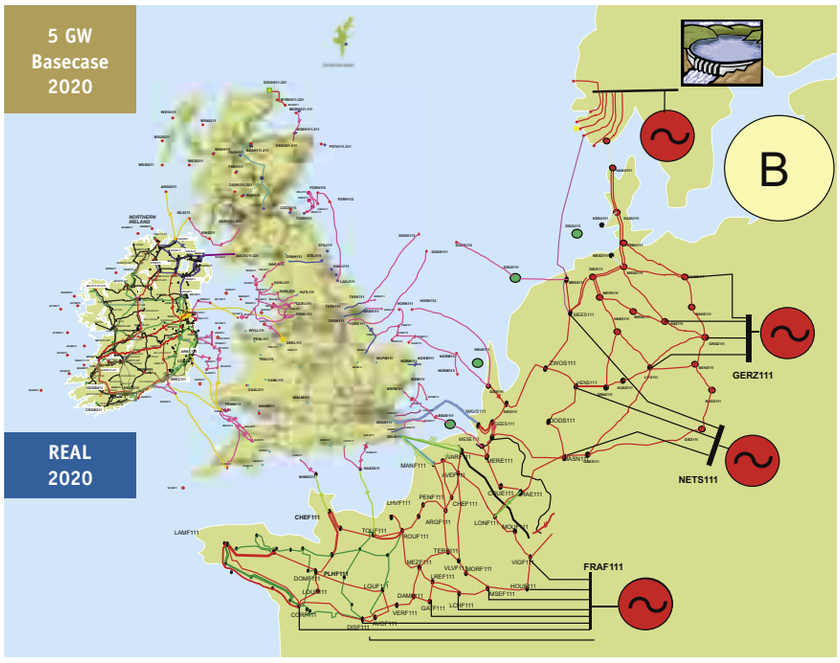




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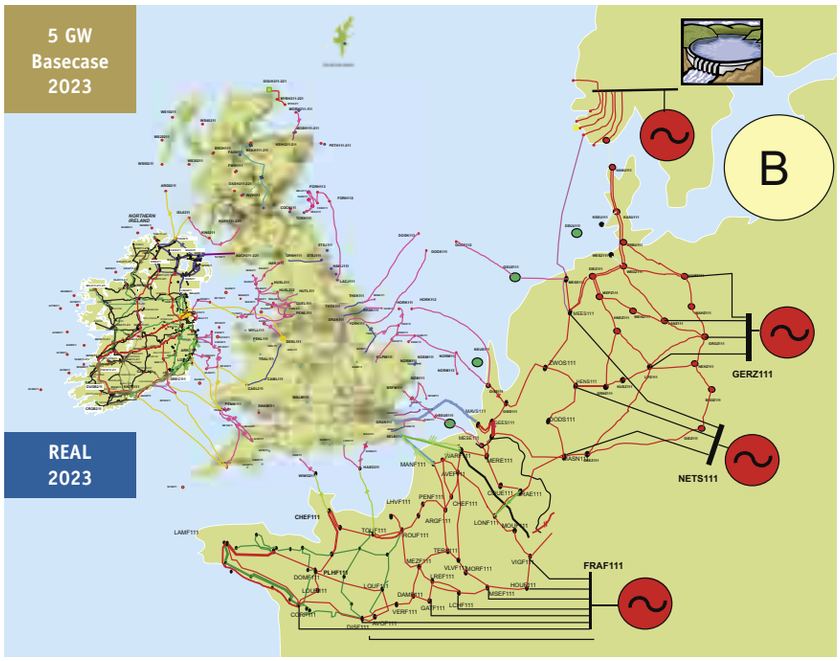


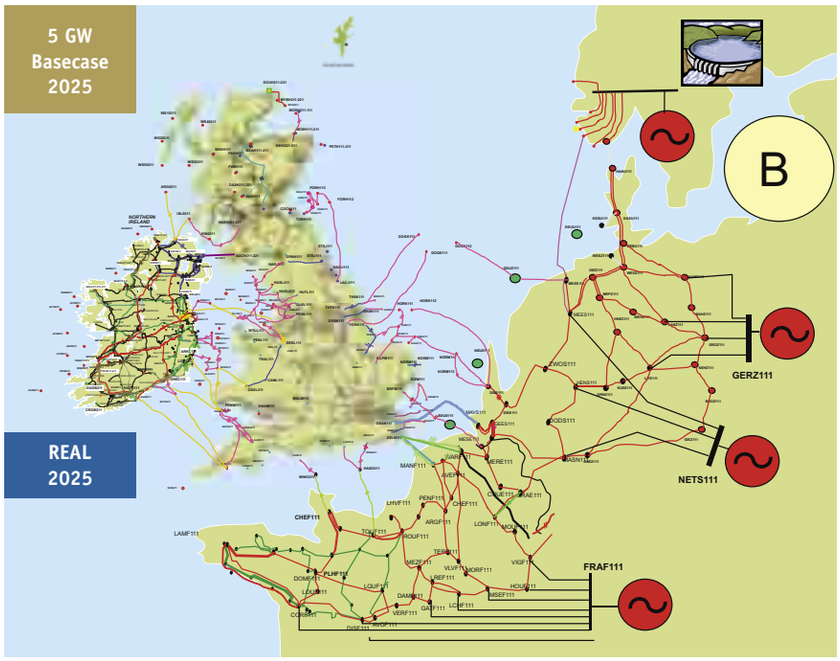




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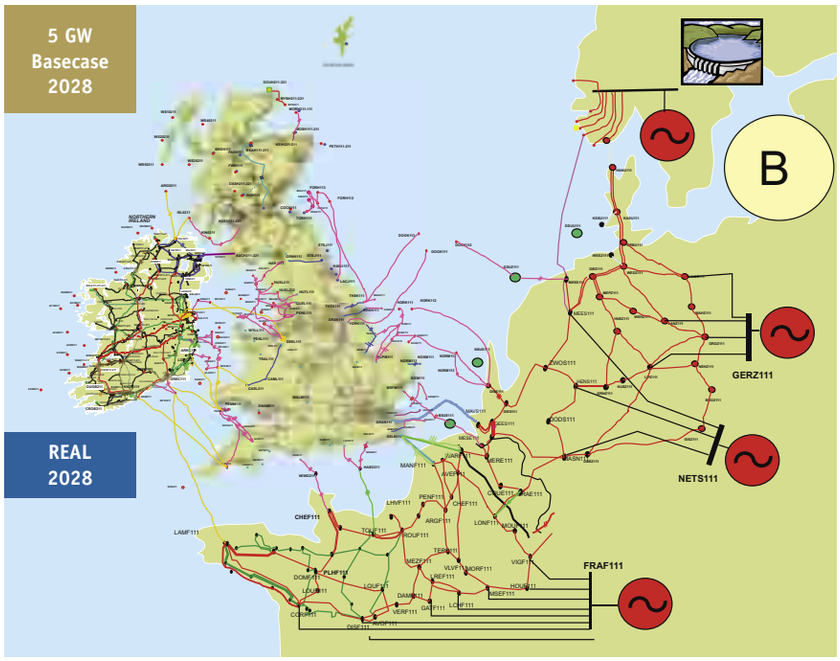


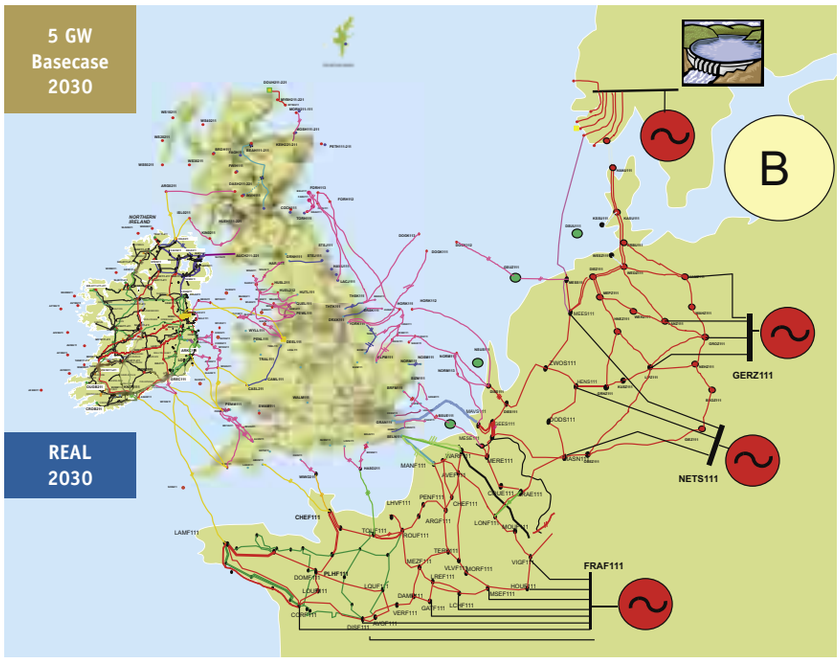




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