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Estimating the electricity prices, generation costs and CO₂ emissions of large scale wind energy exports from Ireland to Great Britain



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H I G H L I G H T S

- Modelling the Irish and British electricity markets.
- Investigating the impacts of large scale wind energy within the markets.
- Results indicate a reduction in wholesale system marginal prices in both markets.
- Decrease in total generation costs and CO₂ emissions in both markets.

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A B S T R A C T

The share of wind generation in the Irish and British electricity markets is set to increase by 2020 due to renewable energy (RE) targets. The United Kingdom (UK) and Ireland have set ambitious targets which require 30% and 40% of electricity demand to come from RE, mainly wind, by 2020, respectively. Ireland has sufficient indigenous onshore wind energy resources to exceed the RE target, while the UK faces uncertainty in achieving its target. A possible solution for the UK is to import RE directly from large scale onshore and offshore wind energy projects in Ireland; this possibility has recently been explored by both governments but is currently on hold. Thus, the aim of this paper is to estimate the effects of large scale wind energy in the Irish and British electricity markets in terms of wholesale system marginal prices, total generation costs and CO₂ emissions. The results indicate when the large scale Irish-based wind energy projects are connected directly to the UK there is a decrease of 0.6% and 2% in the Irish and British wholesale system marginal prices under the UK National Grid slow progression scenario, respectively.

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1. Introduction

The majority of European Union (EU) Member States have agreed national binding targets to reduce greenhouse gas emissions by increasing the share of renewable energy sources (RES) in final energy consumption under EU Directive 2009/28/EC (European Parliament, 2009). For the United Kingdom (UK), the target is set at 15% of final energy consumption from RES by 2020, with separate targets for contributions of renewable energy in electricity (30%), transport (10%) and heat (12%) (DECC, 2009). Ireland's overall target is to ensure at least 16% of final energy consumption is produced from RES by 2020. The overall mandatory target

consists of a 40% of electricity consumption from renewable sources (RES-E), 12% renewable heat (RES-H) and 10% renewable transport (RES-T) (DCENR, 2009). Similarly in Northern Ireland (NI), the Department of Enterprise, Trade and Investment published the Strategic Energy Framework in September 2010 which sets out a 40% RES-E target by 2020 (DETI, 2010). The Republic of Ireland (ROI) already exceeded the 13.2% interim target for RES-E by 2010 with 14.8% in that year (SEAI, 2012). In 2010, the UK reached 6.7% towards the interim RES-E target but it faces significant challenges in achieving the RES-E target by 2020 (Renewable Energy Focus, 2013).

The ROI and NI RES-E target is expected to be met by the

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development of indigenous onshore wind given the significant wind resource which exists across the island. Consequently, there will be substantial undeveloped onshore and offshore wind resource areas available across the All-Island of Ireland (All)¹ and, if exported to the UK, this would help contribute towards their 2020 RES-E target. In accordance with EU Directive 2009/28/EC some flexibility measures are available to Member States to help achieve their 2020 targets (European Parliament, 2009). The flexibility measures were originally designed to permit the EU to adopt regional renewable energy (RE) development and allow Member States with abundant RE resources to develop and export energy to other Member States (Barrett, 2013).

For the UK and ROI, the use of the flexibility measures were initially agreed by the signing of a Memorandum of Understanding between the two governments on the 24th January 2013 (DCENR, 2013). As part of the MoU both governments agreed to consider how Irish wind resources, both onshore and offshore, might be developed to their mutual benefit. An intergovernmental steering group was established to guide and monitor the project, with a view to implementing a binding Inter-Governmental Agreement (IGA) in early 2014.

Three project developers proposed to build wind energy export projects in the midlands of Ireland which would be connected directly to the Great Britain (GB) electricity market, entitled British Electricity Trading and Transmission Arrangements (BETTA). The 'Clean Energy Hub' project proposed to use cutaway peat lands to accommodate 2000 MW of wind capacity (Bord na Mona, 2013). The 'Energy Bridge' project proposed to use privately owned lands to accommodate 1200 MW of onshore wind capacity and 3800 MW from offshore wind farms in the Irish Sea (Mainstream Power, 2013). Similarly, the 'Greenwire' project proposed to build 3000 MW of wind farms throughout the midlands to be connected to the UK by 2018 (Greenwire, 2013). More recently, the UK regulator Ofgem reassessed an analysis of a 500 MW interconnector from the 'Greenwire' project between the UK and Ireland, which indicated benefits for the UK consumer (Ofgem, 2015). Ofgem are currently seeking views on the updated analysis as to whether the estimated benefits seem reasonable. The approximate footprint of the proposed Irish midlands wind energy export projects and the associated interconnectors are shown in Fig. 1.

The Irish Department of Communications, Energy and Natural Resources (DCENR) stated that the proposed wind energy export projects are unlikely to go ahead by 2020. This is mainly due to the tight deadline originally set and the fact that the UK government did not progress the analysis of the export projects in a way that was expected due to economic, political and regulatory issues (Irish Independent, 2014; Irish Times, 2014). Therefore, in the absence of an IGA, the developers have put their proposed projects (with the exception of the 'Greenwire' project) on hold. Nonetheless, the projects may be reactivated.

The main benefits of the export projects cited by both governments and the developers are the creation of employment, achieving the binding 2020 RES targets, economic gains through taxes (income and corporation) and rent to land owners. The Irish Wind Energy Association (IWEA) commissioned two studies which quantified some of these benefits. The first study by Fitzgerald et al. (2014) indicates the total number of jobs created under 4 GW of domestic Irish wind capacity and an additional 8 GW of dedicated export wind capacity could amount to 35,275. This figure is made up of 22,675 direct jobs and 12,600 induced jobs. The second study by Billington and Mohr (2014) states that 'during the development and construction phase of the wind

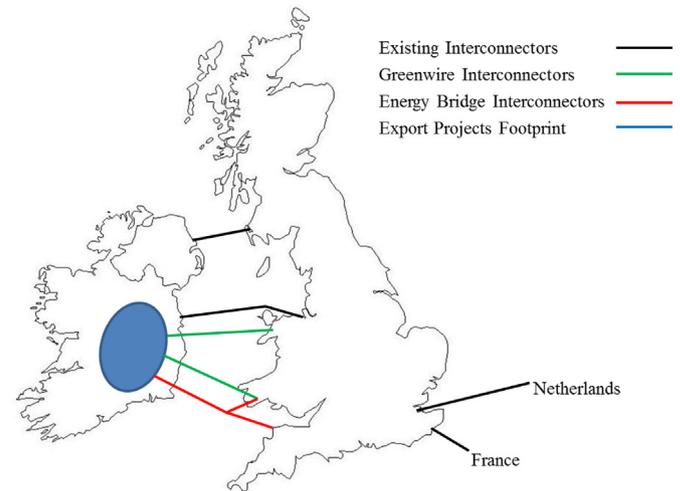


Fig. 1. Layout of proposed Irish midlands wind energy export projects.

export projects, 47,240 jobs could be reached in the wind sector by 2020, on a person-year basis'. Billington and Mohr (2014) also estimates that an investment of €16.6 billion is required from 2013–2020 to achieve the export ambition.

The proposed wind export projects have led to a substantial amount of speculation and debate in terms of the true benefit they will provide to Ireland and the UK. At present, there is no independent publically available detailed economic or policy analysis of the wind export projects. Therefore, the aim of this paper is to contribute to understanding the effects of the Irish midlands wind energy export projects on the Single Electricity Market (SEM) and BETTA markets in terms of wholesale system marginal prices, total generation costs and CO₂ emissions.

2. SEM and BETTA electricity markets

The SEM is the All wholesale electricity market covering the ROI and NI, which has been operational since November 2007 (SEMO, 2014; CER, 2011a). It is a mandatory centralised or gross pool market operating on a bid-based exchange with dual currencies and in multiple jurisdictions. Electricity is bought and sold from the pool through a market clearing mechanism by which generators bid in their offers and receive the System Marginal Price (SMP) for their scheduled dispatch quantities for each trading period (CER, 2013). Generator offers consist of commercial offer data (i.e. fuel cost, no-load cost and start-up cost) and technical offer data (i.e. maximum capacity, minimum stable level and ramp rates). The SMP consists of two components known as the "shadow" and "uplift" prices. The shadow price makes up most of the SMP and relates to the short-run marginal cost (SRMC) of bids from generators, which mainly comprise fuel costs. The uplift price is a payment to help avoid generators making short-term losses and covers the generator's start-up and no-load costs (CER, 2011a).

Generators participating in the SEM receive payments for energy via the SMP but they also receive a capacity payment for making their capacity available, which contributes towards their fixed costs and ensures the security of the system. There are also a number of other payments to generators in the SEM including uninstructed imbalances and constraint payments. In particular, alterations to the scheduled dispatch which inevitably occur in the real time system operation result in constraint payments to ensure the generators are compensated for the difference between the market and actual dispatch schedules. In 2014, the energy, capacity and constraints payments made up 74%, 20% and 6% of the

¹ The ROI and NI are two separate jurisdictions with a common synchronous power system known as the All-Island of Ireland (All)

annual SEM payments, respectively (SEMO, 2014).

In contrast, the BETTA market which has been operational since 2005 is an energy only market and does not offer any form of capacity payments (Ofgem/DTI, 2005). The arrangements under BETTA are based on bilateral trading between generators, suppliers, traders and customers across a series of markets operating on a rolling half-hourly basis. Under these arrangements generators self-dispatch (i.e. generators contract directly with suppliers based on negotiated contract prices and volumes) rather than being centrally dispatched by National Grid Plc, the Transmission System Operator (TSO). There are four stages to the BETTA market: forwards/futures contract market, short-term bilateral market (Power Exchanges), balancing mechanism and imbalance settlement. The contract and bilateral markets typically account for 98% of total traded volumes with the remaining 2% taking place through the balancing mechanism (NZIER, 2005).

A consultation on the redesign of both the SEM and BETTA markets is ongoing. The redesign of the SEM entitled the Integrated Single Electricity Market (I-SEM) is required under the EU's Third Package and the requirement to comply with European Electricity Target Market Model by 2018 (SEM Committee 2014). The UK government's Electricity Market Reform (EMR) program is designed to modify the BETTA market instead of replacing it with a new market (DECC, 2013d). For the analysis presented in this paper, it is assumed that the SEM and BETTA market designs remained unchanged due to future market design uncertainty; further details are outlined in Sections 3.2 and 3.3.

3. Modelling methodology

A representation of the SEM and BETTA markets in 2012 was created as the base year model given that detailed data was available for that year. The 2012 base model was populated with the individual generator technical and commercial characteristics. A comparative validation analysis was conducted between the 2012 base model outputs and the actual market data in that year. Four scenarios with alternative generation portfolios were chosen and the 2012 base model was extended to 2021 as this is when some or all of the proposed wind export projects could be participating in the BETTA market. The scenario parameters were inputted into the model and the outputs simulated for each 2021 model scenario. The following subsections describe the modelling software, model assumptions, model validation and model scenarios in more detail.

3.1. Modelling software

The main proprietary modelling software used in different countries for energy systems modelling include EMCAS, PLEXOS, EnergyPLAN, WASP IV and WILMAR (Foley et al., 2010). The most common modelling software used for the SEM and BETTA markets modelling is WILMAR and PLEXOS. The WILMAR planning tool was first released in 2006 and was originally used to study wind variability in the Nord pool system. It was then modified to analyse the Irish system as part of the All-Island of Ireland Grid Study (DCENR, 2008).

PLEXOS is an integrated energy software tool developed by Energy Exemplar and is used for power and gas market modelling worldwide (Energy Exemplar, 2013). Since 2007, PLEXOS has been used in Ireland by the Transmission System Operators (TSOs) Eirgrid and SONI, Commission for Energy Regulation (CER) and SEM participants to validate and forecast SEM outcomes (Eirgrid and SONI, 2012b; CER, 2011b). Similarly, the UK's TSO National Grid uses PLEXOS to calculate the efficiency of the balancing mechanism in the BETTA market (Energy Exemplar, 2011). Moreover, it is

considered by academia as a well proven tool for policy analysis and development in both Ireland and the UK (Cleary et al., 2015; Denny, 2009; Deane et al., 2014; Edmunds, 2014; Haines, 2014; Higgins et al., 2014; Mc Garrigle et al., 2013).

BALMOREL was originally developed as a cooperation project between research and regulatory organisations in the Baltic Sea region for a project financed by the Danish Energy Agency (RAMlose, 2014). The original purpose of this project was to develop a publicly available model for analysing the power and heating sectors in the Baltic Sea Region as a result of increasing internationalisation of the electricity sector (Ravn et al., 2001). It was initially used as a template for the development of WILMAR and is today developed and distributed under open source (Foley et al., 2010). BALMOREL has been applied to projects in Denmark, Norway, Estonia and Germany as well as projects outside Europe, in particular China and Eastern Africa (Connolly et al. 2010a, 2010b; RAMlose, 2014). It has been mainly used to analyse security of electricity supply, development of international electricity markets, electric vehicle integration, district heating systems and environmental policy evaluation.

The use of both PLEXOS and BALMOREL to build and run the models for this analysis allows for the validation of the 2012 base models and the use of the models for further analyses in 2021. PLEXOS is used for analysing the 2021 model scenarios, whereas BALMOREL is used to produce interconnector flows between BETTA and mainland Europe (Netherlands, France and Belgium) in 2021 for each scenario; which are then used as a fixed input to the PLEXOS 2021 model scenarios as described in more detail in Section 3.3.

3.2. Base model description

A number of publicly available sources were used for the creation of the 2012 PLEXOS and BALMOREL base models. The CER validated forecast model of 2011–2012 was used as a starting point from which the 2012 PLEXOS model for this analysis was developed (CER, 2011b). The 2012 model was populated with the individual generator technical and commercial characteristics which have signed agreements and confirmed dates to connect to the SEM (Eirgrid and SONI, 2012a). The demand and wind capacity for 2012 were obtained from the CER (2011b) and cross-checked with Eirgrid and SONI (2012a). A detailed model of the BETTA market was created using the Deane et al. (2013a,b) model as a starting point. The model was populated with the individual generator technical characteristics based on the reported installed capacities from DECC (2013a). The model also includes interconnector flows between SEM and BETTA as well as flows from the simplified French and Dutch markets in the form of flows produced by BALMOREL.

Similarly, the 2012 BALMOREL model was built using the CER (2011b) and DECC (2013a) generation portfolio data for the SEM and BETTA markets, respectively. For the BETTA market, aggregated generator types were used instead of individual generators due to data availability restrictions. Both models treat the SEM and BETTA markets as centralised pool markets. The BETTA market is particularly difficult to model given the bilateral contracts which exist between generators and suppliers and the strategic bidding practices by vertically integrated utilities. Therefore, it is assumed that the centralised pool approach will yield similar outcomes to the bilateral trading arrangements in the BETTA market as outlined in Section 2. This approach has also been adopted by Curtis et al. (2013) and Deane et al. (2013a,b).

The PLEXOS model simulation engine reads the input data such as system demand and wind data as shown in Fig. 2. It simulates 365 individual daily optimisations at half-hourly intervals while ensuring the generation portfolio meets demand at least cost

PLEXOS System

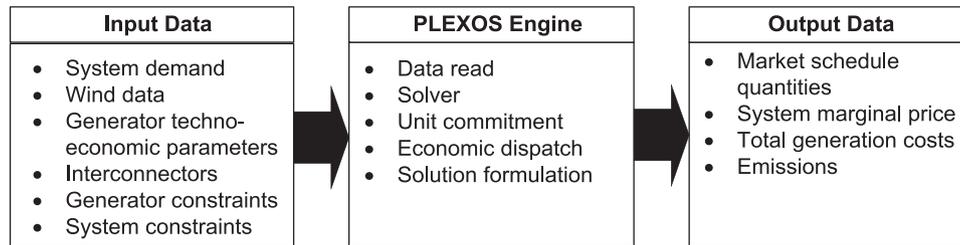


Fig. 2. PLEXOS system modelling structure.

while taking into account the individual generator's techno-economic parameters. Prior to dispatch, the model calculates the availability of each generator for the year taking into account their planned and unplanned maintenance. Similar to the SEM and BETTA markets, the model calculates the electricity prices and generator output schedules for each half hour trading period, therefore providing an accurate representation of the dispatch of generators in both markets.

The BALMOREL model simulates and optimises the hourly dispatch of the generation portfolio in the SEM, BETTA, French and Dutch markets to meet demand at least cost while taking into account the generators techno-economic constraints. An hourly time interval was chosen due to data availability and to align with the hourly dispatch interval of mainland Europe markets. The following subsections describe the model assumptions in more detail.

3.3. Base model assumptions

A set of common technical and economic input parameters were used where possible for the 2012 PLEXOS and BALMOREL base models. The PLEXOS model incorporates detailed characteristics for individual generator types for both markets, while the BALMOREL model incorporates detailed individual and aggregated generator types for the SEM and BETTA markets, respectively. The demand for each half hourly period in 2012 is included in both models. The BALMOREL model uses the average of the half hourly periods to create an hourly demand profile. The annual demand is estimated to be 36.5 TWh with a peak demand of 6.5 GW and 308.6 TWh with a peak demand of 55.8 GW for SEM and BETTA markets, respectively.

Table 1 shows the aggregated conventional generation portfolio for the SEM and BETTA markets in 2012. The gas- and coal-fired generators provide the largest contribution to the generation portfolio in both markets. Subsequently, gas has been the predominant marginal generator type in both markets and a high correlation exists between the price of gas and electricity prices (CER, 2011b). A restriction on the number of operating hours of the BETTA coal generators was enforced to reflect the Large Combustion Plant Directive (LCPD, 2001/80/EC) (National Grid, 2007), therefore a maximum annual load factor of 38% was set in both models. Nuclear generation in the UK also experienced reduced operating hours due to technical problems and annual load factors of 80% for 2012 were set in both models.

The renewable generation portfolio for the 2012 SEM and BETTA markets is shown in Table 2. Onshore and offshore wind provides the predominant share of the renewable generation portfolio in both markets. There is only 25 MW of installed offshore wind capacity from a single wind project in the SEM compared to 2995 MW in the BETTA market.

Wind generation in the SEM is modelled in PLEXOS under the assumption of perfect foresight in aggregated form, split into 13 regions. Each region has an associated hourly capacity factor

Table 1

2012 aggregated conventional generation portfolio capacity (MW).

Generator type	SEM	BETTA
Coal	1331	25,774
Gas	5478	36,070
Oil	804	4032
Nuclear	0	9231
Distillate Oil	640	0
Peat	346	0
Total (MW)	8598	75,107

Table 2

2012 aggregated renewable generation portfolio capacity (MW).

Generator type	SEM	BETTA
Hydropower	216	1680
Pumped hydro storage	292	2828
Onshore wind	2224	5438
Offshore wind	25	2995
Solar PV	0	1700
Solid biomass	0	1014
Biogas	0	1223
Waste	17	0
Total (MW)	2774	16,878

profile which represents the wind availability in that region for a typical meteorological year. The onshore and offshore wind for the BETTA market is represented by hourly profiles for the GB region for the year taken from Deane et al. (2013a,b). Moreover, the British wind is time lagged by 3 h, meaning that the wind appears in GB later than it has appeared in Ireland. Similar studies have used a time lag ranging from 2–4 h (Mc Garrigle et al., 2013; Weiss et al., 2013). Hourly profiles for the solar PV were also obtained from Deane et al. (2013a,b) and implemented in the model. In the BALMOREL base model, wind generation in the SEM is modelled in the same manner as in PLEXOS. For the BETTA market, the Irish wind profiles are assigned to the British district regions with respect to their location in Ireland (i.e. South West Britain is assigned the profile from South West Ireland) and time lagged by 3 h relative to the Irish wind profiles.

The pumped hydro storage generators are optimised and dispatched based on the pumping and generation cycles which are subject to the head and tail reservoir capacities. The hydro generators in the SEM are optimised based on fixed daily hydro resource limits for each month in 2012. In the BETTA market, the hydro generators are assigned a 36% annual capacity factor as detailed hydro resource limits were not publically available. The biogas and biomass generators are assigned 56% and 75% annual capacity factors set within the model based on historic market data, respectively (DECC, 2013a).

The complete transmission network is not included in either model and localised network constraints are not modelled.

Instead, the models' consist of two separate nodes representing the SEM and BETTA market. The Moyle interconnector (MI) links the SEM to BETTA market and flows on the interconnector are largely driven by arbitrage of the relative prices in the two markets. There is uncertainty in relation to the actual maximum import and export capacity of the MI for the foreseeable future due to an undersea cable fault (Eirgrid and SONI, 2013). Therefore, in the PLEXOS model, the MI is assumed to be limited to exporting 250 MW and importing 450 MW November–March and 410 MW April–October all year. The MI in the BALMOREL model is set to export and import based on historical weekly flows.

The BritNed interconnector and England–France interconnector (IFA) links the BETTA market to the Dutch and French markets, respectively. The import and export flows for the BritNed and IFA interconnectors are fixed within the PLEXOS model based on historic 2012 data (Unicorn, 2013). Therefore, the PLEXOS model does not optimise the hourly dispatch of generation in the French and Dutch markets. This approach was adopted as it reduces the need to create a detailed representation of the Dutch and French markets and significantly reduces computational time. In the BALMOREL model, the BritNed and IFA interconnectors and the Dutch and French markets are represented in detail given that the representation of these markets were developed for a previous study by Ea Energy Analyses (2014).

Both models apply on average 2% transmission losses to all generators to account for the possible losses within the SEM and BETTA markets. Line losses are also applied to the interconnectors to allow for losses between the markets. The planned and unplanned maintenance outage schedules for each generator during the year are taken into account. The former is assigned manually based on the 2012 schedule and the latter is modelled as a random event using forced outages from CER (2011b) for the SEM in the model. For the BETTA market, planned maintenance outage schedules were not publically available; therefore maintenance outage schedules for each generator are modelled as a random event based on outage rates from Deane et al. (2013a,b).

Fuel prices for the ROI, NI and GB are based on quarterly predictions for 2012 as shown in Table 3 from two main sources (Clancy and Gaffney, 2014; DECC, 2012). The fuel prices are based on the quarterly spot market prices in 2012 and include transportation costs to the generator. The transportation costs are calculated using a fuel delivery calculator developed by the CER (2011b).

Quarterly predictions for carbon prices based on the European Union Emissions Trading Scheme (ETS) were applied to fossil fuel

Table 4
Quarterly carbon prices for 2012.

Market	Carbon price (€/tCO ₂)			
	Q1 2012	Q2 2012	Q3 2012	Q4 2012
SEM	8.01	7.07	7.55	7.18
BETTA	7.30	6.42	6.87	6.53

generators in the SEM and BETTA markets as shown in Table 4 (Clancy and Gaffney, 2014; National Grid, 2013b).

Generator VOM costs were obtained from several sources (Mott MacDonald, 2010; Connolly, et al. 2010a, 2010b; Doherty et al., 2006) and start-up costs were derived from historic start-up costs (CER, 2011b). All cost data was normalised to 2012 values using historic consumer price indices from CSO (2013). The general approach is to model wind generation with zero short-run marginal costs (fuel, carbon and start-up costs equal zero) based on the assumption that it will always run when available, due to its priority dispatch status. Similarly, hydro, waste and solar PV are assigned zero short-run marginal cost to ensure they are dispatched fully when available. The peat, biomass and biogas generators are considered as must-run generators and have associated fuel costs.

3.4. Base model validation

A comparative validation analysis was conducted between the PLEXOS and BALMOREL 2012 base model outputs and the actual SEM and BETTA markets data in 2012. It should be noted the BALMOREL model outputs are compared with the hourly SMP in order to coincide with the simulation time resolution used. The mean absolute percentage errors (MAPEs) were 13% and 5.3% for the average daily SMP in the SEM for the PLEXOS and BALMOREL models, respectively. Both models produce a profile for the average daily SMP which is consistent with the actual market. It was noticeable there were regular price spikes and dips for the on-peak and off-peak hours as observed in the actual market, respectively. The models determine the least-cost optimal solution to meet demand but in the actual SEM and BETTA markets there can be substantial deviations from the optimal solution given that more expensive generators maybe dispatched to account for real time conditions.

In general, the PLEXOS model produces higher SMP than the actual market, while the opposite is observed for the BALMOREL model. The discrepancies can be attributed to the models' tendency to schedule different generator types and their capability in modelling the uplift component of the SMP which covers the generator's start-up and no-load costs. In both models, quarterly fuel and carbon prices were used as a result of publically available data, whereas if daily fuel and carbon prices were available and used in the models a more representative SMP profile would be expected. The MAPEs were 2.4% and 2.6% for the annual production (GWh) in the SEM for the PLEXOS and BALMOREL models, respectively. This suggests both models are scheduling a similar amount of total generation capacity over the year but they have a tendency to schedule different generator types, particularly coal and gas generators. This can mainly be attributed to the approach each model uses for modelling the generators' heat rate functions. In the BALMOREL model, this is represented by an average efficiency which remains constant during the generator's operating capacity range. In the PLEXOS model, a more detailed representation of the heat rate function is used in the form of marginal capacity points and incremental heat rate pairs at several instances during the generator's operating capacity range.

Table 3
Quarterly fuel prices for 2012.

Fuel type	Fuel price (€/GJ)			
	Q1 2012	Q2 2012	Q3 2012	Q4 2012
NI gas	8.01	7.73	7.74	8.60
Rol gas	7.98	7.69	7.70	8.57
NI oil	17.20	16.10	16.72	15.41
Rol oil	17.55	16.45	17.07	15.75
NI coal	3.51	3.11	3.17	3.06
Rol coal	3.10	2.70	2.76	2.65
NI distillate	21.63	21.26	21.90	20.50
Rol distillate	21.99	21.62	22.25	20.86
GB coal	3.37	3.33	3.05	2.93
GB oil	16.11	15.63	16.56	15.24
GB gas	7.83	7.28	7.21	7.93
GB diesel	16.11	15.63	16.56	15.24
GB nuclear	0.71	0.71	0.71	0.71
GB biomass	1.53	1.53	1.53	1.53
GB bioenergy	1.53	1.53	1.53	1.53

Moreover, the PLEXOS model takes account of three generator start-up states (hot, warm and cold), where as in the BALMOREL model, the warm state is only modelled.

Compared to the SEM, it is more difficult to obtain BETTA market data given the bilateral trading arrangements which exist and the limited public availability of the data. For the comparative validation analysis, the average of the buy/sell price from Elexon (ELEXON, 2014) for the balancing mechanism is used to determine the balancing or spot price and then compared with the modelled SMP. For the BETTA market, the MAPEs were 9.5% and 9.3% for the average daily SMP for the PLEXOS and BALMOREL models, respectively. Again, both models produce a profile for the average daily SMP which is similar to the actual balancing price profile. However, it should be noted that the balancing price is not entirely representative of the BETTA market wholesale price given that circa 2% of the total trade volumes take place in the balancing mechanism. The MAPEs were 15.1% and 11.8% for the annual production (GWh) in the BETTA market for the PLEXOS and BALMOREL models, respectively. The larger MAPE for the annual production for the BETTA market models compared to the SEM models was due to the reliability of the BETTA market production data. It proved difficult to obtain a breakdown of these data for all of the different generator types and therefore several sources were used, some of which was conflicting (ENTSOE, 2014; Gridwatch, 2014; DECC, 2014).

The validated PLEXOS base model in 2012 is used for the analyses presented in this paper instead of the BALMOREL model as it can consistently replicate the SEM and contains a more detailed representation of the BETTA market. The PLEXOS model also has the ability to capture more variability in the system demand and renewable generation at higher temporal resolutions. Moreover, a better representation of the flexibility/inflexibility of conventional generation is also achieved at this resolution which leads to more realistic estimations in total generation costs as indicated previously by Deane et al. (2014).

3.5. Model scenarios

The validated PLEXOS base model in 2012 was used as a starting point from which the 2021 model for this analysis was developed. The year 2021 was chosen for the model scenarios analyses as this is the year some or all of the proposed Irish midlands wind export projects could be connected to the UK. The generation portfolio for the SEM remains the same for all the model scenarios and it is assumed the portfolio achieves Ireland's 2020 RES-E target. The chosen generator types are based on the projected generation portfolio in 2021 given the new entrants and retirements planned for the SEM over the next 10 years (Eirgrid and SONI, 2012a). A breakdown of the generator types from both the ROI and NI participating in the SEM in 2021 is shown in Table 5.

For the BETTA market, two main scenarios are adopted from National Grid (2013a); Slow Progression and Gone Green. The Slow Progression scenario represents a generation portfolio which does not meet the UK RES-E and emissions targets for 2020. The Gone Green scenario represents a generation portfolio which meets the UK RES-E and emissions targets for 2020. These scenarios are chosen as they are assumed to be representative of the projected generation portfolios in 2021 derived from National Grid's stakeholder engagement programme (National Grid, 2013a). For each National Grid scenario, two options are considered; with and without 10 GW of capacity from the Irish wind energy export projects (abbreviated as Imports). A description of each model scenario is shown in Table 6.

The generation portfolio for the BETTA market varies for each model scenario and a breakdown of the generator types used in

Table 5
SEM 2021 model scenario generation portfolio capacity (MW).

Generator type	SEM
Coal	1331
Gas	5269
Distillate oil	635
Peat	346
Hydropower	216
Pumped hydro storage	292
Onshore wind	4718
Offshore wind	600
Solid biomass	320
Waste	98
Wave	201
Total (MW)	14,026

this analysis is shown in Table 7. It should be noted for each model scenario the BETTA market consists of generators located in GB with the exception of the UK Slow+Imports and UK Green+Imports scenarios which contains the onshore and offshore wind Imports from Ireland.

3.6. Model modifications and assumptions

A number of modifications were applied to the validated 2012 PLEXOS base model in order to reflect the SEM and BETTA markets model scenarios in 2021. Similar to the 2012 comparative validation analysis, the 2021 model scenarios analyses employs a deterministic approach using a main set of assumptions based on published data where possible. The analysis assumes perfect foresight for all variable renewable generation and system demand with no significant design or rule changes to the SEM and BETTA markets.

The SEM demand is expected to increase 12.8% between 2012 and 2021 based on the median demand forecast by Eirgrid and SONI (2012a). The annual median demand is estimated to be 41.1 TWh with a peak demand of 7.3 GW. In contrast, the BETTA market demand is expected to decrease by 4% during the same period due to the implementation of energy efficiency measures based on National Grid projections (National Grid, 2013a). The annual demand is estimated to be 296.2 TWh with a peak demand of 53.5 GW. Accordingly, the 2012 demand time series profiles are linearly scaled to reflect the 2021 demand forecasts.

Onshore wind generation in the SEM is again modelled in aggregated form, split into 13 regions. The installed capacity for each region in 2021 is based on the proposed regional distribution of renewable capacity by Eirgrid (2010). Offshore wind generation in the SEM is assumed to be installed off the Northern Ireland coast and is assigned an hourly profile from Deane et al. (2013a,b). The onshore and offshore wind Imports capacities are set at 6200 MW and 3800 MW, respectively. Hourly profiles for the onshore and offshore wind Imports are derived from the CER (2011b) and Deane et al. (2013a,b), respectively. The onshore and offshore wind for the BETTA market is represented by hourly profiles for the GB region taken from Deane et al. (2013a,b).

A main constraint restricting the amount of non-synchronous generation, mainly wind, participating in the SEM and BETTA markets is enforced in the model. This is known as the System Non-Synchronous Penetration (SNSP) limit and is a measure of the non-synchronous generation at an instant in time. The SNSP limit ensures that the amount of wind generation, when added to interconnector imports, does not exceed the sum of system demand and interconnector exports. The TSOs in Ireland aims' to increase the current SNSP limit of 50% up to 75% by 2020, while empirical evidence from industry sources suggests that the equivalent SNSP

Table 6
Model scenarios.

National Grid scenarios	Model scenarios	
Slow progression	UK Slow	UK Slow+ Imports
This scenario represents a generation portfolio which does not meet the UK RES-E and emissions targets for 2020	This scenario represents a generation portfolio which meets the binding 2020 RES-E target in Ireland but not in the UK. This scenario can be considered as the base case scenario given the likelihood of the UK not achieving the 2020 RES-E target.	This scenario is similar to the UK Slow scenario but with an additional 10 GW of capacity from the Irish wind export projects (abbreviated as Imports) connected via a direct point interconnector to the UK. The Imports are not connected directly to the SEM and are considered a participant in the BETTA market. Therefore, the addition of the Imports helps the UK achieve the 2020 RES-E target.
Gone Green This scenario represents a generation portfolio which meets the UK RES-E and emissions targets for 2020	UK Green This scenario represents a generation portfolio which meets the binding 2020 RES-E targets in both Ireland and the UK.	UK Green + Imports This scenario represents a generation portfolio which excludes 10 GW of domestic onshore and offshore wind capacity from the UK and then adds the Imports instead to the UK to make up the deficit. Therefore, the Imports are contributing towards meeting the UK 2020 RES-E target.

Table 7
BETTA 2021 model scenarios generation portfolio capacity (MW).

Generator type	UK Slow	UK Slow+ Imports	UK Green	UK Green+ Imports
Coal	13,652	13,652	13,652	13,652
Gas	33,352	33,352	30,082	30,082
Oil	951	951	951	951
Nuclear	8980	8980	10,650	10,650
Hydropower	1123	1123	1123	1123
Pumped hydro storage	2744	2744	2744	2744
Offshore Wind	7778	7778	14,331	10,531
Offshore wind imports (from Ireland)	0	3800	0	3800
Onshore Wind	6224	6224	9363	3163
Onshore wind imports (from Ireland)	0	6200	0	6200
Solar PV	2040	2040	2040	2040
Solid biomass	1821	1821	1821	1821
Biogas	476	476	476	476
Total (MW)	79,141	89,141	87,232	87,232

limit in GB will remain at approximately 50%. Therefore, the SNSP limit is assumed to be 75% and 50% for the SEM and BETTA markets model scenarios in 2021, respectively.

There are a number of new interconnectors due to come online between 2012 and 2021. The East-West interconnector between the SEM and BETTA markets is added to the model scenarios, a maximum flow of 500 MW was assumed both ways. The proposed Nemo-link interconnector between the BETTA and Belgium markets is included in the model with a maximum flow of 1000 MW both ways (Nemo link, 2014). Also the proposed IFA2 interconnector between the BETTA and French markets is included in the model with a maximum flow of 1000 MW both ways (National Grid, 2014). A dedicated one-way interconnector with maximum flow of 10,000 MW is included in the model for the onshore and offshore wind Imports to connect to the BETTA market. The interconnector flows between the SEM and BETTA markets are allowed to be freely optimised for each model scenario. The import and export flows for the interconnectors from mainland Europe to the BETTA market are fixed within the PLEXOS model scenarios based on flows obtained from the 2021 BALMOREL model.

Fuel prices are adjusted according to projections for 2021 from two main sources (DECC, 2013c; IEA, 2013). A carbon price of €30/t CO₂ based on the European Union ETS was applied to fossil fuel-based generators in the SEM. This figure is based on the carbon taxes used for previous SEM case studies, which ranged between €15–45/t CO₂ (Tuohy and O'Malley, 2011; Doherty et al., 2006; Grant and Phillips, 2011; Connolly et al. 2010a, 2010b; Deane et al., 2012). A carbon price of €34/t CO₂ based on the Carbon Price Floor (CPF) was applied to fossil fuel-based generators in the BETTA market (DECC, 2013c).

4. Results and discussions

The 2012 validated PLEXOS base model was adapted as described in Sections 3.5 and 3.6 for each model scenario. The unit commitment and economic dispatch model was run for a full year for the SEM and BETTA markets model scenarios in 2021 and the results are presented in the following subsections. For ease of reference, the results are presented for each of the SEM and BETTA markets model scenarios with and without the Irish wind energy export projects (abbreviated as Imports).

4.1. System marginal prices

A comparison of the simulated annual load-weighted average wholesale system marginal prices (SMPs) for all scenarios are shown for both the SEM and BETTA markets in Fig. 3. A sensitivity analysis of the SMPs for all scenarios was also conducted based on high and low fuel prices from (DECC, 2013c). The maximum and minimum whiskers shown in Fig. 3 represent the high and low fuel prices, respectively. It can be seen that the SEM prices are always higher than those in the BETTA market, primarily due to the different generation portfolio and system size which exists in the two markets. But another contributing factor is the higher cost of gas due to increased transportation costs for generators operating in the SEM. The introduction of the Imports reduces SMPs in all cases because each additional unit of wind, which has a zero marginal cost, displaces the more costly marginal generator, which is typically gas. The Imports therefore changes the generator merit order, resulting in lower average wholesale prices.

The largest reductions are observed in the BETTA market for

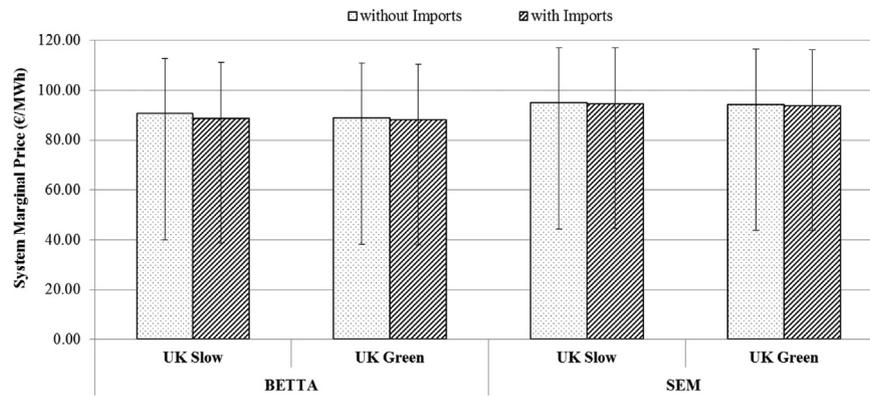


Fig. 3. Annual load-weighted average wholesale system marginal prices.

the UK Slow scenario, where Imports displace a greater amount of conventional generation than in the UK Green scenario, which has a higher proportion of low marginal cost renewable generation. The UK Slow+Imports scenario has an additional 10 GW of Irish-based wind energy Imports, whereas this 10 GW displaces the planned GB-based onshore and offshore wind in the UK Green+Imports scenario. In the latter scenario for example, the decrease in price is due to the higher capacity factors achieved by the onshore wind Imports which has a capacity factor of 30% compared to the GB-based onshore wind capacity factor of 24%. Fig. 3 shows the BETTA SMPs reductions due to the Imports, which are over twice as high for the UK Slow scenario (2%) as for the UK Green (0.8%) scenario.

The typical Levelised Cost of Energy (LCOE) for an Irish wind energy project in 2012 was €62/MWh (Duffy and Cleary, 2015) and assuming the Irish wind energy export projects have a similar LCOE, the SMPs for both UK scenarios should provide sufficient remuneration. A similar pattern of SMPs reductions is observed in the SEM, with the introduction of the Imports to the BETTA market resulting in reductions to Irish SMPs by 0.6% for the UK Slow and UK Green scenarios. This reduction in Irish SMPs is due to the lower priced BETTA electricity being imported via the interconnectors to the SEM. This is evident from the interconnector imports from the BETTA market to the SEM increasing for the UK Slow+Imports and UK Green+Imports scenarios relative to the UK Slow and UK Green scenarios, respectively.

4.2. Generation output mix

The estimates of generation output mix for the UK Slow and UK Green scenarios, both with and without Imports in the BETTA market are shown in Fig. 4. Gas generation dominates the UK Slow scenario, with nuclear, coal and wind representing important portions of the generation output mix. The generation output mix is more balanced for the UK Green scenario; however it contains greater Inter Imports from mainland Europe relative to the UK Slow scenario due to the additional 1 GW of interconnection capacity under this scenario. In both cases, the introduction of the Irish-based wind generation Imports reduces the marginal gas-fired generation, but has a minor impact on the other sources such as coal and nuclear generation.

As regards the UK Slow+Imports scenario, gas- and coal-fired generation decreases by 8% and 1% relative to the UK Slow scenario. These figures are 5% and 1% for the UK Green+Imports scenario relative to the UK Green scenario. Consequently, gas generator utilisation decreases significantly, with the annual BETTA capacity factors falling from 33.8% to 25.3% in the UK Slow scenario as shown in Table 8. This would have significant economic implications for gas generator investments under the

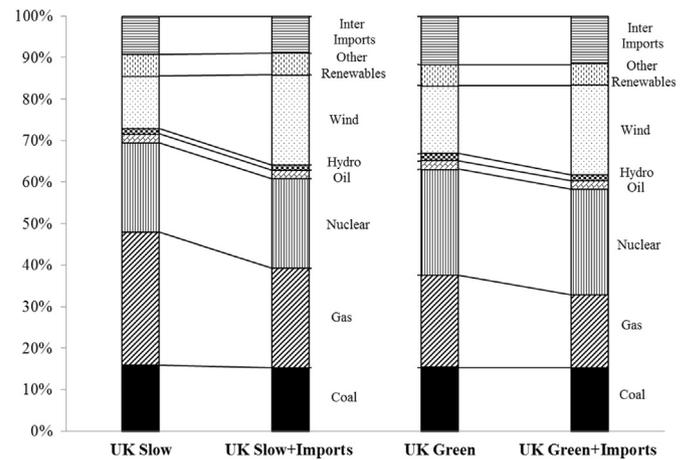


Fig. 4. BETTA generation output (%) by type.

current market structure. Coal generators are not as severely impacted, with annual capacity factors decreasing from 41.1% to 39.8% for the UK Slow scenario.

The typical Levelised Cost of Energy (LCOE) for an Open Cycle Gas Turbine (OCGT) and Combined Cycle Gas Turbine (CCGT) in GB is €244/MWh and €109/MWh (DECC, 2013b), respectively, which is significantly higher than the UK Slow scenarios average wholesale SMPs. Based on these LCOE estimates and in combination with the reduced capacity factors, gas generation will receive less revenue through the BETTA energy-only market. Therefore, remuneration mechanisms in the form of a capacity and/or ancillary services payments will be required. A complete analysis of the GB power system for energy and ancillary services provision exceeds the scope of this analysis but a detailed cost-benefit analysis would determine whether gas generation remains an economically viable technology.

4.3. Total generation costs

The economic impact of altering the generation portfolio in each model scenario with the inclusion of the Imports can be quantified by comparing the total generation costs for both markets. Fig. 5 presents the total generation costs (which include VOM cost, fuel cost, emissions costs, start and shutdown costs) for each scenario over the year 2021. The total generation costs are primarily a function of generation output by type and system size. This is reflected by the higher total generation costs in the BETTA market relative to the SEM.

Imports have a significant impact on the total generation costs in BETTA. Fig. 5 shows that costs fall to €10.4bn (16.8% decrease) and €8.9bn (11.6% decrease) for the UK Slow+Imports and UK

Table 8 BETTA 2021 model scenarios annual capacity factors (%).

Generator type	UK Slow	UK Slow+ Imports	UK Green	UK Green+ Imports
Coal	41.1	39.8	40.3	39.7
Gas	33.8	25.3	26.0	20.7
Nuclear	84.5	84.5	84.8	84.4
Oil	77.4	76.7	77.3	76.4
Hydropower	15.0	15.0	15.0	15.0
Pumped hydro storage	11.8	11.0	17.2	12.3
Offshore Wind	37.7	37.8	36.5	32.0
Offshore wind imports (from Ireland)	–	35.5	–	35.6
Onshore Wind	23.9	23.9	23.0	18.1
Onshore wind imports (from Ireland)	–	30.3	–	30.3
Solar PV	9.3	9.4	7.2	8.7
Solid biomass	73.5	72.5	73.0	72.2

Green+Imports scenarios, respectively. The majority of the reduction occurs in the generation cost component as opposed to the start and shutdown component of the total generation costs. Less significant reductions are observed in the SEM with the introduction of the Imports: €1.18bn (1.3% decrease) and €1.19bn (3.6% decrease) for the UK Slow and UK Green scenarios, respectively.

The cumulative annual reductions in total generation costs are primarily the result of the switch from gas-fired generation to wind generation from the Imports. There is greater cost savings potential for both the SEM and BETTA markets in the UK Slow scenario due to the greater displacement of gas generation than for UK Green scenario where the greater deployment of renewables limits the potential for the Imports to displace this generation technology.

Under the current market structures as modelled for this analysis, the reduction in total generation costs also results in lower SMPs, thus benefitting the end electricity consumer. However, since only short-run marginal costs are estimated for this analysis, additional fixed costs including wind turbines and transmission investment costs are not considered. While such costs are assumed to be negligible for the SEM (since no investment is occurring here) this would not be the case for BETTA market, where, for example, substantial infrastructure such as wind farms and interconnection must be financed.

Based on capital cost (which include wind turbine, transport, project advisory and grid development) estimates of €1.6 million/MW (Duffy and Cleary, 2015), €3.7 million/MW (Lacal Arantegui, 2014) and €0.66 million/MW (Trichakis et al., 2013) for the onshore wind exports projects (6.2 GW), offshore wind exports

projects (3.8 GW) and subsea High Voltage Direct Current (HVDC) interconnectors (10 GW), respectively; the total cost is circa €30bn. The inclusion of the Imports in the UK Slow and UK Green scenarios provides annual savings of €2.1bn and €1.2bn, respectively. This results in a simple payback period of 14 and 26 years from a systems perspective for the UK Slow and UK Green scenarios, respectively. However, a detailed cost-benefit analysis is outside of the scope of this analysis.

4.4. CO₂ emissions

Carbon dioxide (CO₂) emissions were estimated for the SEM and BETTA markets for all scenarios and are presented in Fig. 6. It can be seen that the BETTA UK Slow scenario and UK Green scenario emissions decrease by 13% (11 MtCO₂) and 9% (6 MtCO₂) with the addition of the Imports, resulting in average CO₂ emissions intensities of 259 tCO₂/GWh and 239 tCO₂/GWh, respectively. While coal-fired generation is responsible for the majority of BETTA market emissions under all scenarios, the greatest CO₂ emissions reductions are from gas-fired generation since it is this technology which is displaced by the Imports. CO₂ emissions also decrease in the SEM for both scenarios with the Imports, albeit to a much lesser extent: 1% (0.1 MtCO₂) and 2% (0.2 MtCO₂) decreases are estimated for the UK Slow and UK Green scenarios, respectively. In the case of the SEM, emissions reductions are due to the interconnector imports from the BETTA market and its impact on displacing gas and coal generation in Ireland.

However, it should be noted an unconstrained energy market model is used for the analysis, which does not reflect the total operational CO₂ emissions. While, a complete analysis of the Irish

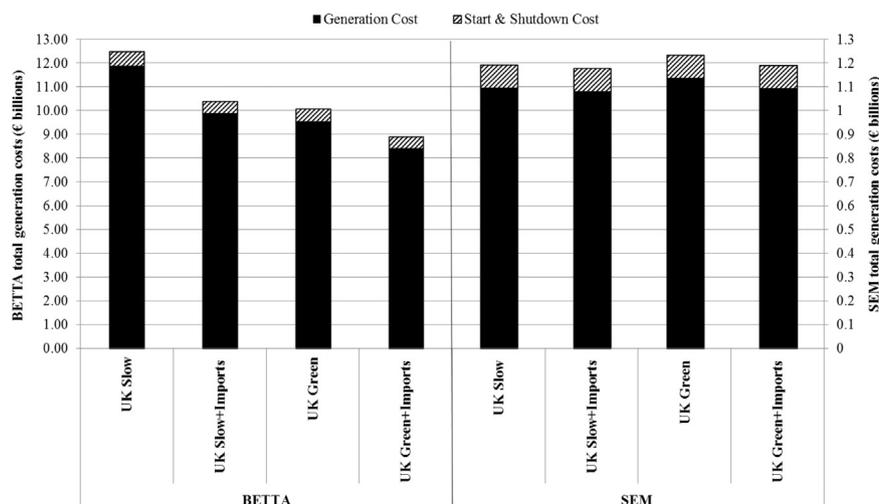


Fig. 5. Total generation costs for each model scenario.

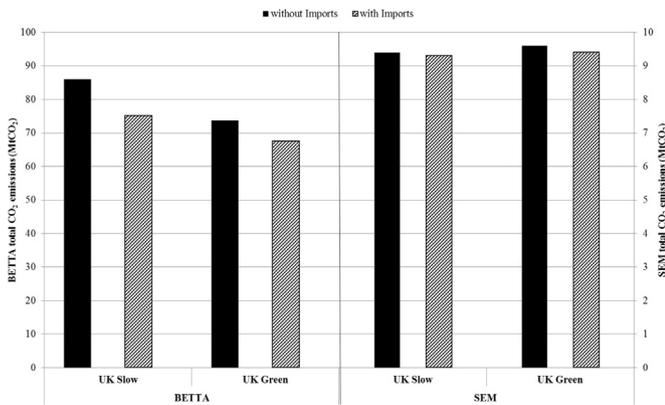


Fig. 6. Total CO₂ emissions for model scenarios.

and GB power system including the energy and ancillary services provision such as spinning and non-spinning reserve may lead to different total CO₂ emissions. Furthermore, the interconnector flows from GB to mainland Europe are fixed for each model scenario which may lead to economically irrational flows, thus affecting the CO₂ emissions in the BETTA market.

5. Conclusion and policy implications

Based on the simulated model scenarios, it was estimated that the Irish wind energy export projects (abbreviated as Imports) can reduce the SMPs in the BETTA market by 2% between the UK Slow and UK Slow+Imports scenarios. There was a minor reduction in SMPs from €88.62/MWh to €87.91/MWh between the UK Green and UK Green+Imports scenarios in the BETTA market. In the SEM, the introduction of the Imports to the BETTA market results in reductions to Irish SMPs by 0.6% for both the UK Slow and UK Green scenarios. The lower SMPs would primarily benefit the British electricity consumer. However, British producers particularly those with gas generating assets will experience a significant reduction in asset utilisation and energy revenues. Gas generator utilisation decreases significantly, with the annual BETTA capacity factors falling from 33.8% to 25.3% in the UK Slow scenario.

The models also indicate that the addition of Imports leads to lower total annual generation costs in 2021. In the BETTA market, costs fall to €10.4bn (16.8% decrease) and €8.9bn (11.6% decrease) for the UK Slow+Imports and UK Green+Imports scenarios, respectively. In the SEM, less significant reductions are observed with the introduction of the Imports: €1.18bn (1.3% decrease) and €1.19bn (3.6% decrease) for the UK Slow and UK Green scenarios, respectively.

Imports also contribute to a reduction in total operational CO₂ emissions. In the BETTA UK Slow and UK Green scenarios, total CO₂ emissions decrease by 13% (11 MtCO₂) and 9% (6 MtCO₂), respectively, with the addition of the Imports. The greatest CO₂ emissions reductions are from gas-fired generation since this is the main generation which is displaced by the Imports. Total CO₂ emissions also decrease in the SEM for both scenarios with the Imports, albeit to a much lesser extent: 1% (0.1 MtCO₂) and 2% (0.2 MtCO₂) decreases are estimated for the UK Slow and UK Green scenarios, respectively. The reduction is mainly driven by increased interconnector imports from the BETTA market to the SEM. Overall, the results from this analysis provide evidence that the Imports have an impact particularly on the generation costs and CO₂ emissions in the BETTA market and much less of an impact in the SEM.

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