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Economic assessment of high renewable energy penetration scenario in 2030 on the interconnected Irish power system

Shurui Wang [a,c,*], Ye Huang [c], Inna Vorushylo [c], Haisheng Chen [a], Dominic McLarnon [c], Paul MacArtain [b], Neil Hewitt [c]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, China
[b] Centre for Renewables and Energy, Dundalk Institute of Technology, Ireland
[c] CST, Ulster University, Jordanstown, UK

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ABSTRACT

The Irish Government has set very ambitious targets for the penetration of renewables into the Integrated Single Electricity Market (I-SEM), aiming for 40% electricity generation by 2020. This renewable share is expected to increase further in the I-SEM, British Electricity Trading and Transmission Arrangements (BETTA) and French electricity market by 2030. This research presents a case study testing the various levels of renewable energy integration in the three regions and assessed the economic impacts and benefits at elevated renewables penetration. To measure the economic and environmental sustainability, four indicators, i.e. annual wholesale system marginal prices (SMPs), total generation costs, total generation net revenues and CO_2 emissions were selected. The results showed that the I-SEM 2030 wholesale electricity market pricing would range from €101.26/MWh to €50.77/MWh with the increase of renewable integration from 44% to 75%. In the BETTA and French market, the addition of the renewable generation contributes to reductions to SMPs by 51.10% and 51.61% at most, respectively. It was also found that these enhanced renewable targets for 2030 could lower consumers' electricity bills and expand the total social welfare.

1. Introduction

The island of Ireland has recently experienced significant transformations in the electricity sector. Evolutions in the electricity sector on the island are different from other places primarily because of limited local natural resources, the isolated geographic location and the uncertainty of geopolitics (Gaffney et al., 2017). Integrated Single Electricity Market (I-SEM) is designed as a further market evolutionary step to integrate the all-island electricity market with European markets, enabling the free flow of energy across borders. The wholesale electricity markets in Great Britain (GB) have been integrated since the British Electricity Trading and Transmission Arrangements (BETTA) came into effect in April 2005.

Ireland has set the target of 40% of electricity to be produced by variable renewable energy (VRE) by 2020. This level of VRE integration will be the highest for any separate synchronous system anywhere, which requires instantaneous penetration of up to 75% non-synchronous power (mostly delivered by wind generation) (EirGrid, 2017d). BETTA and French electricity market set the 2020 renewable generation targets to 31% and 27%, respectively. Nevertheless, the 2030 renewable targets for the three markets remain officially unsettled. In the long term, the power market design could be totally different (Newbery et al., 2018). This paper focuses on the 2030 time horizon for a relatively steady market operation strategy.

The transition pathways of renewable generation are largely affected by its market value, which is typically determined by fuel prices, power generation mix, and emission prices (Winkler et al., 2016). Winker et al. found out that the fluctuation of the oil, gas and CO_2 emission prices are crucial to the development and the market value of renewable energy penetration. Higher international oil price and renewable portfolio standard (RPS) implementation will lead to higher future renewable power diffusion (Lee and Huh, 2017). Barton et al. research about future UK electricity pathways with the background of the renewable targets and transition to low-carbon economies and societies in Europe (Barton et al., 2018). Cleary et al. (2016) estimated the impact of large-scale wind generation by analysing 2021 I-SEM and BETTA models using the PLEXOS software tool. Their research shows that Irish-based wind generation projects can result in a decrease in I-SEM and BETTA wholesale system marginal prices. Di Cosmo et al. (Di Cosmo et al.,

* Corresponding author.Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, China.
E-mail address: wang-s8@ulster.ac.uk (S. Wang).

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Nomenclature

BETTA	British Electricity Trading and Transmission Arrangements
CO_2	carbon dioxide
EDF	Electricite de France
EU	European Union
FES	Future energy scenarios
Fr	France
FUI	I-SEM, GB and France electricity markets combined
GB	Great Britain
HVDC	High Voltage Direct Current
IC	interconnection
IEM	Internal Energy Market
I-SEM	Integrated Single Electricity Market
LCOE	Levelized cost of electricity
MIP	Mixed Integer Programming
O&M	operation and maintenance
OTC	Over-the-Counter
PSO	Power System Optimizer
SEM	Single Electricity Market
SMP	system marginal price
TOD	Technical Offer Data
VO&M	variable operation and maintenance costs
VRE	variable renewable energy

2019) found that interconnectors could reduce wholesale prices in France and Ireland.

Another piece of research (Vorushylo et al., 2016) pointed out the policy importance of emerging and renewable technologies in future markets. The comprehensive policy for renewable power generation can be designed for better social welfare (Iychettira et al., 2017). This research sets up and models the future I-SEM scenario with various levels of renewable generation considering fuel prices and market policy possibilities.

This paper is of importance for the individuals, such as power market participants, policy makers, and market regulators. Quantitatively analysing the impact of renewable generation is quite meaningful for the informed strategy development of individuals (Winkler et al., 2016). The same electricity market policy can result in different impacts on different stakeholders (Levin et al., 2019). Levin et al. found that without the support policies, the VRE penetration level is lower (Levin et al., 2019). With the right regulatory framework, incentives are provided for the right grid location of renewable investments (Costa-Campi et al., 2020). For power generators, their profitability affects the decisions of generators' operating strategies, market entry, market exit, or investment decisions. For consumers, direct support of the VRE policy can cause lower emissions with a small or negative impact on the costs of power customers (Trujillo-Baute et al., 2018).

The aim of this paper is to identify the economic benefits of high renewable penetration on the 2030 interconnected Irish power system. The modelling is focused on 2030-time horizon for the I-SEM, BETTA and French electricity market. This paper is structured as follows: Section 2 focuses on the power market current situation, external policy factors affecting the region, development trends and the outlook for I-SEM's policy. Section 3 explains the development of models and scenarios for the 2030 I-SEM, GB, and France regions. Section 4 describes the detailed modelling result of average annual wholesale electricity prices, total generation costs, total generation net revenues, CO_2 emissions and intensities. Section 5 finally concludes this paper by analysing the results and highlighting policy implications.

2. I-SEM, BETTA and French electricity market

European Union (EU) countries work together aiming to provide a competitive, sustainable and secure supply of power transitioning to low-carbon societies. With the entry into force of two directives concerning the third legislative package for an internal electricity and natural gas market, the priority of the integrated and single energy market was advanced in 2011 (EWEA, 2012; Paliament, 2016). The European Parliament associates the objectives for Internal Energy Market (IEM) with ensuring a functioning high-level market with fair access, consumer protection, adequacy of interconnection and generation capacity (Fiedler, 2015).

The 20-20-20 target which means reducing primary energy use by 20%, increasing the renewable component in energy to 20%, and reducing 20% in greenhouse gas emissions (from 1990 levels) by 2020 has been set to guarantee sustainability step by step (eurostat, 2017). Table 1 shows quantified targets for climate change and energy with regard to 2030 in I-SEM, GB, and France.

The EU IEM aligned and standardised each electricity market. However, within these markets, differences are still manifest. Neighbouring market structures have differences in the form of offer submission timeframes and trading contract types. At the European level, Ireland, UK and France are collectively called the FUI region. Fig. 1 shows interconnectors both inside and outside Ireland supporting the integration of European energy markets (Welsch et al., 2014). Offering diverse product portfolios and opening cross border access to all market participants can increase competitiveness, provide commercial opportunities and apply downward pressure on the cost of electricity to consumers.

The SEM (Single Electricity Market, which differs from I-SEM) project went live on 1 November 2007 which successfully combined two separate wholesale electricity markets in Northern Ireland and Ireland. All electricity across the island is bought and sold through the cross-jurisdictional, dual-currency (sterling and euro) single pool (or spot) market. This gross mandatory SEM represents the first market of its kind in the world (Department of Enterprise, 10 2016). It is designed to offer the least cost source of electricity generation whilst maximising long term reliability and sustainability. Under the EU's macro framework and the SEM local policy, all participants and stakeholder practice, test and amend electricity market policies.

The new I-SEM project, which went live on 1 October 2018, is a further step change for the Irish market. The IEM, including the I-SEM, is one of the key pillars for the European single market aiming at free trade across borders and non-discrimination between internal and cross-border transactions for electricity and natural gas.

I-SEM includes the electricity market in Northern Ireland, which politically and jurisdictionally is part of the United Kingdom. Therefore, Brexit will also have an impact on I-SEM. Leaving IEM is not only likely to make it very difficult for GB to meet the electricity demand with high efficiency, but also potentially raise the cost for consumers (Committee, 2017-19). For I-SEM which has been a key dividend of reducing energy prices and helping to achieve decarbonisation targets on the island of Ireland, it is vital to continue post-Brexit (Committee, 2017-19). New arrangements and careful consideration will be required for the mechanism of the I-SEM, because of the former implementation of EU energy laws in Northern Ireland. The fact that all key generators and suppliers must participate in I-SEM differs from other European markets where most trade takes place bilaterally between generators and suppliers. More transparency is therefore associated with I-SEM prices and market outcomes.

UK has a fully privatised electricity market, and is also at the forefront of liberalising its electricity sector (Electricity, 2014). Northern Ireland runs a separate wholesale electricity market that operates in accordance with the wholesale market in the Republic of Ireland with a

Table 1
EU quantified targets for climate change and energy in 2020, 2030 and 2050 (IRENA, 2015).

Main objectives	Organization	Renewable energy penetration		Greenhouse gas emissions reduction (compared to 1990 levels)	Energy efficiency
		All Sectors of Total Final Energy Consumption	Power Sector		
2020	EU	20%	20%	20%	20%
	UK	15%	31%	34%	–
	France (Deloitte, 2015)	23%	27%	–	–
	Ireland	16%	40%	–	–
2030	EU	No less than 27%	45%	40%	27%
	UK	–	–	57%	–
	France	32%	–	40%	–
	Ireland	–	–	40%	–
2050	EU	No specific targets		80%–95%	–
	UK	–		at least 80%	–
	France	–		75%	–
	Ireland	–		80%–95%	–

Fig. 1. Map of Irish I-SEM related HVDC electricity interconnectors (Commission, 2013-08-22; Department of Enterprise, 10 2016; EirGrid, 2017a, b, EirGrid, 2016; Grid, 2017; SHAKESPEAREMARTINEAU, 2017).

pool system, to form an integrated I-SEM. The wholesale electricity markets in Great Britain (including England, Wales and Scotland) have been integrated since the BETTA came into effect in April 2005 (Ofgem, 2002). Wholesale market contains day-ahead, real-time, energy, capacity, and ancillary services.

Bilateral contracts, trading markets, and power exchanges are available in BETTA. In forward contract markets, over 84% of GB electricity can be traded by Over-the-Counter (OTC) contracts, whilst others on power exchange. A relatively standard form of trading is generally taken, and then the amount of energy agreed will be delivered at a certain price per unit (MWh), at some point in the future. A very small amount of electricity is traded and subject to balancing arrangements.

The French electricity market is a highly concentrated power market, in which generation and retail markets are still highly dominated by Electricite de France (EDF), the vertically integrated French incumbent utility that is still controlled by the French state. The French transmission system operator Rte, 2017, and the distribution network operator ERDF, are 100% owned by EDF (Deloitte, 2015).

This paper aims to assess the impact of high renewables by modelling scenario with various renewables penetrations. Evidence is supplied in terms of annual wholesale system marginal prices (SMPs), total generation costs, total generation net revenues and CO_2 emissions in 2030 I-SEM, BETTA, and French interconnected electricity market.

3. Modelling methodology

To evaluate the impact and potential of the renewable energy generations and interconnection capacities, the best way is to build the regional and interconnected electricity market model. The market model should reflect the real market arrangements and structures with all the stakeholders. What's more, the model should also be flexible enough for the analysis of various market allocations and potentials. The Power System Optimizer (PSO) software from the Polaris Systems Optimization company has been used to model the market in this research.

The objectives for this chapter include: overview of software, modelling methodologies, scenario development, macroeconomic assumptions, model validation and simulation fuel cost data.

3.1. Modelling software

The PSO software was chosen for modelling the I-SEM. PSO is developed upon AIMMS, which is the developer of the modelling and optimization platform (Inc., 2018). Its modelling approach is based on Mixed Integer Programming (MIP) algorithms, which is quite suitable to simulate I-SEM in actual market operations. The PSO allows flexibility to simulate various market structures, new market policies, emerging generation technologies and testing of various market strategies.

All the I-SEM generators in the PSO model include: wind, gas, peat, hydro, storage, etc. The price taking generators means units with zero fuel price, such as wind generators. The price making generators contain thermal generators, energy storage, interconnections, hydro, etc. Thermal generators are price making generators. The peaking thermal generators, mainly as system marginal units, are quite important for market simulation accuracy. As a result, various modelling methodologies are needed to simulate different types of generators.

The generation input files into PSO software for power plant contains (Inc., 2018a):

- Capacity, heat rate curve, forced outages, Technical Offer Data (TOD), start-up profiles, etc;
- fuel and CO_2 costs, variable operation and maintenance (VO&M) costs, Levelized cost of electricity (LCOE) costs.

The generation input data for renewable generation contains (Vithayasrichareon et al., 2017):

- VO&M costs, LCOE costs;
- Half hourly wind generation profile.

The input data for energy storage includes:

- Storage capacity, forced outages, efficiency;
- VO&M costs, discharge costs, recharge costs.

The generation input data contain many main factors that affect the flexibility of power generation combinations. Through the modelling technique, the future generation framework can be integrated with short term generation dispatch and unit commitment. The expected results of the PSO software simulation contain (Inc., 2018b):

- 2030 I-SEM spot SMP;
- 2030 GB average electricity price;
- 2030 French average electricity price;
- 2030 I-SEM, GB, France power system total net revenue;
- 2030 I-SEM, GB, France total system generation cost;
- 2030 I-SEM CO_2 emission.

Associated extended results of this research using PSO software involves:

- Policy overview and recommendations;
- Identify the benefits of high VRE.

LCOE, sometimes called a life-cycle cost, is the average cost of generation converted into an equivalent unit in £/MWh over the lifetime (Tran and Smith, 2018). It contains the cost to build, operate, and decommission a generic plant for each technology. LCOE is also treated as an essential metric for the ranking of electricity generation competitiveness.

All plants in I-SEM with a capacity of over 10 MW bid in the day-ahead market and generate electricity based on the merit order, shown in Fig. 2. The bid containing fuel costs, operation costs and the carbon dioxide emission permits needed for the generation of electricity per MWh can reflect the plant's short-run marginal costs.

Under the Pool arrangements described above, the price known as the System Marginal Price (SMP) is the price at which all generator units receive and all supplier units purchase in each trading period for electricity. SMP is bounded by a Market Price Cap and a Market Price Floor, which are set by the Regulatory Authorities.

The software inputs are mainly technical and economic parameters, that are used by generators to produce their bids, among them: cycle period, emission type, fuel type, fuel thermal unit, heat curves, injector commitment, schedule timepoint, and storage ID for the three areas.

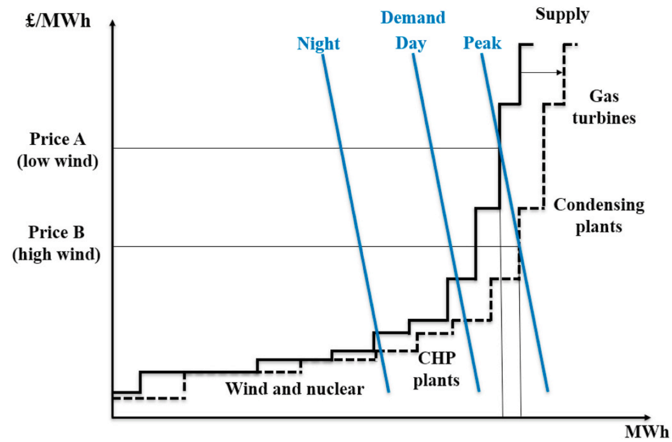

Fig. 2. Explanation of merit order effect (EWEA, 2012).

PSO will match the demand with generators according to the merit order. The output files are spot prices, dispatch profile for all generator units, CO_2 emissions, and so on.

3.2. 2030 market model description

A market model aiming to replicate I-SEM trading arrangements is created to perform a techno-economic analysis of the future SEM operation. The model should also be flexible enough to simulate different market operation strategies and scenarios.

The I-SEM model is based on the Regulation Authorities' PLEXOS SEM model (Consulting, 21 2018) with further development assumptions. More detailed future market generation portfolios, as well as upcoming I-SEM design changes are based on a number of I-SEM consultation, decision and review reports (EWEA, 2015; IWEA, 2018; EirGrid, 2018a).

The future I-SEM PSO models focus on a nominal 2030 time horizon. The model overview is presented in Fig. 3. 'IC' and 'Fr' represents interconnection and France, respectively. 'O&M' is short for operation and maintenance. The I-SEM now connected with BETTA with a total capacity of 1 GW, which could be 1.5 GW by 2030. I-SEM does not currently have interconnectors with the French market, however, it will be connected by Celtic interconnector with a capacity of 0.7 GW in 2025. The PSO model consists of three regions, which are the I-SEM, GB, and France regions.

The I-SEM region PSO model has detailed representation of all thermal generators at individual unit level, featured with a full range of techno-economic characteristics and constraints. The generators' economic inputs (fuel and carbon emission prices, operational and maintenance costs, etc.) combined with their technical characteristics (ramp rates, heat rate curves, start-up profiles, forced and maintenance outages data, minimum up and down times, etc.) can replicate complex bids submitted on a daily basis. Complex bids reflect generators' short marginal costs, however, exclude profit components or fixed costs, in line with the real market arrangements. I-SEM PSO models dispatch generators according to the "merit order effect". As a result, all renewable generators bid with zero costs and have priority dispatch as price takers. The objective function is to maximize social benefits and minimise total power system costs. Optimised results, including unit commitment and spot price settlement, are obtained based on the mandatory pool market structure.

The BETTA and French electricity market in the PSO model should represent the corresponding future market properly. The establishment of the GB market in the model needs to comprehensively consider the potential changes in market structure, facilitate the performance of the mean I-SEM model and the behaviour of interconnectors with I-SEM.

For the better performance of I-SEM simulation, GB and France

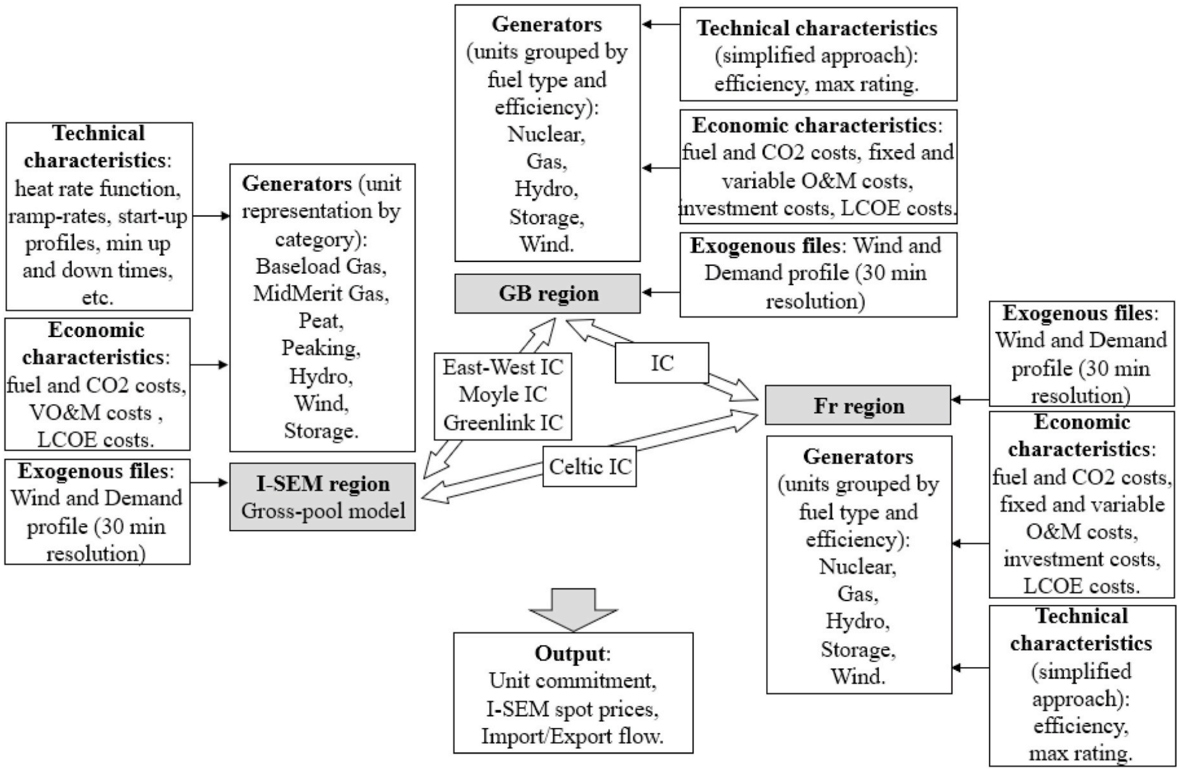

Fig. 3. I-SEM PSO model overview.

region is introduced as a simplified model allowing simulation of the interconnector flows. The BETTA and French electricity market's unit commitment and spot price settlement are optimised using a levelized cost algorithm.

3.3. Scenario development

Officially proposed scenarios of different transition options are compared in Fig. 4. There are four scenarios shaping the 2030 Ireland power system structure, namely Tomorrow's Energy Scenarios. The Tomorrow's Energy Scenarios contain Slow Change scenario, Steady Evolution scenario, Consumer Action scenario and Low Carbon Living scenario, with the VRE penetration of 47%, 57%, 55%, and 75%, respectively. They are proposed by the system operator EirGrid (EirGrid, 2017c, 2018b). Compared to the other three scenarios, the Low Carbon Living scenario has high society economic growth, the highest electricity demand, and the strongest public decarbonisation incentives in the demand side. At the same time, there are more new emerging renewable generation technologies, higher levels of low carbon generation in the Low Carbon Living scenario. In the 2030 Slow Change scenario, generation portfolios have little changes and consumers would like to avoid uncertainties.

The Northern Ireland 2030 scenario has been represented in two possible ways, including Fossil Fuel 2030 scenario and Renewable Energy 2030 scenario (Baringa, 2018). The Fossil Fuel 2030 scenario shows no progress in renewable generation after meeting the 2020 40% renewable electricity targets, in which power generation is assumed to rely primarily on fossil fuels in 2030 (IWEA, 2018).

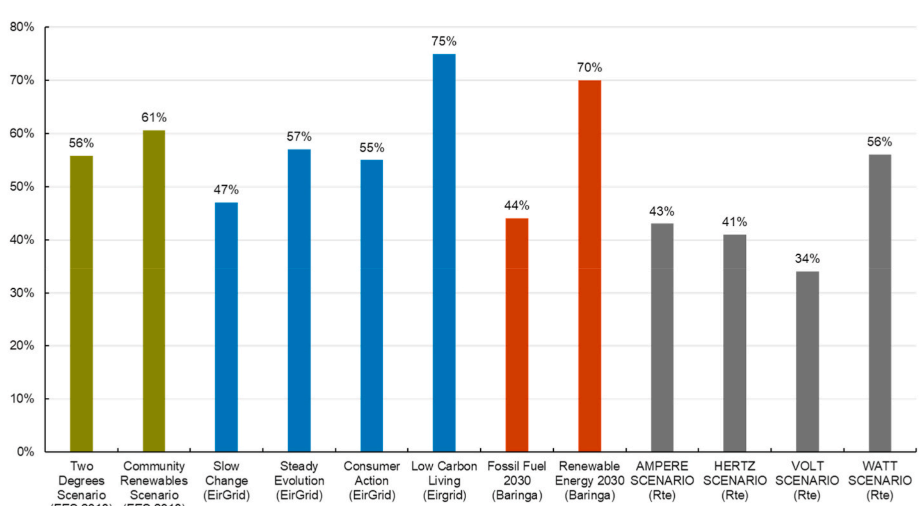

Fig. 4. Share of renewables in 2030.

Future energy scenarios (FES) are put forward to shape the energy future for GB by the transmission system operator National Grid (Grid, 2018a,b). There are four FES, namely Community Renewables Scenario, Two Degrees Scenario, Consumer Evolution Scenario, and Steady Progression Scenario. All scenarios in FES have higher levels of decentralized power than today. The trend that coal contributes to no electricity at all is seeing an increasing prevalence in GB. Natural gas continues to also provide some baseload power. Wind capacity increases, much of which growth is in offshore wind. It is expected to have significant solar growth due to the falling cost of solar technology and its co-location with energy storage. New business models could be developed aiming to add more flexibility for power system scenarios with a hydrogen economy. A reduction in nuclear capacity is anticipated for the next decade, because of older nuclear plants shut down before new power plants are ready for generation. Over 7 GW of new nuclear generation is expected, with much of which will be constructed in the 2030s (Grid, 2018a). A marked increase in energy storage capacities is expected in most FES scenarios. Restrictions on the amount of biomass that can be grown or imported exist on a large scale. Two of these four FES scenarios can finally meet the 2050 target, namely Two Degrees Scenario and Community Renewables Scenario, shown in Fig. 4. The share of renewables for the Two Degrees Scenario and Community Renewables Scenario are 56% and 61%, respectively. The higher interconnection capacity with other countries is also considered. Because of a higher carbon price floor and coal generating plant closure, increasing net annual electricity interconnector flows go into GB in the early 2020s. However, it is less of a driver for electricity trade after this point, as the carbon price in Europe becomes similar to the UK. After the mid-2020s, Two Degrees scenario starts to show net exports to connected markets, as the increasing levels of renewable and nuclear capacities. Imported electricity provides flexibility to support renewables, especially in the Community Renewables scenario. In this more decentralized scenario, there is less baseload generation driving exports to connected power markets.

Given targets should be implemented when designing French scenarios (Deloitte, 2015). The targets include 50% nuclear energy in power generation by 2025, technical decommissioning of nuclear power plants, and so on. Five scenarios are studied to meet these targets, among which four concern the year 2030. The four scenarios are AMPERE SCENARIO, HERTZ SCENARIO, VOLT SCENARIO, and WATT SCENARIO, as is shown in Fig. 4. The highest and lowest VRE penetration for the 2030 French electricity market are 56% and 34%, respectively. Coal and heavy fuel oil are considered to be zero in these scenarios.

After considering all the officially proposed reports, three VRE case studies are created, namely FUI high, FUI baseline, and FUI low. The three case studies' VRE installed capacities are compared for 2030 I-SEM, BETTA, and French electricity market, as is illustrated in Table 2.

The 2030 I-SEM baseline scenario is created on the basis of the Steady Evolution scenario for Ireland and the Renewable Energy 2030 scenario for Northern Ireland. The baseline scenario for BETTA and French electricity market is based on Two Degrees scenario and AMPERE scenario.

For the FUI high case study, the I-SEM, BETTA and French market are established based on the Low Carbon living scenario, Community Renewables scenario and WATT scenario. The I-SEM, BETTA and French market is on the basis of Slow Change scenario, Two Degrees scenario and VOLT scenario, respectively, for the FUI low case study.

The 2030 modelling scenario of this paper is illustrated in Table 3.

3.4. Main model assumptions

In this FUI high case study, these three places are all assumed to achieve the highest renewable electricity targets and highest demand, due to more strong economies. Electricity supply has the highest solar and onshore wind. The main assumption for Northern Ireland is that the I-SEM continues to be a world leader in renewable electricity, particularly in wind. It is in line with corresponding Ireland's Low Carbon Living forecasts (Baringa, 2018).

The FUI baseline case study shows the four regions with a medium level of VRE penetration, due to steady improvements in the economy, and in generation technologies. For France in this case study, the reduction in nuclear power generation matches the actual pace of renewable energy development.

In the low VRE scenario, there is little change in the way electricity is generated when compared to today. There is no further renewable generation deployment after the 2020 renewable electricity target is met. Domestic consumers and commercial users are also avoiding the risk and uncertainty of new renewable generation technologies. The economy experiences very slow growth. This scenario provides a counterfactual against which we have measured the additional costs and benefits of the Renewable Energy scenario for Northern Ireland.

The I-SEM total interconnection capacity is assumed to be 1780MW. It means that Greenlink interconnector, Moyle interconnector, East-West interconnector, and Celtic interconnector are in operation in 2030.

By conducting techno-economic analysis and investment analysis on the VRE FUI scenario results, a blueprint of future wind dominated I-SEM is revealed.

3.5. Model validation

The model established is a forward-looking model. The model validation is done by comparing the historic model simulation result with the historic real market operation data. The aim of this process is to find out the difference and readjust the model settings for the best performance of its software outputs. The I-SEM model is validated against the historical SEM trading data to guarantee it reflects the market operation with accuracy.

For model validation, the PLEXOS SEM model dataset (Baringa,

Table 3
Overview of the modelling scenarios.

Scenarios	Case studies	Description
VRE scenario	FUI high	Highest VRE penetration
	FUI baseline	Medium VRE penetration
	FUI low	Lowest VRE penetration

Table 2
Installed capacity on total capacity in 2030 I-SEM, BETTA and French electricity market for three case studies (Unit: MW).

	FUI high case study			FUI baseline case study			FUI low case study		
	I-SEM	BETTA	French market	I-SEM	BETTA	French market	I-SEM	BETTA	French market
Wind	10690	47000	51300	8030	48700	51300	6002	48700	40200
Photovoltaic	2900	33000	3600	900	24300	36000	470	24300	27700
Hydro	248	2200	26600	248	2000	25600	248	2000	25600
Ocean	100	1900	800	50	3300	800	20	3300	600
Biomass	802	6200	3500	442	5900	3500	322	5900	3100
Gas	5432	31700	29600	5882	30700	13100	6382	30700	10300
Nuclear	0	2900	1910	0	9000	48500	0	9000	57600

2017) has been used. The dataset provides all needed input parameters, such as demand profile, wind power output profile, fuel prices, historical available generators information, corresponding technical characteristics, VO&M, etc. Validation is performed by comparing the I-SEM PSO modelling results with the historical real SEM outcomes during the period of 01/09/2017–01/09/2018.

I-SEM PSO model simulation outcomes shown in Fig. 5 are within acceptable deviations (δ<3%) in contrast to the historical data. The validation tests prove the model can provide an accurate representation of I-SEM. GB was experiencing a cold March in 2018 with an unexpected cold wave causing low temperatures and heavy snowfall. According to the National Grid report, transmission system demand peaked at 50.7 GW on 1/03/2018, which occurred outside the Triad period due to the unseasonably cold weather (Grid, 2018a,b).

Apart from SMP, another important parameter, which is the total generation cost, is validated. The deviation of the system total generation cost between simulation result and the historic market result is 4.91%.

As a result, the validated PSO model can be used in this paper due to its accuracy in replicating the market operation. This model also has the flexibility to simulate variable system demand, renewable generation, emerging technologies happening to the market arrangements.

3.6. Cost data

Fuel and carbon emissions prices implemented in the model are presented in Table 4. The prices are calculated based on the Future Energy Scenario database (Grid, 2018a) by comparing the cost data provided by the SEM Committee (NERA, 2018) and IEA (HeatRoadmapEU, 2017). Gas prices are considered seasonal.

The CO_2 emission rates are 0.0561 t/GJ for gas, 0.0946 t/GJ for coal and 0.0774 t/GJ for oil.

4. Result and discussion

The I-SEM, BETTA and French electricity market model is run for a full 2030 forecast year. The sensitivity analysis will show how the potential differences in different fuel price scenarios and the retirement of old units will affect the final modelling outcomes. Results of performance and sensitivity analysis are demonstrated in the following subsections.

4.1. System marginal prices

The 2030 FUI annual average wholesale SMPs in VRE scenarios are compared in Table 5.

Table 4
Fuel and carbon emissions prices implemented in the model.

	Gas (€/GJ)	Coal (€/GJ)	Oil (€/GJ)	Carbon (€/kg)
2030Q2Q3	7.812	3.869	8.541	$4.34*10^{-2}$
2030Q1Q4	8.312			

It is shown that the I-SEM prices are always higher than BETTA, which also has higher prices comparing to those in French electricity market. This is mainly because of the market difference in system size, interconnection capacities, demand and generation portfolio. As the higher levels of VRE, more wind generation units with zero marginal cost are considered replacing the costlier marginal units, which is typically gas generators. The VRE penetration alters the position of generators' merit order. As a result, it transfers the electricity market with lower average spot wholesale prices.

4.2. Generation output mix

Renewable shares in created 2030 VRE scenario are compared in Fig. 6. The I-SEM, BETTA and French electricity markets' renewable shares in FUI high case study are 75%, 61%, and 56%, respectively. In the FUI baseline case study, renewable portfolios are 57%, 56%, and 43%. The FUI low case study is with renewable shares of 44%, 50% and 34% in the I-SEM, GB, and France region.

4.3. Total generation costs

The techno-economic analysis of changing the renewable generation portfolio in the VRE scenarios can be quantified by separately comparing the three regions' total generation costs and net revenues in the next subsection. Fig. 7 illustrates the I-SEM, BETTA and French electricity market total generation costs for three case studies in the 2030 VRE scenario. It can be concluded that the total generation cost is a function of VRE generation output and power generation system size.

Renewable generation share has a huge impact on the total

Table 5
Average spot wholesale electricity prices in 2030.

	I-SEM (€/MWh)	GB (€/MWh)	France (€/MWh)
FUI high	50.77	49.21	48.00
FUI baseline	66.84	56.49	54.10
FUI low	101.26	100.63	99.19

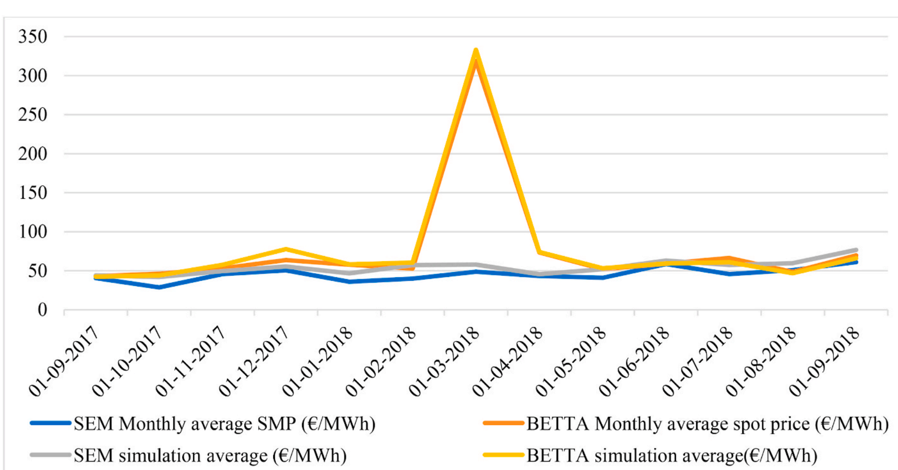

Fig. 5. SEM vs. BETTA Monthly average SMP.

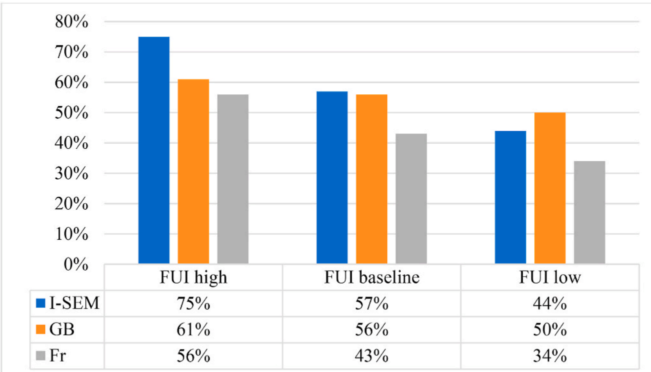

Fig. 6. 2030 case studies renewable share comparison.

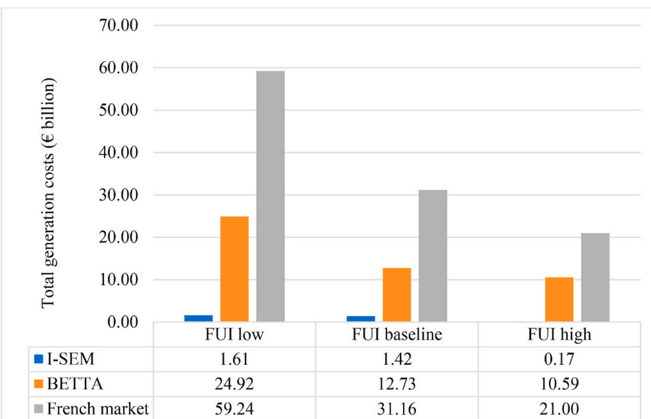

Fig. 7. I-SEM, BETTA and French electricity market total generation costs for each case study.

generation cost for three regions. It demonstrates that the I-SEM total generation cost falls to €1.42bn and €0.17bn for the FUI baseline and FUI low case study, respectively. The FUI high case study has greater cost saving potential for I-SEM, BETTA and French market in all VRE case studies. The total annual generation costs will fall to €0.17bn, €10.59bn and €21.00bn for I-SEM, BETTA, and French market, respectively, in the FUI high case study.

4.4. Net revenue

Fig. 8 demonstrates the net revenue for VRE case studies in I-SEM, BETTA, and French market. The simulation result of the FUI high case study shows that 2030 I-SEM's net revenue will be €0.31bn. And the corresponding total generation cost is €0.17bn. The net revenue and total generation cost for I-SEM in the FUI low case study are €1.61bn and €2.00bn. As is compared in Table 6, the FUI high case study has the highest earnings yield for investment. The same trend applies to all three regions. The generators net revenues are €14.30bn and €21.09bn for BETTA and French market, respectively.

4.5. CO_2 emissions

CO_2 emissions are also estimated for the I-SEM for all case studies, which is shown in Fig. 9. With the increase of VRE penetration, emissions decrease dramatically ranging from 6.95 Mt to 0.07 Mt. Total operational CO_2 emissions reduce due to replacing fossil fuel generation in I-SEM.

Table 7 illustrates the 2030 I-SEM CO_2 emissions intensities for the VRE scenario. The FUI low case study remains almost the same 2030 I-SEM VRE level as it is in 2020. As a result, the VRE level in the FUI high case study and FUI baseline case study are economically and environmentally achievable.

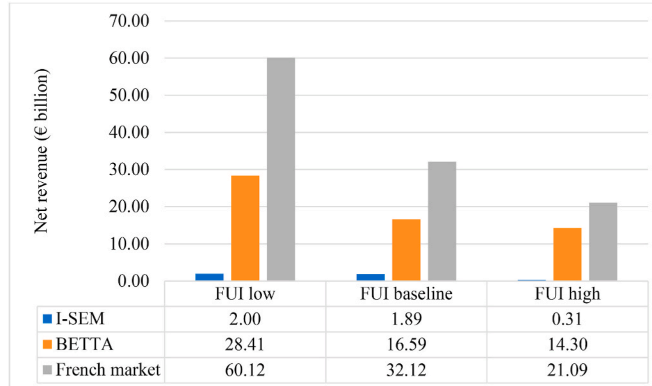

Fig. 8. I-SEM, BETTA and French electricity market net revenue for all case studies.

Table 6
Earnings yield for three case studies.

	I-SEM	GB	France
FUI high	0.242236	0.330986	0.823529
FUI baseline	0.140048	0.303221	0.350331
FUI low	0.014855	0.030809	0.004286

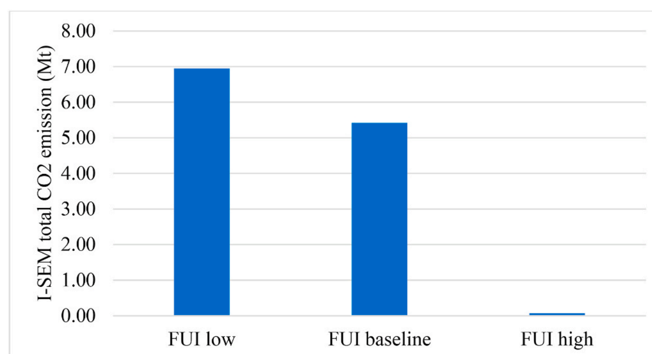

Fig. 9. I-SEM total $\mathbf{CO_2}$ emission for all case studies.

The achievement of high renewable penetration can cause grid uncertainties, which arise technical challenges to maintain the balance of generation and load at any time (Kroposki, 2017). To enhance grid flexibility and reliability, a combination of demand side response, interconnections, electricity storage, and thermal storage can be utilized in the high VRE system (Denholm and Hand, 2011).

4.6. Sensitivity analysis

The conclusions on the economic performance of different strategies drawn before are based on the cost assumptions from existing references. However, there are significant uncertainties in the cost of these technologies which may fundamentally change their competitiveness. The fluctuations of gas, coal, oil, and carbon prices can vitally affect the

Table 7
2030 I-SEM $\mathbf{CO_2}$ emissions intensities for FUI case studies.

	FUI high	FUI baseline	FUI low
CO_2 emissions intensities (tCO_2/GWh)	1.28	115.32	155.48

electricity market and renewable generations' profitability. The sensitivity analysis aims to analyze the influence of future market changes like retirement of older units and different fuel prices.

Due to surplus generation capacity, the installed capacity is enough to meet the system demand. As a result, the indicators' fluctuation is quite low.

Table 8 shows the fuel and carbon emissions prices for sensitivity analysis. The high fuel price for gas, coal, oil, and carbon in 2030 are 10.82 €/GJ, 7.26 €/GJ, 14.63 €/GJ, and 5.63*10-2 €/kg, respectively. The fuel and carbon emissions prices in the FUI baseline are the same as those used in Table 4. A case study of low fuel prices with gas 4.797 €/GJ, coal 2.354 €/GJ, oil 7.269 €/GJ, and carbon1.30*10-2 €/kg is analyzed.

Simulation result of 2030 average spot wholesale electricity price shows in Table 9 for High fuel price, FUI baseline, and Low fuel price. In the high fuel price case study, the average SMP for I-SEM, BETTA, and French electricity market are 67.40 €/MWh, 56.52 €/MWh and 54.11 €/MWh, respectively. The results of the FUI baseline in Table 9 are the same as that in Table 5. The 2030 SMPs are 59.42 €/MWh, 56.27 €/MWh and 54.09 €/MWh respectively for the I-SEM, GB, and France region in the low fuel price case study.

According to the sensitivity analysis simulation results, changes in the average spot wholesale electricity price under the high and low fuel price case study are calculated, as is shown in Fig. 10. The sensitivity analysis deviation for I-SEM is within 11.10%. BETTA and French electricity market simulation outcomes for high fuel price and low fuel price case study are within 1% deviation in contrast to the FUI baseline case study.

5. Conclusion and policy implications

Based on the simulated VRE scenario result, the achievement of higher renewable targets can maximize social benefits. The VRE penetration will make changes to the merit order of generators in I-SEM, BETTA and French market. Gas-fired generation will decrease significantly by 2030. Greater replacement of gas generator utilisation by renewable deployment result in lower average wholesale prices, total generation costs and total operational CO_2emissions. Overall, the results of this research illustrate that the achievement of high renewable penetration targets has a positive impact on the interconnected Irish power system.

SMPs in the I-SEM reduce from €101.26/MWh to €50.77/MWh between the FUI low case study and FUI high case study. In the BETTA and French market, the addition of the renewable generation contributes to reductions to SMPs by 51.10% and 51.61% at most, respectively. The lower spot wholesale electricity prices will benefit not only the local power consumers, but also customers in adjacent markets.

The modelling result also indicates that the increase of VRE generation results in lower total generation costs by 2030. The FUI high case study has the highest yield rate for investment.

High renewable penetration also leads to a reduction in CO_2 emissions. In the I-SEM, total CO_2 emissions decrease by 22.01% for the FUI baseline case study. The total CO_2 emissions reductions come from gas generation displacement by renewable generation.

This research also conducts a sensitivity analysis on the fluctuation of gas price, coal price, oil price, carbon price, and older generation units' retirement in 2030. Within acceptable changes in future fuel prices, the result of the model is quite robust.

Table 8
Fuel and carbon emissions prices implemented in the model.

	Gas (€/GJ)	Coal (€/GJ)	Oil (€/GJ)	Carbon (€/kg)
High fuel price	10.82	7.26	14.63	5.63*10-2
FUI baseline	7.812	3.869	8.541	4.34*10-2
Low fuel price	4.797	2.354	7.269	1.30*10-2

Table 9
Average spot wholesale electricity price in 2030 (Unit: €/MWh).

	I-SEM	GB	France
High fuel price	67.40	56.52	54.11
FUI baseline	66.84	56.49	54.10
Low fuel price	59.42	56.27	54.09

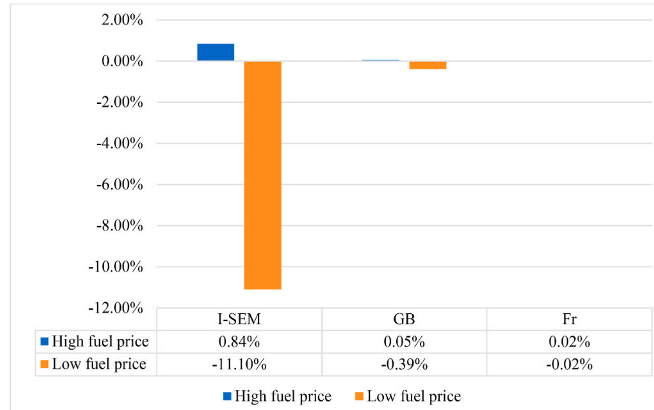

Fig. 10. Changes in the average spot wholesale electricity price under the high and low fuel price case study.

The results show that higher VRE penetration can cause the fuel-cost-intensive generators to be substituted, which are normally the gas-powered plants. The impact of the future market with higher VRE should be investigated by the co-benefit. Even though it seems that I-SEM consumers benefit more compared to BETTA and French electricity market due to the transition, the co-benefit of the whole FUI area can be achieved. At the same time, higher power market efficiency and lower carbon emissions can benefit all market stakeholders.

The importance of high VRE support policies should be emphasised. With the appropriate market signals, more potential renewable generators will be invested to participate in the electricity market. As is illustrated in the results, there are power system cost savings, which can potentially be used as subsidies to support the renewable units. Not only the role of government is crucial, but also the choices of civil society actors and power market consumers are important for the realization of high VRE penetration.

Future work is going to use an econometric way to analyze the influence of renewable penetration according to different grid locations, especially the distribution side. Additional future research will focus on designing future market strategies and policies for a better operation of renewable generators.

CRediT authorship contribution statement

Shurui Wang: Conceptualization, Methodology, Software, Validation, Resources, Writing - original draft. **Ye Huang:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Inna Vorushylo:** Conceptualization, Methodology, Supervision. **Haisheng Chen:** Conceptualization, Supervision. **Dominic McLarnon:** Writing - review & editing, Project administration. **Paul MacArtain:** Writing - review & editing. **Neil Hewitt:** Conceptualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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