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Assessing the future economic performance of wind generation in conjunction with compressed air energy storage in the new proposed Irish electricity market

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Abstract

The Integrated Single Electricity Market (I-SEM) is the proposed wholesale electricity market for Ireland and it is intended to replace the current market by the end of 2017. Under the I-SEM, wind generation will be exposed to forecast risk and the requirement to be balance responsible. The use of Compressed Air Energy Storage (CAES) could represent a better system configuration which would reduce the reliance on expensive generation for system balancing and reduce the financial risk to wind generation. Thus, the aim of this paper is to estimate the future economic performance of wind generation with and without CAES, in the I-SEM. Specifically, the day-ahead and balancing mechanism system marginal prices are estimated under the I-SEM for various scenarios.

Keywords: Electricity Market Modelling, I-SEM, PLEXOS, Renewable Energy, Wind Energy, Day-ahead Wholesale System Marginal Prices
JEL Classification Codes: C63, L94, L98, L100

Nomenclature

AII	All-Island of Ireland
BETTA	British Electricity Trading and Transmission Arrangements
BM	Balancing Mechanism
CAES	Compressed Air Energy Storage
DA	Day-Ahead
GB	Great Britain
I-SEM	Integrated Single Electricity Market
MAE	Mean Absolute Error

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MAPE	Mean Absolute Percentage Error
NI	Northern Ireland
NPV	Net Present Value
PHES	Pumped Hydroelectric Energy Storage
ROI	Republic of Ireland
SEM	Single Electricity Market
SMP	System Marginal Price
TSO	Transmission System Operator
α	Autoregressive parameter
β	Moving average parameter
σ_z	Percentage error of standard deviation

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1. Introduction

The Integrated Single Electricity Market (I-SEM) is the proposed wholesale electricity market for the All-Island of Ireland[1] (AII) and it is intended to replace the current Single Electricity Market (SEM)[2] by the end of 2017. The requirement for the I-SEM has arisen due to the European Union's Third Energy Package; a legislative package which requires the delivery of a common Target Model across all European electricity markets (European Commission 2009). The I-SEM design will consist of four distinct market timeframes; Forwards, Day-Ahead (DA), Intra-Day (ID) and Balancing Mechanism (BM). The detailed I-SEM design is currently ongoing, which has the potential to cause increased uncertainty for certain stakeholders.

Member States that have already adopted the predominant bilateral contracts market design will be in a position to implement the Target Model without extensive reforms. In contrast, the SEM (which is an ex-post mandatory gross pool with centralised dispatch) requires substantial modifications in order to implement and comply with the Target Model. The SEM also features no forecast risk for renewables such as wind and there is no concept of balance responsibility for generators (i.e. financial responsibility for the deviation in market schedules between DA and real-time). In the SEM the cost of deviations between the market schedule in DA and real-time due to network and energy actions are socialised, therefore in effect generators have no balance responsibility exposure. For wind generation, where output is always variable and difficult to forecast beyond 4-6 hours ahead, this element of the SEM currently provides investment certainty.

Under the I-SEM design, by contrast, wind generation will be exposed to forecast risk and the requirement arises for wind operators to balance the deviations between their scheduled position in the DA or ID markets and actual generation in the BM. Subsequently, this will impose additional financial risk on wind generation and will be of major concern to investors in the wind energy sector. Moreover, the governments of the Republic of Ireland (ROI) and Northern Ireland (NI) have set an ambitious target that requires 40% of electricity demand to be met by renewable energy sources, mainly wind, by 2020 (DCENR 2009). The Transmission System Operators (TSOs) are seeking to operate between 4-5 GW of wind capacity across the AII by 2020 (Eirgrid and SONI 2015). This will represent circa 33-35% of the total generation capacity in 2020.

The increasing amount of wind capacity due for connection by 2020 introduces a new challenge for the TSOs in maintaining the security of the system. The use of large scale energy storage such as pumped hydroelectric energy storage (PHES) and compressed air energy

[1] The Republic of Ireland and Northern Ireland are two separate jurisdictions with a common synchronous power system known as the All-Island of Ireland (AII).

[2] The SEM is the All-Island of Ireland (AII) wholesale electricity market covering the Republic of Ireland (ROI) and Northern Ireland (NI), which has been operational since November 2007.

storage (CAES) could represent improvements in system configuration which would reduce the reliance on expensive generation for system balancing and reduce the financial risk to wind generation in the I-SEM. Currently, only one 292 MW PHES plant participates in the SEM and despite PHES being considered a mature technology, further development in Ireland has ceased mainly due to the lack of suitable sites, high initial capital costs and environmental impact concerns.

Apart from PHES, CAES is the only commercial large scale storage technology to have been deployed at utility scale and a number of studies have analysed CAES as a solution to improving wind integration and reducing wind curtailment (Evans et al. 2012; Foley et al. 2013; Loisel et al. 2010; Cleary et al. 2015). A potential CAES site with suitable geological conditions has been identified in Larne, NI (Evans et al. 2006; GES 2011). Hence, the potential exists for a CAES plant to be connected to the AII system and to participate in the forthcoming I-SEM (GES 2011).

Thus, the aim of this paper is to estimate the future economic performance of wind generation with and without CAES, in the I-SEM. Specifically, the DA and BM System Marginal Prices (SMPs) are estimated under the proposed I-SEM design in 2020 for various scenarios including with and without CAES. The economic performances of wind investments under these different scenarios are also assessed.

2. Methodology

The 2012 validated unit commitment and economic dispatch model from Cleary et al. (2015) was used as a starting point from which the 2020 I-SEM model used in this analysis was developed. Two model scenarios are considered; Business as Usual (BAU) and BAU+CAES containing a CAES plant as an additional generator in the I-SEM. The Net Present Value (NPV) of wind generation was then evaluated using cost data from Duffy et al. (2015) and electricity price and generation outputs from the I-SEM model for each scenario. The following subsections describe the modelling software, I-SEM model and associated assumptions in more detail.

2.1 Modelling software

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 TSOs, Regulators and SEM participants to validate and forecast SEM outcomes (Eirgrid and SONI 2012b; CER 2011). Moreover, it is considered by academia as a well proven tool for policy analysis and development in the AII (Deane et al. 2012; Foley et al. 2013; Mc Garrigle et al. 2013; Deane et al. 2014; Denny 2009). Therefore, PLEXOS version 6.4 R02 was used to build and run the models for the analysis presented in this paper.

2.2 I-SEM model description

A high level representation of the I-SEM in 2020 was developed in PLEXOS given that detailed data were available for that year. Consequently, this provides some certainty regarding the model assumptions and scenarios. However, the I-SEM model only includes a representation of the short term DA and BM markets given that limited information is currently available for the ID market design and the forwards market is considered long term. The DA and BM markets were created in the I-SEM model and the interleave method implemented in PLEXOS. The interleave method is a more sophisticated technique of linking the outputs of one model with another. Consequently, the DA and BM models pass information back and forth between each other as shown in Figure 1. This information includes the DA unit commitment (DAUC) schedule of all generators from the DA model (D_{i-1}) to the BM model (D_i) and the generators end state to the DA model (D_{i+1}) for the next day. This process continues daily across the year in order to create a realistic market simulation.

The I-SEM model reads the input data such as system demand and wind data as shown in Figure 1. It simulates 365 individual daily optimisations at an hourly time resolution while ensuring the generation portfolio meets demand at least cost while taking into account the generators' techno-economic parameters. A detailed description of the model is as follows:

1. The purpose of the DA model is the creation of a DAUC schedule. The scheduling of the DA model is carried out stochastically using the scenario-wise decomposition method in PLEXOS in order to account for the uncertainty in system wind and demand. The generators planned maintenance outage schedules are always known in advance of the DAUC schedule and are included in the model. The generators' forced outages are omitted as they occur randomly without advanced knowledge and are included in the BM model. Interconnector flows are optimised based on the price differential between the I-SEM and Great Britain (GB) electricity market, entitled British Electricity Trading and Transmission Arrangements (BETTA).
2. The purpose of the BM model is to re-optimise the DAUC schedule from the DA model by moving generators dispatch levels up and down. The generators dispatch levels are subsequently altered based on their decremental and incremental bids in the form of price quantity pairs in response to the actual outcome of probabilistic events such as system wind and demand. The interconnector flows are fixed in the BM model based on the optimised flows from the DA model; as such the BETTA market is prevented from participating in balancing the I-SEM. This simplification may lead to suboptimal flows based on the simulated SMPs for the I-SEM and BETTA markets. However, limited information is currently available in relation to the Irish and British TSOs counter trading abilities on the interconnectors in the I-SEM. Moreover, considering the significant amount of variable generation which the TSOs will be required to balance in each market in 2020, they may be unable and/or reluctant to share the spare flexible capacity for balancing.

Figure 1. I-SEM model with interleaved DA and BM models

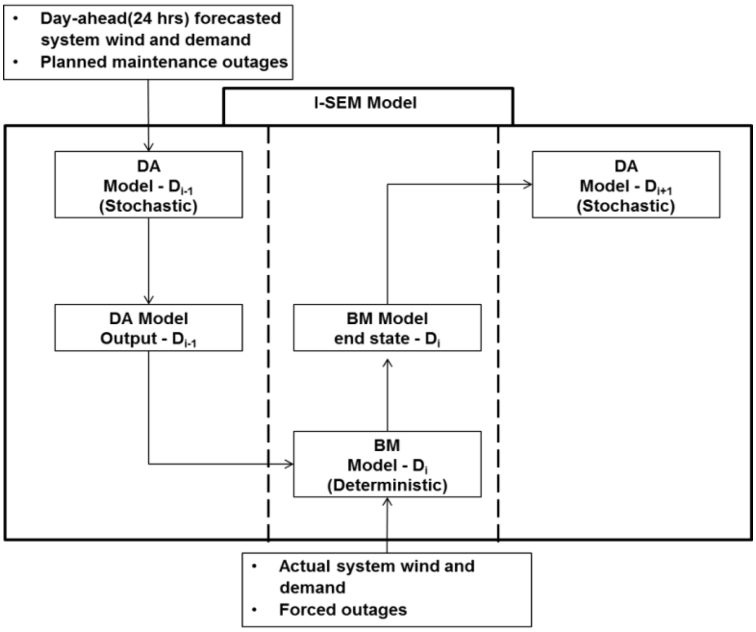


Table 1. Model scenarios generation capacity portfolio (MW)

Generator type	*BAU*	*BAU+CAES*
Coal	1,331	1,331
Gas	5,282	5,282
Oil	592	592
Distillate Oil	764	764
Peat	346	346
Hydropower	216	216
Pumped hydro storage	292	292
Compressed air storage	0	270
Onshore wind	4,780	4,780
Offshore wind	25	25
Waste to energy	94	94
Tidal	201	201
Solar	98	98
Biomass	296	296
East-West Interconnector	500	500
Moyle Interconnector	450	450
Total (MW)	*15,267*	*15,537*

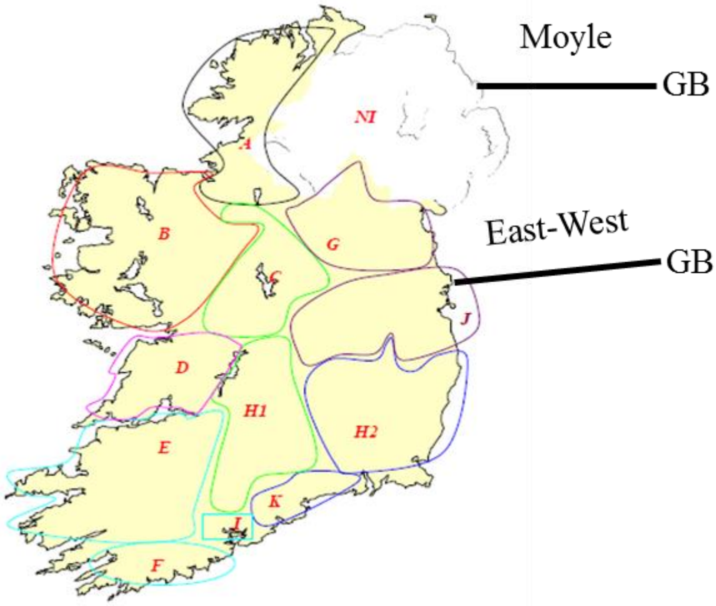
2.3 Main model assumptions

The I-SEM model was populated with the individual generator techno-economic parameters for new entrants and retirements which have signed agreements and confirmed dates to connect to the AII power system over the next 10 years (Eirgrid and SONI 2015). A breakdown of the generator types used for the model scenarios is shown in Table 1.

The system demand and installed wind capacity for 2020 were obtained from Eirgrid and SONI (2015). The annual system median demand is estimated to be 38.42 TWh with a peak demand of 6.8 GW. The onshore and offshore wind capacity as shown in Table 1 remain the same for both model scenarios and it is assumed that no additional offshore wind will be developed in the AII prior to 2020. Wind generation is modelled in aggregated form, split into 13 regions as shown in Figure 2. The installed wind capacity for each region is based on the proposed regional distribution of renewable capacity by Eirgrid (Eirgrid 2010). Each region has an associated hourly capacity factor profile which represents the wind availability in that region for each hour obtained from the CER (2011).

The typical system wide wind forecast error is calculated based on the difference between the 24 hour forecasted and actual wind generation between 2010 and 2014 across the ROI system only based on data acquired from the TSOs website (Eirgrid 2014). A Normalised Mean Absolute Percentage Error (NMAPE) and Mean Absolute Error (MAE) of 5.4% and 87 MW were calculated for the typical wind forecast error, respectively. The statistical control parameters (α, β and σ_z) associated with the typical wind forecast error growth and distribution are derived by using a Autoregressive Moving Average (ARMA) model in statistical package R (The R Foundation n.d.).

Figure 2. I-SEM model wind regions and interconnectors



Source: CER 2011

The same hourly capacity factor profiles are input to the DA and BM models for each region. However, the use of the Box-Jenkins method in the I-SEM model which incorporates an ARMA model allows the DA model to simulate the previously obtained statistical control parameters and randomly generate the typical wind forecast error around the capacity factor profiles for each region. As regards the 24 hour forecasted system demand, there is limited data available for this and therefore a MAE of 50 MW is assumed based on discussions with SEMO (n.d.). Similarly, this is reflected in the DA model with statistical control parameters and the demand forecast error is randomly applied to the system demand profile.

The complete transmission network is not included in the I-SEM model and localized network constraints are not modelled. Instead, the model consists of three separate nodes representing the ROI, NI, and GB systems. The Moyle interconnector as shown in Figure 2 links NI to GB and flows are limited to exporting 300 MW and importing 450 MW November-March and 410 MW April-October. The East-West interconnector between the ROI and GB nodes, maximum flow was assumed 500 MW both ways. Modelling the GB system is required in order to determine the interconnector flows between the I-SEM and BETTA market. A single gas generator of 1,800 MW with multi-band heat rates, variable operating and maintenance (VOM) costs and 1,100 MW of load was therefore used to represent the GB system. The CER (2011) also adopt this simplified GB representation.

Fuel prices (as shown in Table 2) are based on predictions for 2020 from two main sources (Grant et al. 2011; Eirgrid 2009). It is acknowledged that fuel prices have fluctuated since these predictions and they will have a major impact on the simulated SMPs for this analysis. A carbon tax of €30/t CO_2 based on the European Union emissions trading scheme was applied to fossil fuel generators. This figure is based on the carbon taxes used for previous AII case studies, which ranged between €15-45/t CO_2 (Tuohy et al. 2011; Doherty et al. 2006; Grant et al. 2011; Connolly et al. 2010; Deane et al. 2012). Generator VOM costs were obtained from several sources (Mott MacDonald 2010; Connolly et al. 2010; Doherty et al. 2006) and start costs were derived from historic values (SEMO n.d.). Cost data for the CAES plant were based on Thorner et al. (2005). All cost data were normalised to 2012 values using consumer price indices (CSO 2013).

Table 2. Quarterly fuel prices for 2020

	Fuel price (€/GJ)			
Fuel type	*Q1 2020*	*Q2 2020*	*Q3 2020*	*Q4 2020*
I-SEM Gas	9.16	8.87	8.88	9.75
I-SEM Coal	4.37	3.97	4.03	3.92
I-SEM Oil	18.6	17.5	18.12	16.8
I-SEM Distillate	23.04	22.67	23.3	21.91
I-SEM Peat	3.80	3.80	3.80	3.80
BETTA Gas	9.01	8.46	8.39	9.11

Table 3. CAES plant technical operational details

Parameters	*Value*	*Units*
Maximum compression	200	MW
Minimum compression	60	MW
Ramp rate for compression	40	MW/min
Maximum generation	270	MW
Minimum generation	67.5	MW
Ramp rate for generation	54	MW/min
CAES heat rate	4.265	GJ/MWh
CAES storage capacity	3	GWh
Compressing efficiency	80	%
Round trip efficiency	50	%

Source: Thorner et al. 2005

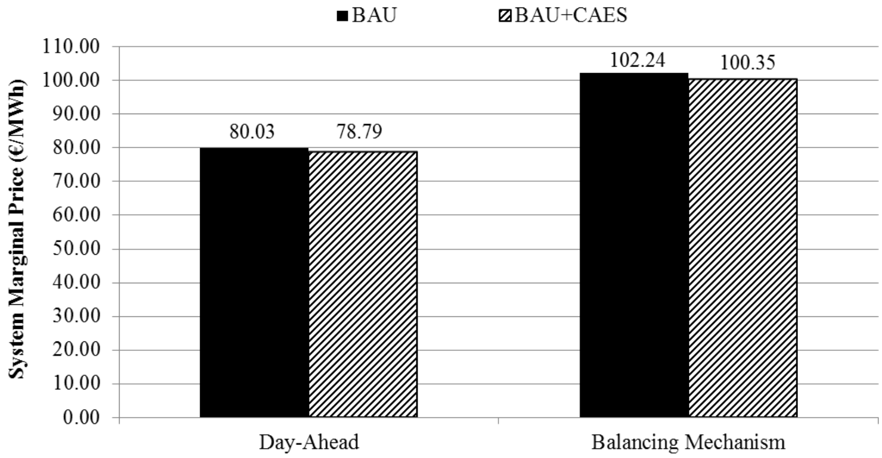
The CAES plant is represented within the BAU+CAES model scenario by a PHES plant coupled with a conventional gas turbine plant using constraints to replicate the operation of the CAES plant. This approximation of the CAES plant configuration was used previously for other case studies (Cleary et al. 2015; Foley et al. 2013; Ming et al. 2012). The details of the CAES plant used for this analysis are shown in Table 3 and are assumed to represent the plant which will be connected to the AII power system in 2020.

3. Results and discussions

3.1 System marginal prices

A comparison of the simulated annual average wholesale SMPs for the DA and BM markets for each scenario are shown in Figure 3. It can be seen that the SMP increases from €80.03/MWh to €102.34/MWh between the DA and BM markets for the BAU scenario. This increase is primarily due to the increased utilisation of fast acting generation in particular gas and distillate oil (which have higher costs because they are generally operating either at part load or from start-up) responding to a 0.7% and 1.9% increase and decrease in the system demand and wind generation, respectively.

Figure 3. Annual average wholesale system marginal prices

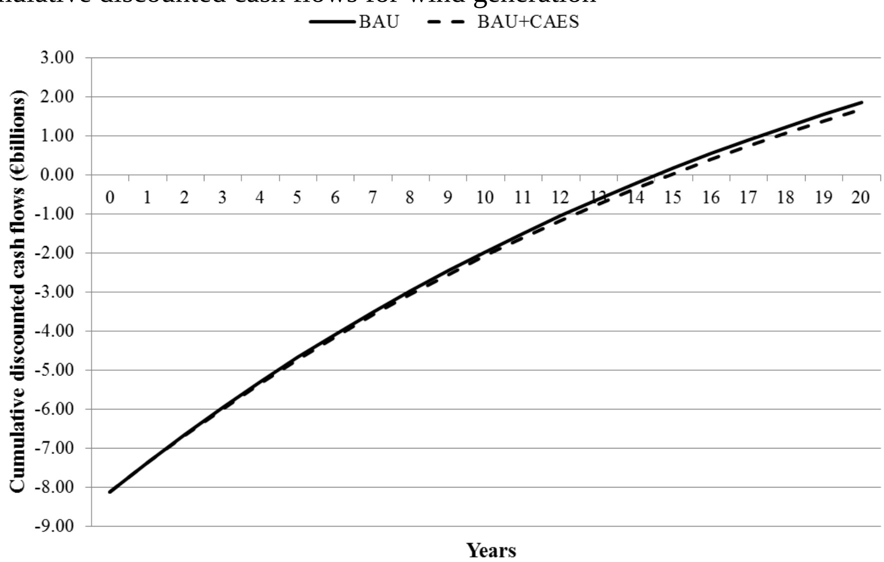


Similarly, the SMP increases from €78.79/MWh to €100.35/MWh between the DA and BM markets in the BAU+CAES scenario. The system demand and wind generation increase and decrease 0.6% and 1.8%, respectively, with the more costly generators ramping and/or starting up to meet to the increased demand and deficit in generation. The CAES plant's ability to provide additional flexible generation in the DA and BM markets under this scenario reduces the reliance on the more costly generators, particularly gas. Consequently, lower SMPs are achieved in both markets under this scenario compared to the BAU scenario.

3.2 Economic assessment of wind generation

Wind generation cumulative discounted (at 4.9% after tax, real) cash flows for total installed wind capacity in 2020 is presented in Figure 4 for each scenario assuming wind receives the SMP. Both scenarios produce positive cumulative cash flows after 14 years. The NPV of wind generation, which is defined as the sum of incoming (product of SMP received in €/MWh and generation in MWh) and outgoing (product of capital+operating costs in €/MW and installed capacity in MW) discounted cash flows over the 20 year lifetime is €1.85bn and €1.68bn for the BAU and BAU+CAES scenarios, respectively. The lower NPV of wind generation in the BAU+CAES scenario is due the addition of the CAES plant and its effect on reducing the SMPs.

Figure 4. Cumulative discounted cash flows for wind generation



4. Conclusion

Based on the simulated model scenarios, it was estimated that the SMPs increase between the DA and BM markets for both the BAU and BAU+CAES scenarios primarily due to the increased utilisation of more costly fast acting generation due to variations in forecasted system demand and wind generation. The inclusion of a CAES plant in the BAU+CAES scenario results in additional flexible generation in the DA and BM markets and in turn, reduces the reliance on costly fast acting generators, particularly gas. Consequently, lower SMPs are achieved in both markets under this scenario compared to the BAU scenario. This is beneficial to the electricity consumer but lowers the NPV of wind investments.

However, it should be noted that the estimated SMPs and NPV are highly sensitive to the underlying assumptions including system demand and wind forecast errors, fuel and carbon prices, generators decremental and incremental bids and wind project capital and operating costs. Therefore, a number of sensitivities will be carried out for the continuing research, which will examine the effects of changes in the underlying assumptions.

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