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Optimal interconnection and renewable targets in North-West Europe

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Abstract: We present a mixed-integer, linear programming model for determining optimal interconnection locations using a cost minimisation approach. Optimal interconnection and capacity investment decisions are determined under various targets for renewable penetration. The model is applied to a test system for eight countries in Northern Europe. It is found that considerations on the supply side dominate demand side considerations when determining optimal interconnection investment. Interconnection is found to be most valuable when targets for renewable electricity are set for the whole system, rather than for different regions within the system.

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Introduction

Cross-border electricity transmission, ie interconnection, is often presented as a panacea for various challenges that surface in electricity systems. Traditionally, electricity systems evolved in an isolated manner, frequently with one dominant player for generation, supply and transmission. As liberalisation of electricity markets has become a policy aim in many jurisdictions, interconnection has been frequently proposed as the primary, if not only, means of increasing market integration across borders and mitigating market power (Gilbert *et al.*, 2004; Brunekreeft *et al.;* 2004, Neuhoff *et al.*, 2005). As concerns over climate change and energy supply security lead to investment in renewable electricity, interconnection is proposed as a means of facilitating such investment by enabling a country or region with a significant level of variable renewable generation to export their surplus electricity and import when supply is low (De Jonghe *et al.*; 2011, EWIS, 2010; EWITS, 2011; Ostergaard, 2003). Interconnection between regions with a diverse demand profile could also serve to bring about a reduction in the range of the total demand curve. This can reduce generation costs by facilitating a proportional increase in cheaper inflexible generation plant, such as coal and nuclear, and reducing dependence on flexible high-cost peaking plant. Indeed, this is the rationale behind large scale power systems – that by meeting demand at an aggregate level, larger and cheaper generation plant can be built which can meet large portions of demand at lower cost. Thus the potential for interconnection to smooth both the supply and demand of electricity is seen as one of the major reasons for interconnection investment.

A single integrated EU market for electricity is a stated aim of the European Union (EC, 1996). An increase in renewable energy is also a specific aim of the European Commission with targets in place which aim to source twenty per cent of electricity from renewable sources by 2020 (EC, 2009). Increased levels of electricity transmission are recommended by the Directive in order to achieve both of these objectives. The Commission also cites the 'development of less-favoured regions of the Community' as a means of justifying increased investment in transmission (EC, 2009b).

While Directive 2009/28/EC specifies that 20% of the EU's gross final energy consumption is to be sourced from renewable energy by 2020, this is to be achieved by imposing specific national targets for each individual country within the EU. Aune *et al.* (2011) find that a policy of differentiated national targets is not a cost-effective way to reach a certain renewable share, even if there is a market for renewable certificates. However they do not consider the effect of increased interconnection on meeting renewable targets. The question of differentiated targets for individual regions as opposed to a global target is of relevance to other jurisdictions such as the USA, where many states have individual targets for renewable generation (Wiser and Bolinger, 2011).

Much of the literature on interconnection considers the effect of building a specific interconnector between two countries or between two regions within a country. Examples include Kanagawa and Nakata (2006), who use the META-Net economic modelling system to conclude that the utilisation of interconnection between Japan and Korea is largely determined by the generation plant mix and emissions or by nuclear energy policy. Schroder *et al.* (2010) use the WILMAR model to examine the implications of interconnecting Sweden, Germany and Denmark while incorporating an offshore wind farm in the North Sea and the Baltic Sea. Maluguzzi Valeri (2009) examines interconnection between Great Britain and Ireland and concludes that the socially optimal level of interconnection is higher than the level of interconnection likely to be delivered by market forces. This is due to the fact that interconnection tends to harmonise prices in the two connected markets, and so interconnection erodes its own value as an investment opportunity.

Some of the more general work in this area studies the economic impacts of interconnection in terms of regulator and generator behaviour, and implications for markets. Brunekreeft *et al.* (2004) concludes that deep connection charging as well as Locational Marginal Pricing (LMP) may be required to signal efficient investment locations, and that merchant interconnection, while raising new regulatory issues, may still be a suitable means of increasing interconnection. Neuhoff and Newbery (2005) find that integrated electricity markets lead to the highest social welfare, but consumer prices may increase in the short run. Brunekreeft (2004) addresses the regulatory issues pertaining to the regulation of merchant interconnection and concludes that competition law is sufficient to justify refraining from sector-specific arrangements. The optimal ownership and operation of interconnectors is also a well-developed strand in the literature. Brunekreeft and Newbery (2006) find that a regulatory decision to prohibit capacity withholding decreases welfare if the capacity withholding is due to uncertainty and demand growth, and increases welfare if the withholding is due to pre-emptive investment. Kristiansen and Rosellow (2006) propose a mechanism to incentivise investment in merchant transmission using long-term financial transmission rights (FTRs). Buijs *et al.* (2007) claim that underinvestment in transmission in Europe is due to regulatory failures and that merchant interconnectors provide an acceptable alternative.

Interconnection also features in some generation resource planning models. De Jonghe *et al.* (2011) use a linear programming model to determine the optimal electricity plant mix with a high level of wind generation. They include existing interconnection in the model but do not examine the effects of adding more interconnection. Neuhoff (2008) includes wind variation and transmission constraints in an expanded investment-planning model, and calculates the additional cost savings from expansions in transmission capacity. Most studies in this area, however, consider interconnection levels as an exogenous variable and do not consider the effects of constructing new interconnection.

Unsihuay-Vila *et al.* (2011) use a multi-objective model to identify optimal generation and interconnection investments while attempting to find the best compromise between three objectives: minimise cost, minimise greenhouse gases and maximise diversification of the electricity generation mix. Their model is one of the few to include transmission as an endogenous variable. However, demand is included as three load-blocks of low, medium and peak demand over the planning horizon, and as such does not capture the variable nature of demand or renewable generation, which may constitute a major component of interconnector value.

There has been little investigation of methods for determining optimal locations for specific interconnectors, other than in specific case studies examining the construction of a particular interconnector such as those mentioned above (Kanagawa and Nakata, (2006); Schroder *et al.,* (2010); Malaguzzi Valeri (2009)). Here we present a model which includes interconnector locations as an endogenous variable, thus solving for optimal interconnection in an objective manner.

The model determines the optimal amount of investment in new generation capacity as well as optimal investment in interconnection. As such, the model captures the interdependent nature of generation capacity and interconnection rather than attempting to solely identify optimal interconnection investment for a given generation portfolio. This is accomplished by means of an iterative approach in which a linear program and then a mixed integer program are run for each year under investigation, with the linear program determining the optimal generation capacity and the mixed integer program determining optimal interconnection investment.

The model captures the increased capacity to balance supply and demand afforded by interconnection by including demand and renewable generation at an hourly resolution. The model can be used to examine the interchangeable nature of investment in generation capacity or interconnection. By including constraints in the model which require certain proportions of electricity generation to come from renewable sources, the complementary nature, if any, of interconnection and variable renewable generation can also be investigated. This is done by applying the model to a test system of eight Northern European countries from the year 2011 to the year 2030. Differentiated renewable targets for each country and a global renewable target are imposed, and the various effects on interconnection are identified. The interplay between interconnection and renewable certificate markets can also be examined by the model.

The paper is structured as follows. Section 2 presents the model. Section 3 outlines the test system to which the model was applied. Section 4 presents the results. Section 5 discusses the insights and implications of the results. Section 6 concludes.

2 Model

The model seeks to meet the electricity demand for all regions modelled while minimising total costs. As such a social planner is assumed, whereby total costs across all regions is minimised rather than each country minimising its own individual costs. This is in contrast to the current approach in which each country or region within a country has a separate Transmission System Operator (TSO), or in some cases more than one TSO, and one regulator which take responsibility for electricity provision. The model therefore provides particularly useful insight into whether decisions taken by separate countries (possibly in response to EU policy directives) which minimise costs within a particular region may contribute to an overall increase in costs.

Ideally the model would optimise both the location and the capacity of new interconnection investment. However, this would introduce a nonlinearity which would render the problem too computationally intensive. For this reason it is necessary to select a default interconnector size and to assume that any interconnection built is of this fixed capacity.

The model meets electricity demand by dispatching available generation capacity while minimising total costs arising from both interconnection investment and generation investment over the course of one planning horizon. An iterative approach is taken (see Figure 1). In the first step of the iterative process a Capacity Optimisation Module is run. The Capacity Optimisation Module is a linear program as all variables are continuous and enter the objective function in a linear manner. The inputs include the existing interconnection portfolio between the regions and the existing generation portfolio for each region. The demand in each region is given as a parameter at an hourly resolution. The Capacity Optimisation Module has the option of building new generation capacity in any given region while determining the optimal dispatch of the generation assets and the optimal utilisation of the existing interconnectors. The model determines the optimal dispatch of the total generation capacity portfolio, given by the existing generation assets as well as any new generation assets solved for by the model.

In the second step of the iterative process an Interconnection Optimisation Module is run. The Interconnection Optimisation Module is a mixed integer program as the decision variable which determines whether to build interconnection between two regions is an integer quantity. The inputs of the Module include the generation portfolio arrived at in the first step along with the existing interconnection portfolio. The model does not, therefore, model retirements of generation or interconnection assets. The Module determines the optimal dispatch of the generation plant and the optimal operation of the existing interconnection, as does the Capacity Optimisation Module. The Module also has an option to build interconnection between any two regions, in which case it determines the optimal operation of the total interconnection portfolio, given by the existing interconnection capacity and the new interconnection capacity arrived at by the model.

If interconnection is built in the Interconnection Optimisation Module, the portfolio of existing interconnection which was given as an input to the Capacity Optimisation Module is updated to include this new interconnection. The Capacity Optimisation Module is then rerun using the original portfolio of existing generation assets and the new interconnection portfolio. The generation capacity portfolio arrived at is then given as a parameter to the Interconnection Optimisation Module which is rerun using the original existing interconnection portfolio. If the new interconnection investments arrived at differ from those arrived at in the first step, the new interconnection portfolio arrived at is reintroduced to the Capacity Optimisation Module and the process is repeated. When the Interconnection Optimisation Module arrives at the same interconnection investments as in the previous iteration, the model terminates for that planning horizon and carries the generation and interconnection portfolios arrived at on to the next planning horizon.

The objective functions and constraints for each Module are outlined below.

2.1 Cost function

Total costs are broken down below into several components.

The first component considered is the cost of building generation capacity, given by the following expression:

$$\sum_{g,r} capacity_{g,r} * capacity\_costs_{g} \ldots (1)$$

where *capacity* stands for capacity in MW of generation technology *g* in region *r*. The generation technologies considered are coal, nuclear, wind and gas.

The second component of total costs is the cost of interconnection between two regions and is given below as expression (2):

$$\sum_{r} ic_{r,r} * distance_{r,r} * ic\_cost \ldots (2)$$

where *ic* is the inter quantity denoting interconnection between two regions. The distance between each region and itself is set to zero which ensures there is no cost to interconnecting within a particular region.

The third component of total costs is the value of lost load (VOLL) term. This term is included as a penalty for failing to meet all the demand while avoiding a binding constraint requiring all demand to be met. The term is given below as expression (3):

$$\left(\sum_{g,r,t} demand_{d} - \ dispatch_{g,r,r,t}\right) * VOLL \ldots (3)$$

While the purpose of the model is to determine optimal investment in interconnection and generation capacity, these investments are influenced by the economic dispatch of generation units. Thus the cost function must also include the costs of generating from dispatchable generation, given by equation (4) below.

$$\sum_{g,r,r,t} generation\_cost_{g} * dispatch_{g,r,r,t} \ldots (4)$$

Figure (1) gives the objective functions for both the Capacity Optimisation Module and Interconnection Optimisation Module, along with a representation of the model process for each time horizon.

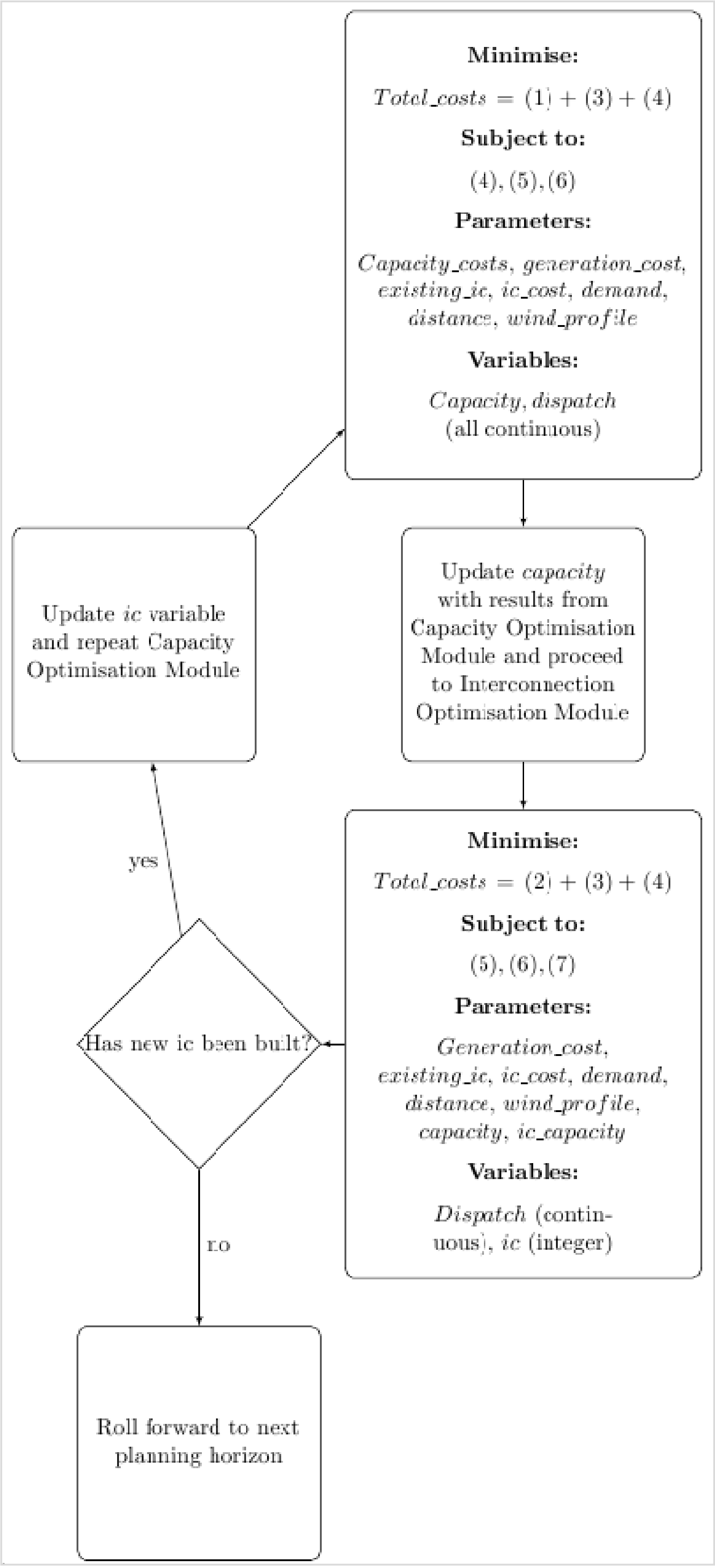


Figure 1: Interconnection investment model

2.2 Constraints

The first constraint in the model specifies the maximum generation of each type of generation given by the capacity of each type of generation. The minimum generation for each generation type is assumed to be zero, ie unit commitment of individual units is not modelled:

$$\sum_{r} dispatch_{g,r,r,t} \leq capacity_{g,r} \;\; \forall\, t \ldots (5)$$

A wind capacity constraint is included separately as wind generation is determined by a time series given by *wind_profile,* the wind available in each region at time *t*:

$$\sum_{r} dispatch\_wind_{r,r,t} \leq wind\_profile_{t,r} * \; wind\_capacity_{g,r} \;\; \forall\, t \ldots (6)$$

Expression (7) below is the constraint representing interconnector capacity:

$$\sum_{g} dispatch_{g,r,r,t} + \; dispatch\_wind_{r,r,t} \leq ic_{r,r} * ic\_capacity + existing\_ic\_capacity_{r,r} \; \forall t \ldots (7)$$

Figure (1) outlines the iterative process that is used to determine optimal generation and interconnection capacity for each year, with an explanation given as to whether each term is a variable or a parameter.

2.3 Limitations of the model

The model considers each region to be a copper plate, ie, transmission within regions is not modelled.

The model does not impose minimum operation constraints, start-up costs or ramping costs and constraints on the conventional generation sources. This means that many of the operational benefits of interconnection, such as the increased operational flexibility available to system operators, are not captured by the model. Market effects such as a reduction in market power are also not examined. The omission of such benefits may lead the model to underestimate the value of interconnection.

The model does not provide an analysis of reliability issues which arise as a result of extreme events of the system. These include failures of thermal plant or transmission lines, and very high or low wind events. The model assumes generators and transmission are reliable, and models wind output deterministically. Modelling wind stochastically would considerably increase computational time (Tuohy *et al.,* 2009). As such the model is likely to underestimate the cost of wind generation.

3 Test system

3.1 Endogenous variables

The model was applied to a case study for eight countries in northern Europe: Ireland, Great Britain, France, Germany, Luxembourg, Belgium, Netherlands and West Denmark. Hourly demand data for these eight northern European countries from 2010 was obtained from ENTSO-E and was scaled up to 2030 according to annual growth estimates contained in the European Commission's report 'EU energy trends to 2030 update 2009' (EC, 2009). Wind data from 2009 in Ireland, obtained from EirGrid plc, was scaled according to the capacity factors in Boccard (2009) and time shifted according to geographical location for the other seven European countries.

The time horizon was set to one year. The start year was set to 2011 and the end year to 2030. Thus the model was run for twenty one-year time steps. While this means the model exhibits myopic expectations, the process of the power system evolution can be seen as a consequence of individual investment decisions.

The 2009 plant mix for each country was provided as the parameter *existing_capacity* (Eurostat, 2011). The 2009 plant mix was selected as it was the most recent date for which generation capacity data for all eight countries under study was available.

Capacity costs for plant and interconnection were taken from the EIA (EIA, 2010) and fuel and carbon price projections to 2030 were taken from the IEA New Policies scenario (IEA, 2011) and converted to a cost per MWh for each type of generation considered.

Estimates of the value of lost load (VOLL) vary depending on country as well as electricity consumer type (Kariuki and Allan, 1996; Leahy and Tol, 2011; de Nooij *et al.,* 2007). For the purposes of this study VOLL was set to €10,000 per MWh, the value which was used in the Single Irish Electricity Market for 2007/2008 (CER, NIAUR, 2010).

The current level of interconnection was obtained from ENTSO-E's Winter 2011 net transfer capacity (NTC) figures (ENTSO-E, 2011). A discrepancy exists between the flow on some lines, depending on the direction, due to regulatory issues or asymmetries on the line. Where a discrepancy existed, the capacity was set to the higher of the two values. This implicitly assumes there are no loop flows.

The default interconnector size was set to 1,000MW in each direction. 1,000MW was chosen as a suitable size as most current and planned European interconnectors are of no more than 1,000MW. The cost of interconnection per thousand km for a 1,000MW interconnector (€1080M) was obtained from EirGrid plc.

3.2 Case study scenarios

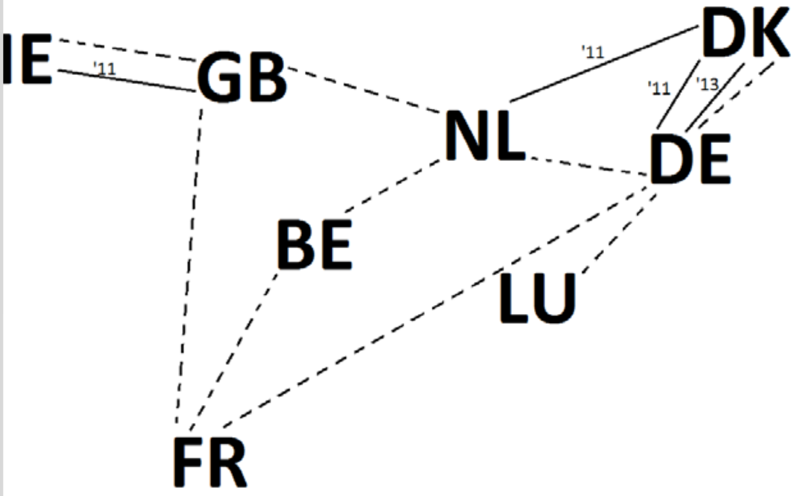
The model was run for three scenarios. Scenario I is a base case with no targets imposed for renewable generation. Scenario II is as Scenario I with a constraint added which requires that 20% of the electricity consumed in each individual country be generated from renewable sources. Scenario III is as Scenario I with a constraint added which requires that

20% of total electricity consumed be generated from renewable sources without including targets for individual countries. Scenarios II and III therefore implicitly assume that there is a market for renewable obligations as the renewable electricity consumed within a country need not have been generated there. Thus the model expands on the approach of Aune *et al.* (2011) by investigating the effects of interconnection investment on markets for renewable obligations.

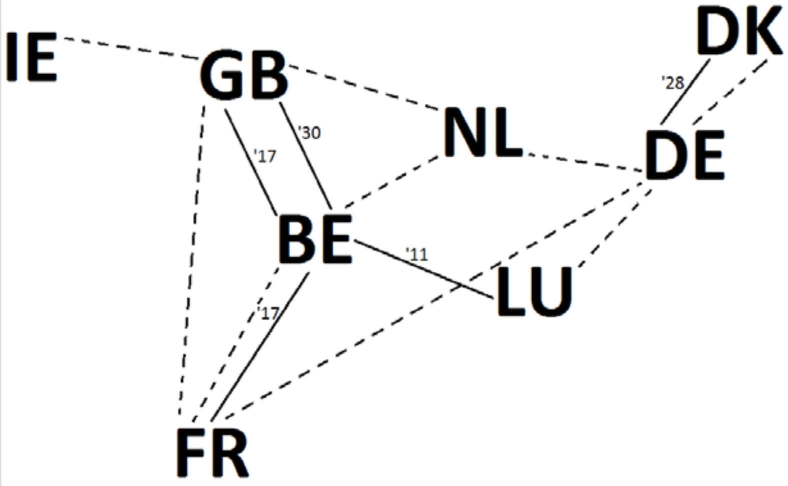
In an attempt to isolate the benefits of interconnection each scenario was run under the Capacity Optimisation Module only, and under the iterative process between the Capacity Optimisation Module (COM) and Interconnection Optimisation Module (IOM). Thus the evolution of the total costs could be seen both with and without the opportunity to invest in interconnection.

4 Results

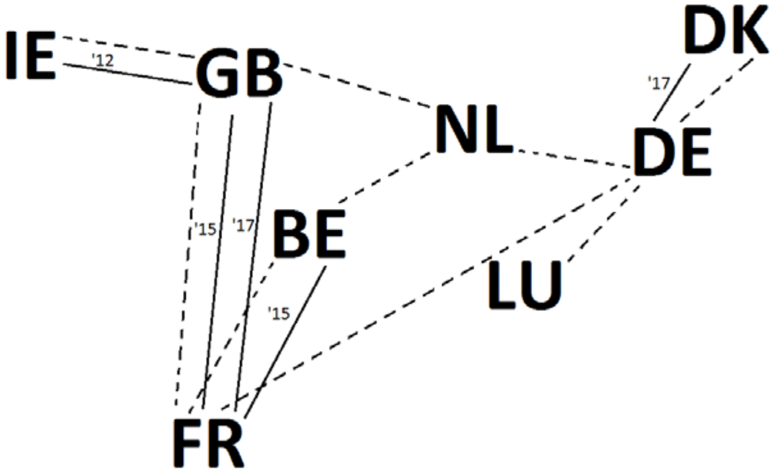
Interconnection is built under each scenario, but the interconnection portfolio varies significantly as the renewable target varies. Figure 2 shows the interconnection built under Scenarios I, II and III in solid lines, along with the years in which each interconnector was built. The dashed lines represent existing interconnection.



(a) Scenario I



(b) Scenario II



(c) Scenario III

Figure 2: Years in which interconnection investment occur (solid lines); existing interconnection in dashed lines

The total costs (in M€) over the twenty years, under each scenario, are given in Table 1, for the COM only (no new interconnection) and the full model (COM and IOM):

	COM & IOM	**COM**
Scenario I	913,356	914,683
Scenario II	750,850	753,431
Scenario III	722,283	739,616

Table 1: Total costs in M€ over 20 years modelled

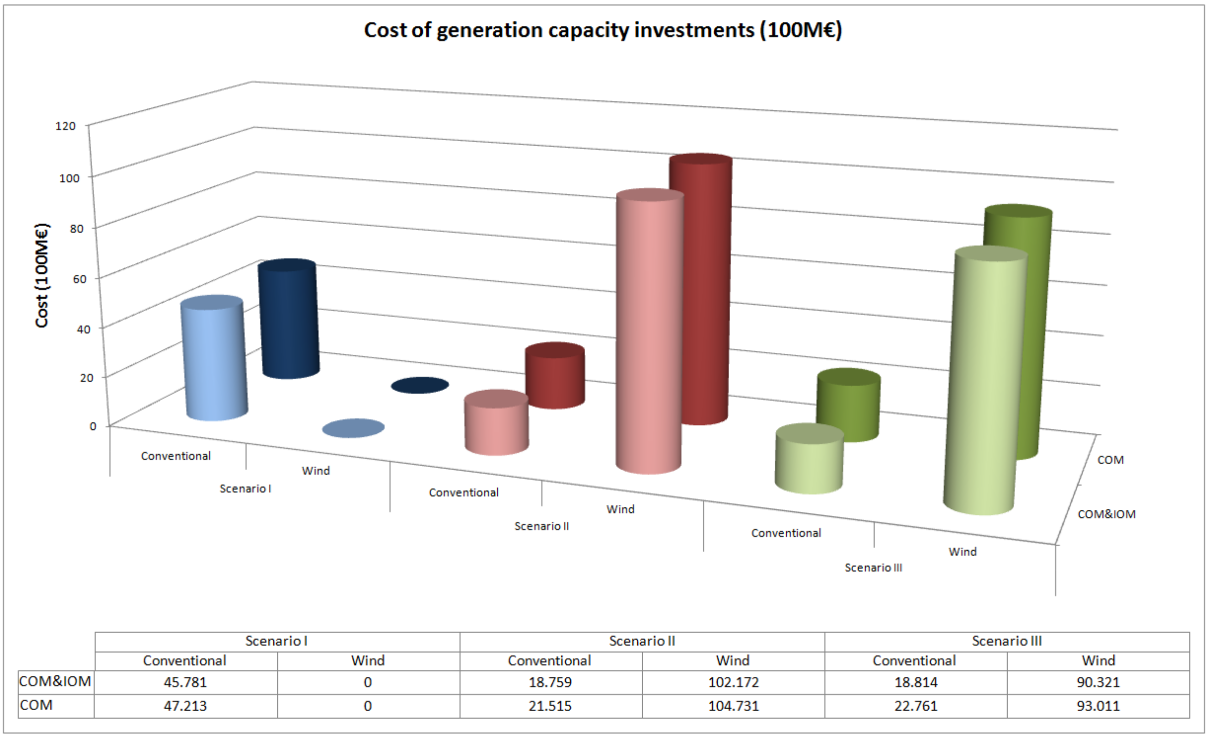
Interconnection reduces total costs in all scenarios, with Scenario III seeing the biggest reduction. It should also be noted that the scenarios with a target for renewable electricity have lower total costs over the twenty years than with no renewable target. However, the capital investment in wind capacity required to bring about this reduction in costs is substantial, and thus the model does not invest in wind capacity unless it is required to do so by a constraint. This is a consequence of the model's myopic expectations.

A major driver of the reduction in costs is the fact that wind generation replaces conventional generation, which carries a fuel and carbon cost. The conventional generation selected by the model was gas, whose low cost was presumably a principle driver for this. The reduction in costs under Scenarios II and III is unrealistically high due to the underestimation of the true cost of wind generation, as outlined above. However the comparison between the cost figures for interconnection and no interconnection under the various scenarios provides insight, as the effects of interconnection under the assumptions inherent in the model can be examined.

While some regions see an increase in generation capacity investment under a scenario that allows interconnection investments, total generation capacity decreases under interconnection. Scenario I sees total conventional generation capacity investment decrease by 8.278GW, Scenario II by 2.047GW and Scenario III by 11.331GW. The difference between the reductions in Scenarios II and III highlight the ability of optimal renewable targets and interconnection investments to reduce necessary investment in conventional capacity.

Wind generation is not built under Scenario I. Scenario II sees wind capacity investment in most regions, while Scenario III sees a concentration of wind investment in Great Britain and Ireland, with some wind investment in France. This is because a total target for all countries allows countries with the highest capacity factors for wind (such as Ireland and Great Britain) to meet more than 20% of their total electricity demands from renewable sources, thus allowing other countries to meet less than 20% of their demand from renewables. Individual targets for each country mean that it is cheaper to build renewable generation in countries with lower capacity factors as the losses incurred in transmitting electricity from high capacity factor countries to countries with a lower capacity factor are sufficiently high to mitigate the benefits of investing in countries with the highest capacity factor. The inclusion of interconnection reduces total wind capacity investment from 79GW to 77 GW in Scenario II, and from 70GW to 68GW in Scenario III. Thus imposing a target for all of the regions studied rather than individual targets increases the amount of wind capacity built while interconnection decreases the wind capacity investment.

The total costs of generation capacity investment, both wind and conventional, are shown in Figure 3, while Table 2 delineates the differences in costs observed between the COM only and the COM and IOM and the different scenarios.



	Scenario I		Scenario II		Scenario III	
	Conventional	Wind	Conventional	Wind	Conventional	Wind
COM&IOM	45.781	0	18.759	102.172	18.814	90.321
COM	47.213	0	21.515	104.731	22.761	93.011

Figure 3: Total cost of generation investment

Unit: 100M€	**Scenario I**	**Scenario II**	**Scenario III**
Total COM	47.2	126.2	115.8
Total IOM	45.8	121.0	109.1
Delta (COM – IOM)	1.432	5.315	6.637
Delta (scenarios)	0 (baseline)	Scen I + 75.2	Scen I + 63.3 Scen II – 11.9

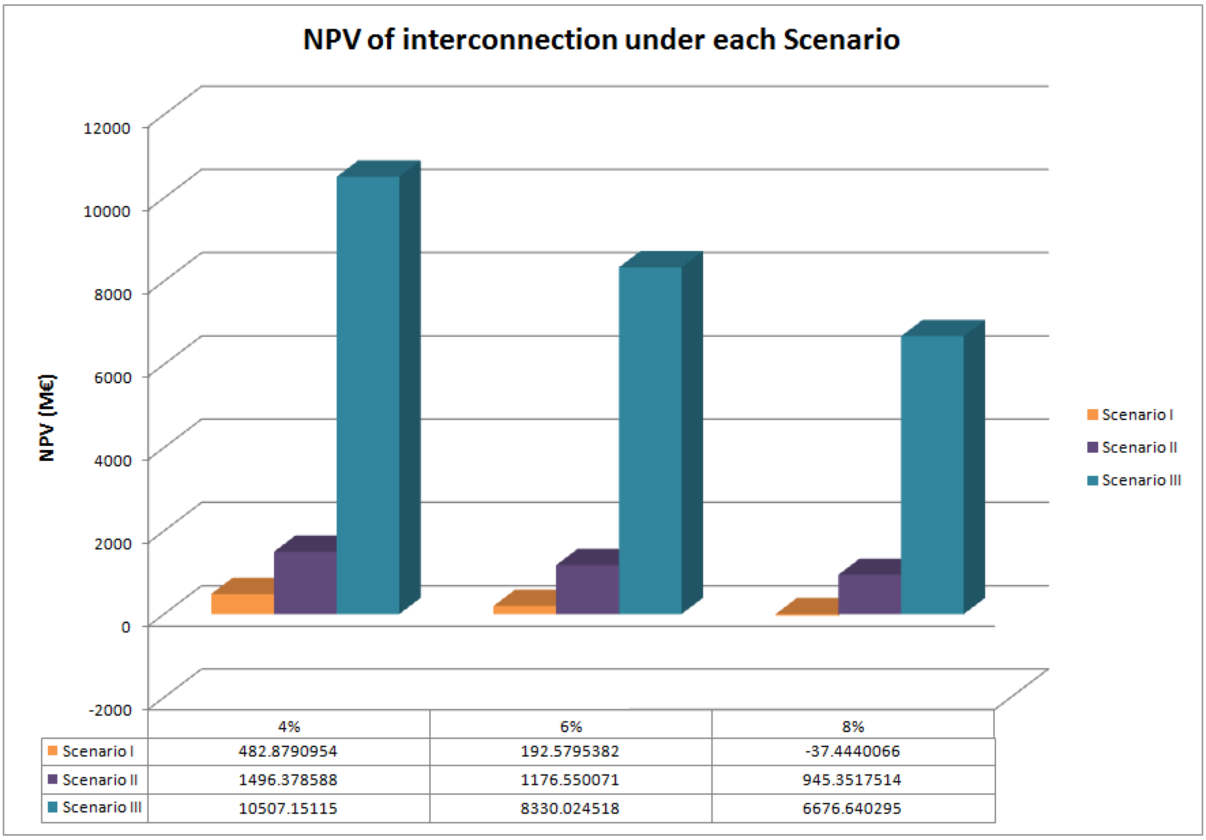
Table 2: Comparisons of total costs (in 100M€) of generation investment

It can be seen that interconnection reduces investment costs in all scenarios, although the reduction is slight. The investment in wind is also lower under Scenario III than in Scenario II, as the investment in countries with higher capacity factors allows 20% of generation to come from renewables for a smaller amount of wind capacity. The total investments costs under Scenario I are significantly lower than in Scenarios II and III, and therefore the reduction in overall costs is due to renewable generation displacing conventional generation which entails a fuel and carbon cost.

The Net Present Value (NPV) of allowing interconnection investment in the model can be calculated as the discounted stream of net benefits, where the net benefits are given by the difference between total costs for each year under a scenario in which interconnection is permitted and interconnection is not permitted. The NPV is calculated at discount rates of 4%, 6% and 8% by equation (8):

$$NPV = \sum_{year}\left(Total\_costs(no\ ic)_{year} - Total\_costs(with\ ic)_{year}) * (1+i)^{-year}\right) \ldots (8)$$

The NPV under each discount rate for each scenario is shown in Figure (4):



	4%	6%	8%
🟧 Scenario I	482.8790954	192.5795382	-37.4440066
🟪 Scenario II	1496.378588	1176.550071	945.3517514
🟦 Scenario III	10507.15115	8330.024518	6676.640295

Figure 4: NPV of interconnection under each of the three Scenarios considered

Scenario I at a discount rate of 8% yields a negative NPV for interconnection; in all other scenarios the NPV for interconnection is positive. However the NPV is significantly higher under Scenario III than Scenarios I or II. This further reinforces the complimentarity between interconnection and renewable electricity which is constructed in locations with high capacity factors.

4 Discussion

The results of the model provide evidence that, subject to the discount rate, interconnection is a worthwhile investment, even under a scenario which sees little investment in renewable electricity. However it must be noted that the fact that the model minimises total costs across all countries , rather than minimising costs on a region-by-region basis, may be a strong driver of this interconnection investment. At present, interconnection investment is primarily funded by TSOs within a particular country, with some funding available at EU level. Unless the cost of interconnection is borne at EU level then each individual interconnector must prove beneficial to the consumers within a particular region or profitable to a merchant interconnector investor in order for the investment to occur, and this may limit investment in interconnection. It is likely that the cost of interconnection investment being borne at EU level will not happen until there is a fully integrated EU market for electricity, or at the very least until a greater amount of these investment decisions are determined at EU rather than national level.

The model can identify which of the potential drivers of interconnection discussed in the introduction (integration of renewable generation, smoothing of demand profiles and thus reduction of investment in generation capacity) are found to have an effect in determining interconnection investment. (Mitigation of market power is also a potential driver of interconnection investment; however the model does not consider markets and so cannot shed light on this issue). There is little evidence in the results to indicate that demand smoothing is sufficiently beneficial to prompt investment in interconnection. While there is some decrease in generation capacity investment when interconnection is allowed (Figure 3), this effect is marginal under Scenario I, where only thermal capacity is built. The decrease in wind capacity when interconnection is included (Scenarios II and III) is much more pronounced. Thus it appears that it is primarily factors on the supply side, rather than the demand side, which drive the observed investment in interconnection. The increased value of interconnection when renewable targets are imposed further suggests that supply factors dominate when determining the value of interconnection.

The reduction in costs that is seen as a result of allowing interconnection investment is greater under Scenario II than Scenario I. This suggests that wind investment and interconnector investment are complimentary. Despite the fact that investment in wind generation occurs in nearly all regions under Scenario II, there is sufficient variation in the demand and wind time series to allow some export and import of wind generation, which reduces dependence on conventional generation. However the individual targets for each region cause regions with lower wind capacity factors to invest in wind generation, which displaces a lower amount of conventional generation than in a region with a higher capacity factor.

It is clear from Scenario III that the complimentarity of wind and interconnection can be best exploited when there is a common target for renewable generation across all regions studied. This allows those regions with higher capacity factors to invest in wind generation and reduce total investment in generation capacity across all regions modelled.

In light of the results presented in this paper it would appear that specific targets for renewable energy consumption for each individual country across Europe are not optimal, for electricity generation at least. In this respect this model confirms the findings of Aune *et al.* (2011) and finds that they hold even when interconnection expansion is considered. The most cost-effective way of meeting these targets is to invest in renewable generation in regions with a high capacity factors and to interconnect to those regions. However in practise the individual targets currently in place for each country are inducing countries in Europe to invest in renewable generation within their own country, even if they may not have the best capacity factor. The model results provide strong evidence that this process will not achieve the least costly outcome for a given renewable target.

5 Conclusion

This paper presented an optimisation model which can be used to determine optimal interconnection investment between regions for a given set of inputs. These inputs include hourly demand, the existing generation portfolio, the existing interconnection portfolio, fuel and generation capital costs and interconnection investment costs. The model can include constraints which require a certain amount of electricity to be generated from renewable sources. The model determines optimal generation and interconnection capacity in an iterative process on an annual basis.

The model was run as a case study for eight Northern European countries under three scenarios, one in which there was no target for renewable generation, one with a target for each individual country and one with a total target for all countries modelled. It was found that interconnection investment reduces total costs under every scenario, with the biggest reduction occurring under the scenario in which there is one total target for renewable generation, rather than specific targets for each individual country. The results suggest that current European policy, which seeks to increase interconnection across Europe as well as increase renewable generation in each country, is not optimal, as the full value of interconnection will not be realised with each country investing in variable renewable generation on an individual basis.

Appendix

Interconnection investments undertaken in each of the three scenarios are outlined below, with existing interconnection given in italics.

	IE	**GB**	**FR**	**BE**	**NL**	**LU**	**DE**	**DK**
IE		*0.95* 1GW(2011)						
GB	*0.95* 1GW(2011)		*2*		*1*			
FR		*2*		*3.4*			*3.2*	
BE			*3.4*		*2.4*			
NL		*1*		*2.4*			*3.85*	1GW(2011)
LU							*0.98*	
DE			*3.2*		*3.85*	*0.98*		*1.5* 1GW(2011) 1GW(2013)
DK					1GW(2011)		*1.5* 1GW(2011) 1GW(2013)	

Table 3: Interconnection built under Scenario I

	IE	**GB**	**FR**	**BE**	**NL**	**LU**	**DE**	**DK**
IE		*0.95*						
GB	*0.95*		*2*	1GW(2017) 1GW(2030)	*1*			
FR		*2*		*3.4* 1GW(2017)			*3.2*	
BE		1GW(2017) 1GW(2030)	*3.4* 1GW(2017)		*2.4*	1GW(2011)		
NL		*1*		*2.4*			*3.85*	
LU				1GW(2011)			*0.98*	
DE			*3.2*		*3.85*	*0.98*		*1.5* 1GW(2028)
DK							*1.5* 1GW(2028)	

Table 4: Interconnection built under Scenario II

	IE	**GB**	**FR**	**BE**	**NL**	**LU**	**DE**	**DK**
IE		*0.95* 1GW(2012)						
GB	*0.95* 1GW(2012)		*2* 1GW(2015) 1GW(2017)		*1*			
FR		*2* 1GW(2015) 1GW(2017)		*3.4* 1GW(2015)			*3.2*	
BE			*3.4* 1GW(2015)		*2.4*			
NL		*1*		*2.4*			*3.85*	
LU							*0.98*	
DE			*3.2*		*3.85*	*0.98*		*1.5* 1GW(2017)
DK							*1.5* 1GW(2017)	

Table 5: Interconnection built under Scenario III

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