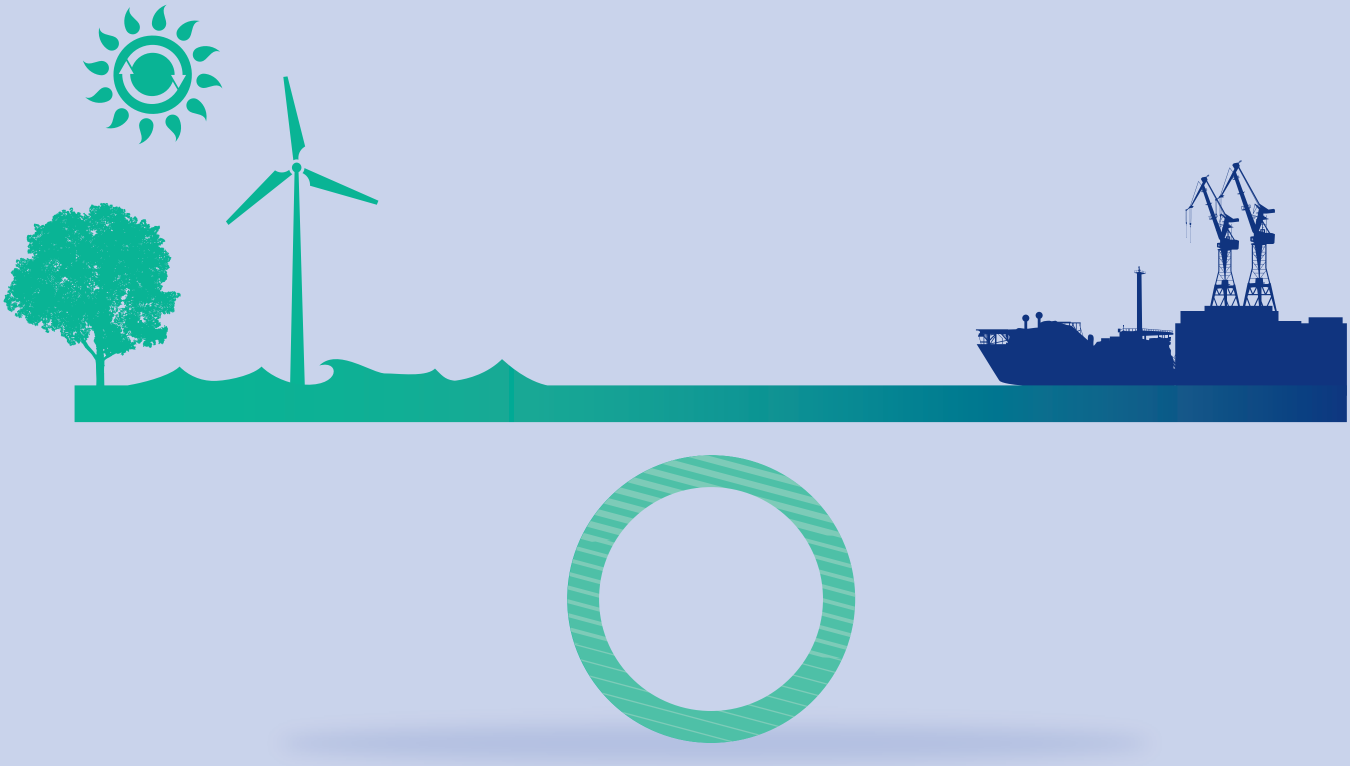
SUSTAINABLE
ENERGY AUTHORITY
OF IRELAND

Quantifying Ireland's Fuel and CO_2 Emissions Savings from Renewable Electricity in 2012



Quantifying Ireland's Fuel and CO_2 Emissions Savings from Renewable Electricity in 2012

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Report Summary

This report sets out the methods and results of a detailed analysis of the real time operation of the All-Island electricity system in order to estimate the fossil fuel savings from wind generation and other renewable electricity sources in 2012. The dispatch model method used for the analysis incorporates the extensive range of dynamic factors that influence the operation of fossil-fuel generators and are accounted for in the evaluation of overall savings from renewable electricity generation. These factors include ramping effects, cycling effects, contingency reserve, network constraints, wind characteristics, generator availability, and cross-border electricity trade.

The report is in three main parts:

Part I sets out the background, context and operational issues applying to the All-Island electricity system. It details the characteristics of the system, including the high level operation of the Single Electricity Market (SEM) and the impact of support schemes currently applying to fossil fuel and renewable electricity generators. It also discusses significant factors influencing system operation and the impact of wind and other renewable electricity generation on the system.

Part II describes the methodology used in the study. It employs a dispatch model of the All-Island electricity system, built using PLEXOS power market simulation software and validated data which takes account of the extensive range of factors influencing system operation and the impact of wind and other renewable electricity generation. The actual portfolio of electricity generators (including renewables) in 2012 is compared with the outcome from two alternative scenarios to assess the impact of renewable electricity in general, and wind in particular, in displacing fossil-fuel usage and CO_2 emissions.

Part III presents the results of the study. It shows the net 'bottom line' effects of renewables in displacing fossil-fuel usage and CO_2 emissions on the system in 2012, for the All-Island system as a whole and for the Republic of Ireland. It also includes a quantification of the individual effects of renewables on the ramping and cycling of fossil-fuel plant, and on the resultant efficiency and CO_2 emissions intensity. These constituent factors are taken into account in determining the overall 'bottom line' fuel and CO_2 savings.

'Bottom line' savings:

Republic of Ireland savings:

- Renewable electricity generation in the Republic of Ireland is estimated to have saved 778 ktoe of fossil-fuel, with an associated CO_2 emissions reduction of 1.94 million tonnes. Wind generation is the largest contributor, with savings estimated at 586 ktoe of fossil-fuel and a CO_2 emissions reduction of 1.51 million tonnes.
- The value of the fossil fuels not consumed in the Republic of Ireland in 2012 as a result of renewable electricity generation is estimated at €245 million, with the value of avoided CO_2 emissions being a further €15 million. Savings from wind generation are estimated at €177 million in fossil fuel and €11 million in CO_2 emissions. Apart from a small quantity of peat, all of the savings are due to the displacement of imported fossil fuels.
- The total fossil-fuel generation displaced by renewable electricity generation in the Republic of Ireland in 2012 is equivalent to the electricity demand of 780,000 Irish households.

All-Island savings:

- On the All Island electricity system as a whole in 2012, renewable energy is estimated to have displaced 1,043 ktoe of fossil-fuel, valued at €297 million with an associated CO_2 emissions reduction of 2.85 million tonnes, valued at €21 million. Wind generation contributed savings estimated at 826 ktoe (€225 million) of fossil-fuel and a CO_2 emissions reduction of 2.33 million tonnes (€17 million).
- 78% of the fuel savings due to renewable electricity arose from the displacement of natural gas, with 20% coming from reduced use of coal. The remaining 2% is due to the displacement of peat through co-firing with biomass. Due to the higher carbon intensity of coal and peat fuels, their displacement is responsible for a higher proportion of CO_2 savings. Coal displaces 29% of the CO_2, peat 3% and gas the remaining 68%.
- The average intensity of net CO_2 displacement by renewable energy sources was 0.43 tonnes of CO_2 per

MWh, while net displacement intensity by wind generation was 0.46 tonnes of CO_2 per MWh.

These overall findings are consistent with the findings of studies of operating conditions in Ireland and elsewhere which have shown that variable renewable generation can be effectively integrated into the electricity system and yield clear energy and emissions saving benefits.

Constituent impacts:

- The overall extent of output changes from fossil-fuel generators is estimated to be up to 7% higher with renewable electricity on the system (additional ramping).
- With renewable electricity on the system, fossil-fuel generators spend less time generating for each time they start (additional cycling).
- Displacement by renewable electricity generation reduces the average output from fossil- fuel generators, indicated by a reduction in the online capacity factor of gas CCGT and coal fired generators.
- As start-up fuel represents only 1% of total fossil-fuel use, this has a minor impact on the overall savings arising from renewable generation.
- Individual fossil-fuel generators run in less efficient modes with renewable electricity generation on the system, showing a 7% increase in the CO_2 emissions intensity for such generators.
- Despite this negative effect, the overall net CO_2 emissions intensity of the electricity system improves by 15%, relative to what would have applied in the absence of renewable generation.
- Due to cross-border electricity trade through the Single Electricity Market (SEM) between the Republic of Ireland and Northern Ireland, a portion of renewable electricity generation in the Republic of Ireland can contribute to fossil-fuel displacement and emissions reductions in Northern Ireland and vice versa. Consumers in both Republic of Ireland and Northern Ireland benefit from displacement savings regardless of where they accrue, as all savings are reflected in the SEM electricity price, common to both jurisdictions.

The Sustainable Energy Authority of Ireland

The Sustainable Energy Authority of Ireland (SEAI) was established as Ireland's national energy authority under the Sustainable Energy Act 2002. SEAI's mission is to play a leading role in transformation of Ireland to a society based on sustainable energy structures, technologies and practices. To fulfil this mission, SEAI aims to provide well-timed and informed advice to Government and deliver a range of programmes efficiently and effectively, while engaging and motivating a wide range of stakeholders and showing continuing flexibility and innovation in all activities. SEAI's actions will help advance Ireland to the vanguard of global clean technology development and practice, so that Ireland is recognised as a pioneer in the move to decarbonised energy systems.

SEAI's key strategic objectives are:

- Energy efficiency first – implementing strong energy efficiency actions that radically reduce energy intensity and usage
- Low-carbon energy sources – accelerating the development and adoption of technologies to exploit renewable energy sources
- Innovation and integration – supporting evidence-based responses that engage all actors, supporting innovation and enterprise for our low-carbon future

The Sustainable Energy Authority of Ireland is part-financed by Ireland's EU Structural Funds Programme, co-funded by the Irish Government and the European Union.

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Any oversights or omissions are the authors' alone.

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1. Introduction

1.1 Renewable electricity policy and context

In 2012, Ireland imported 85% of its energy requirements in the form of fossil-fuels, costing €6.5 billion. The combustion of these fossil-fuels was responsible for 38 million tonnes of carbon dioxide (CO_2) emissions.

Internationally, renewable electricity generation has a growing role in the reduction of fossil-fuel dependency and greenhouse gas (GHG) emissions. The deployment of indigenous renewable electricity generation can improve the security of supply while lowering GHG emissions by displacing imported fossil-fuels. Arising from the EU Renewable Energy Directive (2009/28/EC),[1] EU member states plan to achieve a significant proportion of their renewable energy targets through additional deployment of renewable electricity.[2]

The Republic of Ireland (RoI) aims to provide 40% of its electricity demand from renewable sources by 2020, principally from wind, with smaller proportions from bioenergy, marine sources and existing hydro. This ambition was informed by the findings of an All-Island Grid Study (2008),[3] jointly commissioned by the governments of the Republic of Ireland and Northern Ireland. Subsequent studies have informed the current and planned developments in system operation[4,5] and grid infrastructure.[6]

The SEAI publication *Renewable Energy in Ireland 2012*[7] reports that the share of electricity generated from renewable energy sources has increased between 1990 and 2012 from 4.9% to 19.6%. The principal contribution to this transition has come from wind generation. The Republic of Ireland is currently fourth in the world for the proportion of wind generation in its electricity system, contributing a total (normalised) of 15.3% of electricity demand in 2012.[8] Instantaneous wind penetration regularly exceeded 40% of demand in 2011, peaking at a year-high penetration of over 50% in December 2011.[9] This confirms Ireland's place as a world leader in the integration of renewable electricity generation, particularly from wind, into the power system.

19.6% of electricity demand was supplied by renewable sources in 2012.

1.2 Renewable energy impact on fossil-fuel generation

Some concerns have been raised about the integration of renewable electricity generation into the electricity system. The output from variable renewable electricity generating sources, such as wind, wave and solar photovoltaics (PV), varies with weather conditions, which carry some degree of forecasting uncertainty. These characteristics, and some of the contended consequences for the efficiency of other generators in the system, have led to questions being posed about the effectiveness of these technologies in displacing fossil-fuels and emissions.

Variability and uncertainty of this type is not a new phenomenon. The operation of electricity systems developed in such a way as to account for several sources of variability and uncertainty, notably those of electricity demand and the uncertainty of generator availability. Consequently, electricity systems are equipped to incorporate the characteristics of renewable electricity generation. Detailed studies have shown that large proportions of renewable generation can be effectively and efficiently integrated into the existing electricity system.

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[1] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0028

[2] National Renewable Energy Action Plans (NREAP): http://ec.europa.eu/energy/renewables/action_plan_en.htm

[3] http://www.dcenr.gov.ie/Energy/North-South+Co-operation+in+the+Energy+Sector/All+Island+Electricity+Grid+Study.htm

[4] EirGrid (2010), All-Island TSO Facilitation of Renewables Studies: http://www.eirgrid.com/media/FacilitationRenewablesFinalStudyReport.pdf

[5] EirGrid (2011), *The DS3 Programme, Delivering a Secure, Sustainable Electricity System*: http://www.eirgrid.com/media/DS3_Programme_Brochure.pdf

[6] Grid 25 information: http://www.eirgridprojects.com/grid25/what-is-grid25/

[7] http://www.seai.ie/Publications/Statistics_Publications/EPSSU_Publications/Renewable-Energy-in-Ireland-2012.pdf

[8] SEAI (2013), *'Energy in Ireland'*: http://www.seai.ie/Publications/Statistics_Publications/Energy_in_Ireland/

[9] International Energy Agency (IEA) (2012), Annual Report 2011: http://www.ieawind.org/annual_reports_PDF/2011/Ireland.pdf

1.3 Methods of quantifying the impact of renewable electricity generation

A number of previous Irish and international studies have estimated the displacement or avoidance of fossil-fuel use and associated CO_2 emissions arising from the deployment of renewable electricity generation. These studies used different methods to quantify these effects, including: the Primary Energy Equivalent (PEE) method, empirical statistical methods and a dispatch modelling approach and are discussed in detail in Annex 1.

Using the PEE method, SEAI's Energy Policy Statistical Support Unit (EPSSU) has estimated the level of fossil-fuel and CO_2 displaced by renewable electricity generation. This is based on the *Operating Margin* principle. In the case of renewable electricity from ambient sources (such as wind, solar and marine), it computes the primary energy content of the replaced fossil-fuel that would have been required to produce the corresponding amount of electricity as is produced from the renewable sources. However, this method cannot explicitly account for the fuel used by fossil-fuel generators through possible additional start-ups and load changes.

Empirical statistical methods look at available historic data and use statistical techniques to estimate the marginal displacement impact. This type of method can be effective at relating the level of renewable electricity generation to fossil-fuel use and CO_2 emissions in order to estimate the displacement effect, but generally lacks the detail to explain the particular causative factors contributing to the displacement. The complexities of the underlying factors that influence fossil-fuel displacement are difficult to represent adequately in an empirical model.

Dispatch modelling methods use a whole-system simulation approach to a high level of detail and time resolution, and can be used to incorporate and assess the effects of plant cycling and ramping, as well as a range of other dynamic factors in the system. Dispatch models are commonly used to simulate alternative electricity systems and compare to a central or base case. A number of Irish and international studies have employed such methods to quantify reductions in fossil-fuel use and CO_2 emissions due to renewable electricity generation. The use of such electricity system models can overcome the explanatory limitations in the PEE and empirical methods, but depend on the availability of detailed information about generator capabilities, network constraints and operational rules used by the System Operator as well as the existence of independently validated models. In Ireland's case, this data is publicly available and is published by the Commission for Energy Regulation (CER) and EirGrid, the Transmission System Operator (TSO).

This study employs a dispatch model using the PLEXOS modelling software. This software is widely used by the TSO, the CER, the electricity market operator, numerous academic institutions, electricity market participants in Ireland, and many international institutions and utilities. Using PLEXOS, the dispatch model was developed to simulate the detailed operation of the All-Island system and the characteristics of renewable electricity generators based on detailed data published and validated by the CER. The outputs from the model were then used to estimate the level of fossil-fuel and CO_2 savings due to renewable electricity.

1.4 Report Structure

This report is in three main parts:

Part I sets out the background, context and operational issues applying to the All-Island electricity system. It details the characteristics of the system, including the high level operation of the Single Electricity Market (SEM) and the impact of support schemes currently applying to fossil-fuel and renewable electricity generators. It also discusses significant influencing system operation and the impact of wind and other renewable electricity generation on the system.

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Part I: All-Island Electricity System: Background, Context and Operations

Part I sets out the background, context and operational issues applying to the All Island electricity system. It details the characteristics of the system, including the high level operation of the Single Electricity Market (SEM) and the impact of support schemes currently applying to fossil fuel and renewable electricity generators. It also discusses significant factors influencing system operation and the impact of wind and other renewable electricity generation on the system.

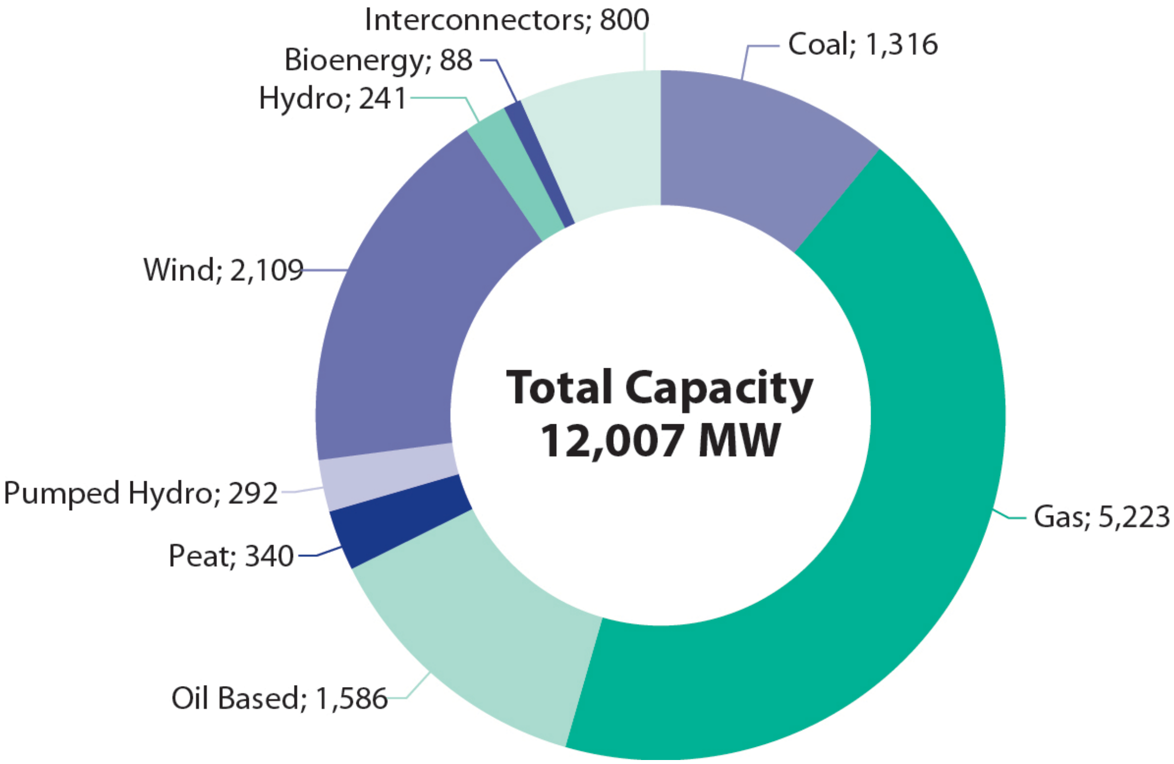
2. Characteristics of the All-Island Electricity System

2.1 All-Island Electricity System

As of 2012 the All-Island system had an installed generation capacity of just over 12,000 MW, consisting of 8,465 MW of thermal fossil-fuel generation capacity, 2,450 MW of renewable capacity, a 292 MW pumped hydro storage plant, and two interconnectors to Great Britain. Interconnection levels are low by international standards, with the generation technologies in the system reflecting the need for flexibility to manage a relatively isolated system.

Figure 1 shows the All-Island capacities in 2012. The system is characterised by a high penetration of natural gas, particularly combined-cycle gas turbines (CCGTs). Baseload generation is mainly provided by coal and a small amount of peat-fired generation, with renewable generation capacity from wind, biomass and hydro. Peaking capacity is provided by open-cycle gas turbines (OCGTs) using distillate oil or gas. A single pumped hydro storage site at Turlough Hill provides generation and demand-side flexibility.

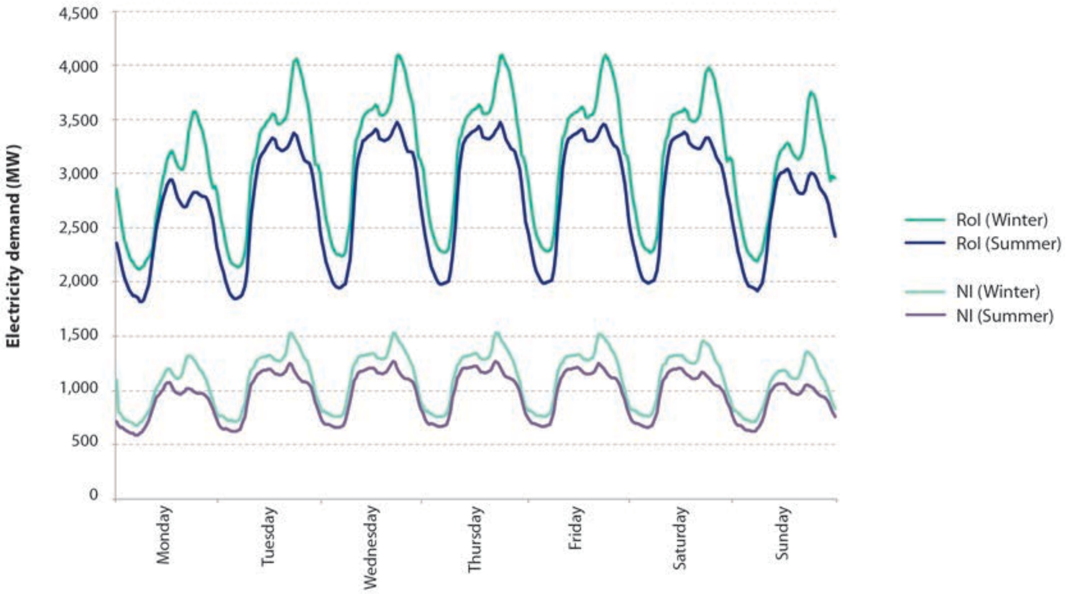
Figure 1: All-Island electricity system capacities by generation type (MW), 2012



The All-Island system has a high proportion of natural gas generation capacity and a low level on interconnection to other systems.

Figure 2 shows the 2012 average system demand over a weekly cycle for summer and winter in both the Republic of Ireland (RoI) and Northern Ireland (NI) systems. The RoI demand typically accounted for around 75% of total system demand. Demand varies between summer and winter, weekdays and weekend, and day and night. The daily variation is largest; the daily peak demand is up to three times that of the lowest demand period. This variation is equivalent to seven times the output of the largest generator on the system.

Figure 2: Weekly average electricity system demand, Republic of Ireland and Northern Ireland, 2012



Electricity demand is variable, with for example the highest demand over a 24 hour period being up to 3 times the lowest demand. This variation is equivalent to 7 times the output of the largest generator on the system.

2.2 The Single Energy Market (SEM)

The Single Electricity Market (SEM)[10] came into force on 1st November 2007 and created a mandatory gross electricity pool market for all electricity trade on the island of Ireland. The All-Island electricity system is a combination of the RoI and NI electricity systems, linked through a synchronous transmission grid. It is operated by two transmission system operators (TSOs), EirGrid and SONI, licensed by the respective regulators. The system operators dispatch generators based on the rules of the SEM subject to a range of real-time operational constraints.

In the SEM all generators over 10 MW are obliged to sell the electricity generated into the wholesale electricity pool market, from which suppliers (electricity retailers) purchase to supply homes and businesses in each half-hour across the day. Generators under 10 MW can choose whether to feed into the pool or not. Generators must bid to sell electricity into the pool at regulated prices based on their short-run marginal costs (SRMC). Short-run costs typically comprise the variable operation and maintenance (VO&M) costs, fuel costs and CO_2 emissions costs for producing the electricity. Generator bids received by the market operator are ranked lowest to highest, creating a merit order or supply curve. Within this merit order, the highest-cost generator required to meet demand sets the system marginal price (SMP), which is the price all generators dispatched in that half-hour period receive. This ensures that the lowest-cost generator is on line for the longest time and the highest-cost generator for the shortest time. The payments generators receive for their power production are known as *energy payments*. Reductions in fossil-fuel consumption due to renewable electricity (which tends to have a low SRMC and to be first in the merit order) act to lower these payments by reducing the SMP.

There are other market payments to make sufficient revenue available to cover the long-term costs of an adequate amount of generation capacity in the system and to guarantee that generation capacity is available

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[10] For further details, see *the SEM Trading and Settlement Code Helicopter Guide*: http://www.allislandproject.org/en/trading-settlement-code-decision.aspx?article=ae9d4aa4-888b-48e0-a973-6845d54ca467

when necessary. These are known as *capacity payments*. In a similar way, there are *constraint payments* to retain a safe and secure electricity system. These costs accrue when the system operator needs to deviate from the merit order and introduce real-time changes for the safety, security and stability of the system. They are known as *dispatch balancing costs* (DBCs).

The total market cost of wholesale electricity in the All-Island market in 2012 was €2.77 billion. Energy payments were responsible for 76% of this total, capacity payments for 19% and DBCs for the remaining 5%. Some generation types receive payments through electricity consumer levies that interact with the wholesale market. Similarly, the upkeep of an adequate and secure electricity grid is also funded through consumer levies.[11]

The total All-Island wholesale electricity market value in 2012 was €2.77 billion. Energy payments were responsible for 76% of this total.

2.3 Public Service Obligation (PSO)

In conjunction with the above market operation and payment regime, a Public Service Obligation (PSO) is levied on electricity consumers to provide funding in support of government policy. The PSO was originally established to subsidise the production of electricity from peat for security of supply reasons. More recently, support for some further gas-fired generation and some combined heat and power (CHP) generation was added to ensure that enough generation capacity was built to provide adequate system security. The PSO also funds support schemes for renewable energy technologies that contribute to reducing CO_2 emissions and improving security of supply.

The total PSO amount levied in 2012/2013 was €131 million; peat accounted for 29% of the PSO, fossil-fuel security of supply contracts for 30% and renewable electricity for 42%.[12]

Peat stations can bid in a low cost to the market as their costs are covered by the government support through the PSO. This means that they have a ‘must run’ status irrespective of their short-run cost for generating electricity. The system operator will dispatch peat generation when available and only reduce this generation output in order to abide by priority dispatch rules[13] or for system security reasons.

Renewable electricity generators like wind have no fuel cost and are dispatched in the market when the wind is blowing. If the market payments are not high enough to cover the long-term cost of these generators, the government support schemes provide a top-up through the PSO. When the market price is higher than the long-term cost of the renewable generators, those generators in the Alternative Energy Requirement (AER)[14] scheme pay back the additional market revenue to the PSO fund, while generators in the Renewable Energy Feed-In Tariff (REFIT)[15] scheme receive no additional revenue.

The wholesale market price (SMP) is primarily determined by the cost of fossil-fuels, most commonly gas. By displacing fossil-fuel generation from higher up the merit order, renewable electricity generation acts to reduce the wholesale market price. This is known as ‘the merit order effect’. In recent years the reduction in wholesale market price due to renewable energy generation has tended to cover the cost of the PSO.[16,17]

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[11] For information on the consumer charges associated with the Transmission Grid see CER, Decision Paper CER/10/206: http://www.cer.ie/docs/000837/cer11216.pdf, and EPSSU (2013), *Electricity and Gas Prices in Ireland, 1st Semester (January–June) 2013*: http://www.seai.ie/Publications/Statistics_Publications/EPSSU_Publications/Price_Directive_1st_Semester_2013.pdf

[12] CER Decision Paper (2012), ‘Public Service Obligation Levy 2012/2013’, CER/12/121: http://www.dcenr.gov.ie/NR/rdonlyres/E4E9814A-A79A-4FA7-8CBA-DDA822D26024/0/cer121211August.pdf

[13] SEM Committee Decision paper (2011), ‘Principles of Dispatch and the Design of the Market Schedule in the Trading and Settlement Code’, SEM-11-062: www.allislandproject.org

[14] DCENR, Alternative Energy Requirement Programme: http://www.dcenr.gov.ie/Energy/Sustainable+and+Renewable+Energy+Division/Electricity+from+Renewables+inc+REFIT+and+AER+Change+me.htm

[15] DCENR, Renewable Energy Feed-In Tariff (REFIT): http://www.dcenr.gov.ie/Energy/Sustainable+and+Renewable+Energy+Division/REFIT.htm

[16] EirGrid and SEAI (2011), *Impact of Wind Generation on Wholesale Electricity Costs in 2011:* http://www.seai.ie/Publications/Energy_Modelling_Group_/Impact_of_Wind_Generation_on_Wholesale_Elec_Costs/Impact_of_Wind_Generation_on_Wholesale_Electricity_Prices_in_2011.html

3. Electricity System Operational Elements and Dynamic Factors

This section describes a range of characteristics in the electricity system that influence the effects of variable renewable energy generation on the system. Extensive international analysis incorporating all these factors has shown that the characteristics of renewable energy at high penetrations can be accommodated in existing system operations, and that renewable energy is effective at displacing fossil-fuel use.[18,19] The quantity of fossil-fuel and CO_2 emissions displaced by renewable sources depends on the combined impact of all sources of variability and uncertainty, the flexibility of the electricity system and the influence of fuel prices on the relative costs of thermal generators.

These factors described here have been taken into account in the dispatch model methodology employed in this study.

3.1 Overall system operation

The role of the system operator is to dispatch the available generation output and transport this electricity to consumers at the lowest cost while ensuring that the electricity system is operated in a safe, stable and secure way. The market rules, supplemented by a range of operational strategies, guide the system operator in the dispatch decisions.

System frequency is the metric the system operator uses to ensure a high-quality electricity supply and prevent blackouts. For the All-Island system the system frequency is 50 Hz. To maintain the system close to this, the system operator must ensure that the demand from electricity customers is balanced at all times with the output of the generators on the system.

As Figure 2 shows, the maximum range of daily demand variation in the overall system amounts to several times the maximum output of the largest generator. As a result, a portion of the generation portfolio is brought online and turned off during each day, while others vary in operation between their maximum and minimum output capabilities. Generators can take a number of hours to start up and shut down, and different types of generation technology can vary their output more quickly than others. This means that the system operator must make advance scheduling decisions on what units are required to meet electricity demand based on forecasts of electricity demand and the output of renewable electricity generators.

Electricity systems have developed to manage variability and uncertainty from a number of sources, primarily electricity demand and generator availability.

Variability and *uncertainty* are therefore inherent in electricity systems. System operators have developed operational strategies to ensure the available generation is dispatched in an economically optimal way to meet demand. It is recognised that the variable nature of renewable energy sources like wind can add a further degree of variability which may lead to increased *ramping* and *cycling* of thermal generators.

Ramping refers to the requirement for electricity generators to change output upwards or downwards. *Cycling* refers to the requirement for generation units to start up and shut down to maintain system stability. Both ramping and cycling may lead to some reduction in fuel efficiency in individual generators as compared to full load operation, and over time may also lead to increased maintenance costs due to additional thermal stresses introduced by the changed running regime.[20]

Figure 3 illustrates the principal factors that a system operator considers during normal operation.

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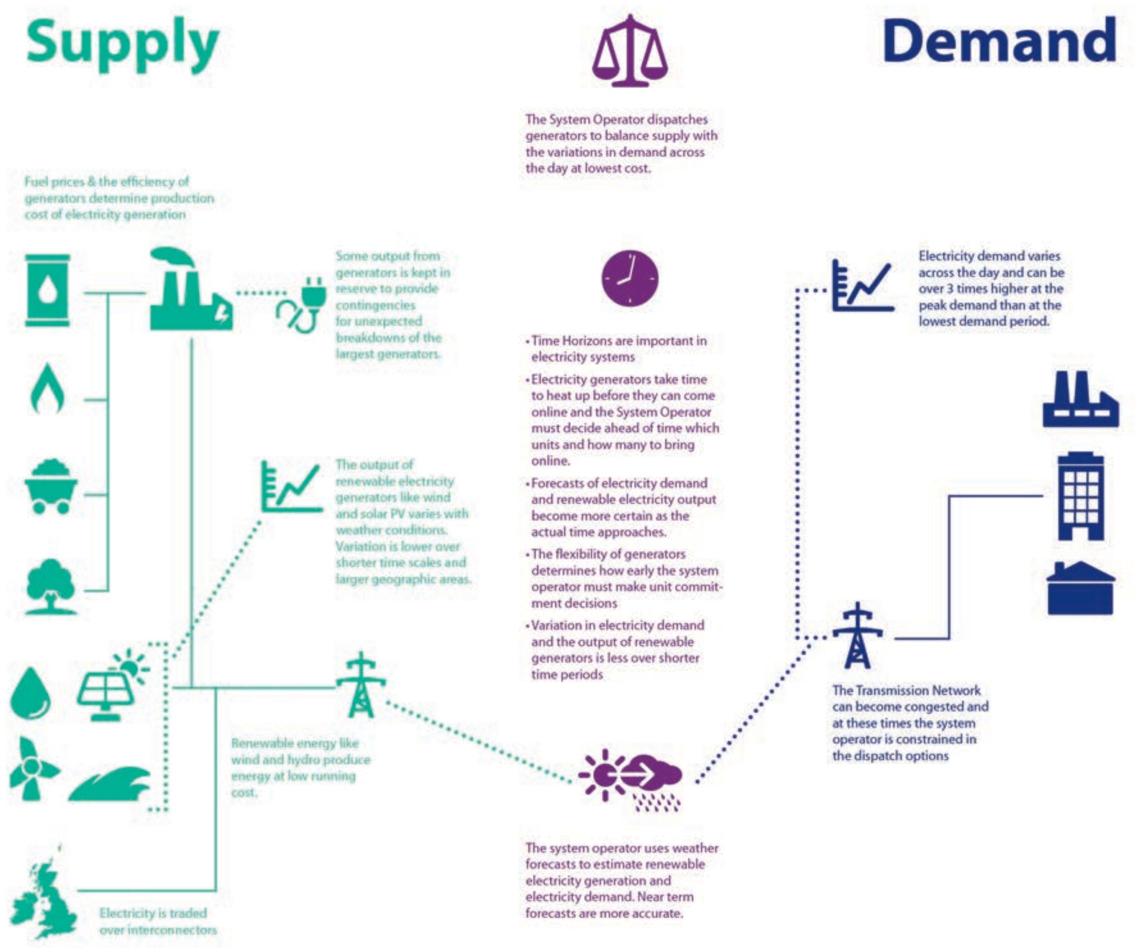
[17] O'Mahoney, A. and Denny, E., 'The Merit Order Effect of Wind Generation in the Irish Electricity Market', 30th IAEE/USAEE North American Conference, Washington DC, Oct 2011: http://www.usaee.org/usaee2011/submissions/OnlineProceedings/USAEE%20Washington%20Paper.pdf

[18] IEA Wind Task 25, 'Design and operation of power systems with large amounts of wind power, Final summary report, Phase two 2009-2011: http://www.vtt.fi/inf/pdf/technology/2012/T75.pdf

[19] IEA (2014), 'The Power of Transformation; Wind, Sun and the Economics of Flexible Power Systems'.

[20] Lew, D., Brinkman, G., Kumar, N., Besuner, P., Agan, D. and Lefton, S., 'Impacts of wind and solar on emissions and wear and tear of fossil-fueled generators', Power and Energy Society General Meeting, 2012 IEEE , vol., no., pp.1,8, 22-26 July 2012.

Figure 3: Schematic of All-Island electricity system operation



3.2 Electricity system variability and uncertainty

Variation and uncertainty can arise due to a number of factors, including demand, output from renewable generation (such as wind) and the reliability of generators.

Variability

On average, in the All-Island system, *demand variation* between the highest and lowest demands in a single day period averages 1,986 MW or 32% of the average daily peak. The maximum recorded change within a single day in 2012 was three times the lowest demand that day. Variation on the minute-to-minute timescale is considerably less than the variation in hourly or daily time resolution. To put the variability in context of what it means for generators, the largest single generator in the system has a maximum output of 480 MW, and the equivalent of seven times this capacity must be brought on and ramped up to cover a change of this magnitude within a day. System operators plan for the worst cases of variability to ensure enough generation is online to meet electricity demand.

Variability in electricity demand and wind output is less over shorter time intervals and over wider geographical areas.

Wind variation, like that of demand, reduces as the time horizons fall from daily to hourly to minutes. The geographical distribution of renewable technologies connected to the grid also influences variation. The total generation output from a distributed group of wind-farms fluctuates less and more slowly than the output from a single wind-farm. The more widely dispersed that wind-farm sites are within a power system, the smaller the aggregated changes in output; the total variability of wind reduces as the area covered by the electricity system increases.[21] The largest recorded change in wind-power output over a 15-minute period in the All-Island system was 17% of the installed capacity, with the average change in output over 15 minutes being 1% of installed wind capacity.[18] As more wind is connected, the aggregation benefit is likely to reduce variability further.

A statistical comparison between the temporal variation in demand and wind output shows that the variation in wind output in 2012 was less than the variation demand.[22] However, in a system context it is important to consider the combined effect of these sources of variability.

Wind generation variability in 2012 was less than electricity demand variability.

Electricity demand and wind output are not strongly correlated.[23] The variation in the output of wind-farms has an almost equal chance of either offsetting the variation in demand or adding to the variation. The remaining system demand not served by variable renewable generation is referred to as the *net load*. At certain times of the day, such as the morning ramp-up, the demand changes at a steep rate. Downward variation in the output of wind generators that coincides with these periods can increase the rate of change of output from other generators necessary to meet the net load. Conversely, upward variation at times of low demand can cause output reductions and possible shutdowns (cycling) of other generators.

Figure 4 illustrates the combined effect of wind and demand variation on net load over a seven-day period. Larger variations in net load over shorter periods can result in more frequent ramping of thermal generators. Over longer periods, an increase in net load variation can result in additional cycling of thermal generators, with some generators shut down at times of high wind and low demand. A coincidence in demand variability with a steep change in the output of renewable generators can result in a requirement for generators to change output more rapidly. More frequent and more intense variability due to renewable electricity can increase the ramping requirements on fossil-fuel generators and thus offset some of the overall savings arising from fossil-fuel displacement. For the All-Island system the interaction of wind output and electricity demand variability are potential drivers of additional ramping.

Figure 4: Variations in electricity demand, wind generation output and 'net load' over a seven-day period

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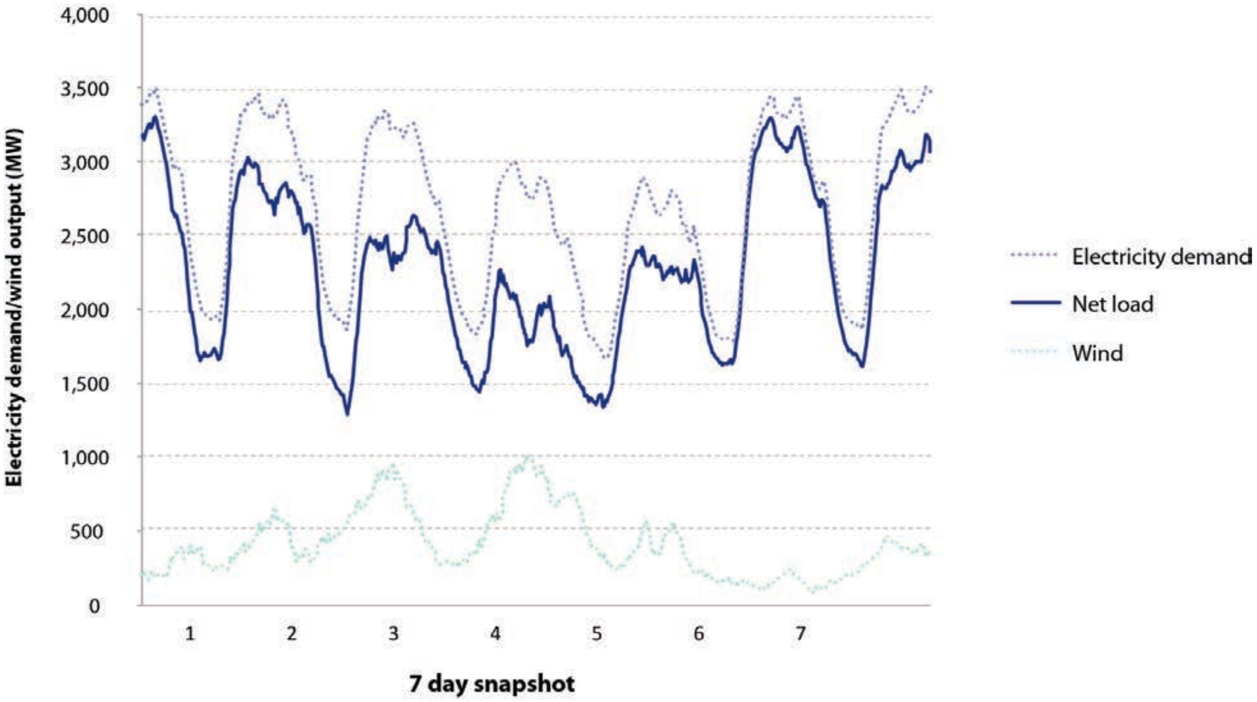
[21] Holttinen, H. 2005. 'Impact of hourly wind power variations on the system operation in the Nordic countries'. *Wind Energy*, Vol. 8, No. 2, pp. 197-218.

[22] F-test for equality of variance at 95% confidence interval for 15 minutes, 1 hour, 4 hours and 12 hours.

[23] Government of Ireland (1999), 'Strategy for Intensifying Wind Energy Deployment': http://www.dcenr.gov.ie/NR/rdonlyres/ADD4AF22-E434-403B-A3A4-87716C9EE7C0/0/RenewableEnergyStrategyGroupReport.pdf



A statistical comparison of the net load and the demand in 2012 shows that net load tends to be more variable than electricity demand, by 2 MW on average over 15 minutes, with just five periods of 15-minute duration out of 35,136 periods in 2012 having a higher maximum variation.[24] Table 1 shows the average and maximum variation in wind output, demand and net load at various time resolutions in 2012. For all time periods, it shows that the variation in net load to be met by other generators is significantly less than the sum of the variations in demand and in wind output.

Net load accounts for the combined impact of wind and demand variability. In 2012, net load variability was higher than electricity demand variability alone.

Table 1: Demand, wind generation output and net load variability at various time intervals in 2012

	Time Resolution							
	15 Minutes		***1 hour***		***4 hours***		***12 hours***	
	Standard Deviation (MW)	Maximum Change (MW)	Standard Deviation (MW)	Maximum Change (MW)	Standard Deviation (MW)	Maximum Change (MW)	Standard Deviation (MW)	Maximum Change (MW)
Demand	36	277	130	778	370	1,458	470	2,241
Wind Output	26	238	69	444	69	825	308	1,263
Net Load	**38**	**293**	**131**	**902**	**368**	**1,798**	**496**	**2,877**

Variability also occurs over longer time horizons. Electricity demand is lower in the summer than the winter and has a different daily profile. Hydro resources differ from week to week with changes in rainfall. The availability of generators and transmission lines changes across the year as generators go off for scheduled maintenance or breakdown unexpectedly. This annual forced outage rate typically ranges from 0.7% to 11% of installed capacity,

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[24] EirGrid (2011), 'The DS3 Programme, Delivering a Secure, Sustainable Electricity System': http://www.eirgrid.com/media/DS3_Programme_Brochure.pdf

depending on the type of generator, the age of a generator and its running profile history. Analysis of the declared availability of thermal generators in 2012[25] shows over 300 occasions where generators were unavailable, outside of the scheduled outages.

Uncertainty

The predictability of demand and generation is a source of uncertainty that the system operator plans for during normal operation. As many generation units must have notice periods of a number of hours before they can start generating electricity, the system operator has to decide ahead of time, based on forecasted information on demand and generator output, what generators should be online to meet future net load in an economically optimal way. Some generators require instructions over 24 hours ahead of time, while others require less than an hour. These timescales determine the forecast that the system operator uses; several forecasting timescales from over 24 hours ahead to one hour ahead are incorporated into decision making.

As fossil-fuel generators can take several hours to warm up and come on-line, the system operator must decide in advance, with the aid of forecasts of wind output and electricity demand, what units are required to meet net load.

If the forecast is higher than actual net load, it is possible that some units may have to run at lower output or come off line. Should the forecast be lower than the actual, then units that can turn on at short notice are required to make up any shortfall. The resultant arrangement of generators may be less efficient than optimal dispatch in a situation of full certainty. Forecasting accuracy plays a key role in optimising generator dispatch to help the efficient use of thermal generators and minimise fuel use.[26]

Electricity demand forecasts are strongly dependent on weather forecasts, particularly temperature, and typically have a high level of accuracy over 24 hours ahead of time.[27] Wind output predictability can be 80% accurate for a day-ahead forecast, while a one-to-two-hour-ahead forecast can result in even higher accuracies, up to 95%.[28] There is a strong aggregation benefit for wind forecasting accuracy; a more geographically dispersed wind-farm pattern provides greater accuracy as forecast errors in one location balance those elsewhere. Forecasting error is measured using the Normalised Mean Absolute Error (NMAE), which expresses the deviation of the forecasted output from the actual as a proportion of overall installed capacity. In 2012 the 24-hour wind forecast showed an average NMAE of 5.6% – equivalent to 92 MW – with a maximum of 46% equivalent to 751 MW. Figure 5, in the form of a cumulative frequency distribution, shows how the wind forecast errors in MW amounts occurred in 2012: 50% of the errors are below 65 MW, equivalent to 14% of the output of the largest generator, and 90% of the errors are below 200 MW, equivalent to 42% of the output of the largest generator.

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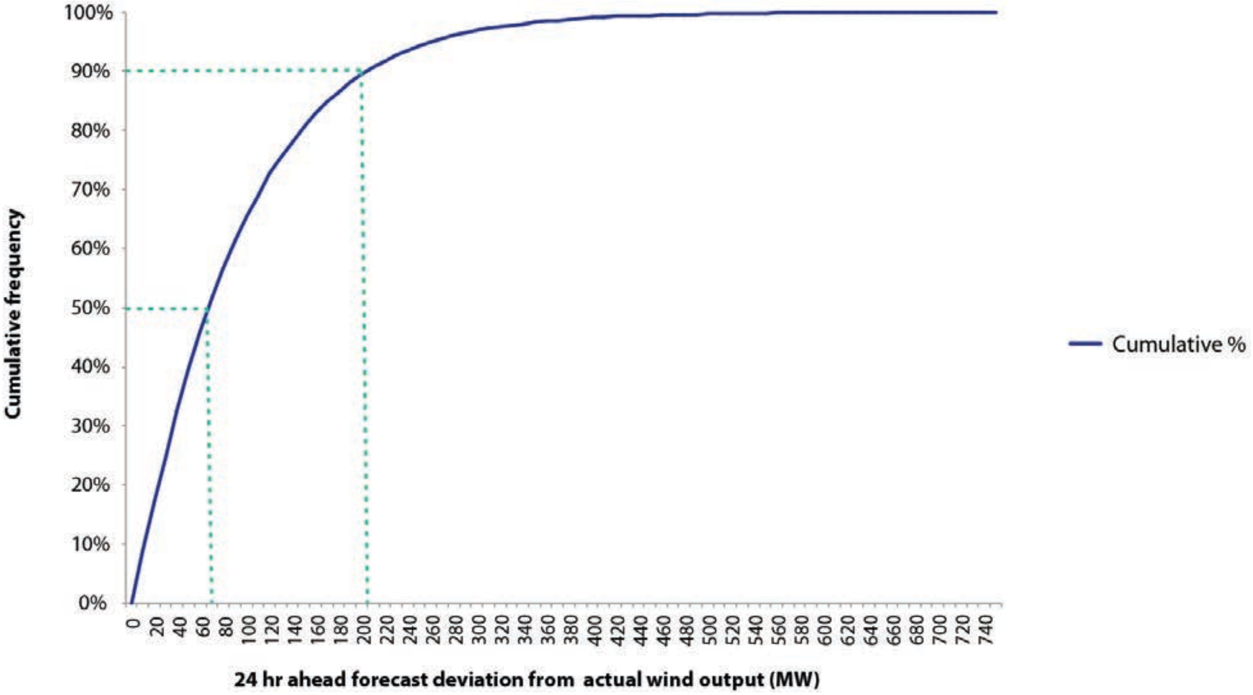
[25] Data available from SEMO: http://www.sem-o.com/marketdata/Pages/dynamicreports.aspx

[26] D. Lew, M. Milligan, G.Jordan, R.Piwko, (2011), *The Value of Wind Power Forecasting (Preprint)*, presented at 91st Meteorological Society Annual Meeting, the Second Conference on Weather, Climate and the New Economy, Washington DC.

[27] Fay, D.; Ringwood, J.V. (2010) 'On the Influence of Weather Forecast Errors in Short-Term Load Forecasting Models', Power Systems, IEEE Transactions, vol.25, no.3, pp.1751,1758.

[28] M. Milligan, K. Porter, E. DeMeo, P. Denholm, H. Holttinen, B. Kirby, N. Miller, A. Mills, M. O'Malley, M. Schuerger and L. Soder, 'Wind Power Myths Debunked', published by *IEEE Power & Energy Magazine*, vol. 3, no. 6, pp. 65-74, Nov/Dec 2009.

Figure 5: Cumulative frequency distribution of 24-hour-ahead wind forecast errors in 2012



Wind output is more predictable over wider geographical areas and over shorter time periods.

3.3 Operating reserve and frequency stability

In addition to the forecasting accuracy of net load, the breakdowns or 'trips' of thermal generators introduce uncertainty that is managed in the All-Island system through the use of operating reserves. Generator trips differ in character from the uncertainty introduced by demand and wind forecast in that they tend to be unpredictable. Contingencies are included in the operational strategies of the system operator to deal with these events by holding some of the available output from other generators as a backup that can be quickly called into action. Reserve requirements are not influenced by wind generation or other renewable electricity generators at current levels of installed capacity; reserve requirements are determined by the largest online generator.

In the All-Island system, reserve is broken into four categories:

1. Primary Reserve
2. Secondary Reserve
3. Tertiary Reserve
4. Replacement Reserve

Primary reserve accounts for system changes at the 5 to 15-second timescale and acts to stabilise system frequency after an unexpected event.

Secondary operating reserve is implemented at the 15 to 90-second timescale and acts to return frequency to nominal levels (50 Hz in the All-Island system) after an unexpected event. Both primary and secondary reserves are provided by units already running on the system that can quickly change output to deal with unexpected changes in demand or generation output.

Contingency reserve requirements in the All-Island are related to the maximum capacity of the largest individual generator or interconnector online.

Tertiary operating reserve acts from 90 seconds to 20 minutes and is provided by generators already running and generators that can start quickly at short notice. Replacement reserve is from 20 minutes to four hours and is provided by offline generators that can start up in this period. Tertiary and replacement reserve act to ensure that sufficient capacity is available to replace primary and secondary reserve to ensure the system is prepared for further unexpected events.[29]

Contingency reserve requirements in the All-Island system are related to the maximum capacity of the largest individual generator or interconnector online. At present the East West Interconnector (EWIC), with a 500 MW maximum capacity, typically sets the contingency reserve requirements in the RoI system. At present, renewable energy generation on the All-Island system does not influence reserve requirements. This means that no additional operating reserve is required for renewable electricity generation at current levels.

Below the five-second timescale the regulation of system stability is provided by the inertia from the spinning momentum of the larger generators on the system. Generators that can provide inertia and load following services are known as synchronous generators. Extensive studies on the impact of wind on frequency stability have established operational rules for the All-Island system. These specify that at least 50% of system load must be provided by synchronous generators at all times.[30] Wind generator output is turned down or *curtailed* at times when this 50% limit is reached. The All-Island DS3 programme ('Delivering a Secure Sustainable Electricity System'), led by Eirgrid and SONI, details plans to extend this limit to allow up to 75% of instantaneous system load to come from non-synchronous sources, like wind, by 2020. [30]

Future planned increases in wind capacity will influence the reserve requirements, particularly tertiary reserve requirements.[31] The All-Island grid study showed that additional reserve requirement in hypothetical 2020 scenarios is related to the amount of wind installed but that the largest contributing factor remains the loss of the largest conventional unit.[32] Wind power does not necessarily require larger amounts of primary and secondary reserve, when the characteristics of the wind are taken into account in the calculation of reserve requirements.[33] The relative electrical isolation of the All-Island system means that the reserve levels consider the need for a high degree of generator flexibility, while additional rules ensure a sufficient number of units remain online to ensure frequency and voltage stability.[34] Reserves allow the electricity system to respond to unexpected events but the ability of the system to incorporate variability and uncertainty due to renewable electricity generation is primarily determined by system flexibility.

At present, renewable electricity generation on the All-Island system does not influence the quantity of reserve required.

3.4 System flexibility and curtailment of wind generation

System flexibility is defined as "*the ability of a (electricity) system to deploy its resources to respond to changes in net load*".[35] With an electrically isolated island system, with light interconnection to other electricity systems, the issue with flexibility in Ireland is not a new or entirely wind-focused concern.[36] The All-Island system has developed a

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[29] For a full discussion on reserve, see: Ela, E., Milligan, M. and Kirby, B. (2011), 'Operating Reserves and Variable Generation. A Comprehensive Review of Current Strategies, Studies, and Fundamental Research on the Impact that Increased Penetration of Variable Renewable Generation has on Power System Operating Reserves', NREL/TP-5500-51978. Golden, CO: National Renewable Energy Laboratory.

[30] EirGrid (2010), All-Island TSO Facilitation of Renewables Studies: http://www.eirgrid.com/media/FacilitationRenewablesFinalStudyReport.pdf

[31] Doherty, R. and O'Malley, M., 'A new approach to quantify reserve demand in systems with significant installed wind capacity', IEEE Transactions on power systems, vol. 20, No 2, 2005.

[32] Peter Meibom et al., 'All Island Grid Study Workstream 2B: Wind Variability Management Studies', July 2007.

[33] Ortega-Vazquez, M.A. and Kirschen, D.S., 'Estimating the Spinning Reserve Requirements in Systems with Significant Wind Power Generation Penetration', Power Systems, IEEE Transactions on, vol.24, no.1, pp.114,124, Feb. 2009.

[34] Söder, L., Abildgaard, H., Estanqueiro, A., Hamon, C., Holttinen, H., Lannoye, E.,Gomez Lazaro, E., O'Malley, M., Zimmermann, U. (2012), *Experience and Challenges With Short-Term Balancing in European Systems with Large Share of Wind Power,* IEEE Transactions on Sustainable Energy, vol .3, No. 4, pp. 853-861.

[35] Lannoye, E., Flynn, D. and O'Malley, M., 'Evaluation of Power System Flexibility', Power Systems, IEEE Transactions on , vol.27, no.2, pp.922,931, May 2012.

[36] Yasuda et al., 'Flexibility Chart: Evaluation of diversity of flexibility in various areas', IEA Task 25.

flexible generation portfolio, based on appropriately sized units that are capable of changing load and starting up quickly to deal with unexpected variability over short time horizons.[37]

As an electrically isolated island system, with light interconnection to other electricity systems, the issue with flexibility on the All-Island system is not a new or entirely wind-focused concern.

Yasuda et al. summarise the factors identified in a number of studies that influence power-system flexibility and allow for the integration of variable renewable electricity generation. Levels of interconnection, pumped storage hydro capacity and conventional hydro along with the available combined-cycle gas turbines (CCGT) capacity are identified as being the main sources of flexibility in the All-Island system.[38] Hydro capacity, interconnection and storage can provide flexibility without inducing cycling or ramping emissions. CCGTs and open-cycle gas turbines (OCGTs) can provide flexibility through cycling and ramping.

System flexibility varies due to changes in the availability of these components, and the reduction in capacity of one source of flexibility places extra burden on the other sources. Changes in interconnection capacities and scheduled or forced outages for flexible capacities such as pumped hydro storage are influential when considering a system on a particular day, week or year. Outages at units that can start up and/or change output relatively quickly would mean that the system operator may have to make unit commitment decisions earlier – when uncertainty is greater. A fall in flexibility constrains the system operator in dispatch choices, and at times of low flexibility the output of variable renewable generators may be *curtailed*.

Wind generator curtailment occurs when grid security issues can only be resolved by reducing the output of wind electricity generators. EirGrid reported that wind power in the RoI was dispatched down by 103 GWh in 2012[39] and 106 GWh in 2011.[40] The years 2011 and 2012 were higher-than-average for curtailment due to reduction in the availability of the Moyle (UK–NI) interconnector, which coincided with a long-term outage in the Turlough Hill pumped storage plant. Outages of interconnectors and pumped storage will tend to increase cycling (all else being equal) as system flexibility is required from the CCGT and OCGT generators.

3.5 Generation mix and fossil-fuel/CO_2 prices

The mix of generation in an electricity system and the relative cost of producing energy from generators, fuelled from different fossil-fuel sources, will influence what type of fossil-fuel and how much emissions tend to be displaced by renewable electricity. The emissions from coal and peat combustion are considerably greater than those from natural gas combustion.

Electricity systems with high proportions of gas generation, like the All-Island system, tend to have lower emissions than a system dominated by coal. Thus renewable electricity generation added to a gas system will tend to displace lower amounts of CO_2 than if added to a coal-dominated system.

Changes in fossil-fuel and CO_2 prices can alter the relative costs of coal and gas fired generation. Electricity generation from ambient renewable sources, such as wind and solar PV, have low or zero short-run costs and tend to displace the marginal fossil-fuel generator. If gas generation is more expensive than coal within the merit order, then gas generation tends to be displaced, all else being equal, and vice versa. For the All-Island system, when gas is the marginal plant, the displacement due to wind tends to be below the system average; when coal is the marginal plant, displaced emissions will tend to be above the system average. Displacement of coal results in an offset of a greater amount of CO_2 than where gas is displaced by virtue of the higher carbon intensity of coal, but some of the gain is offset by additional emission-intensive start-ups of coal units. Denny and O'Malley (2007) describe how changes to the merit order can induce higher cycling emissions in the All-Island system. When fuel prices are such that coal is the marginal plant, the cycling costs are higher as the coal generation technology requires more fuel input to change load and start up than gas.[41] This offsets some of the CO_2 gains from having coal as the marginal plant.

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[37] IEA Task 25 (2012), 'Design and operation of power systems with large amounts of wind power': http://www.ieawind.org/task_25/PDF/T75.pdf

[38] Yasuda et al., 'Flexibility Chart'.

[39] EirGrid (2013) '2012 Curtailment Report'. This equated to 2.6% of wind generator output that year.

[40] EirGrid (2012) '2011 Curtailment Report'. This equated to 2.4% of wind generator output that year.

[41] Denny, E. and O'Malley, M., 'Quantifying the Total Net Benefits of Grid Integrated Wind', Power Systems, IEEE Transactions on , vol.22, no.2, pp.605,615, May 2007.

The fossil-fuel generation mix and the relative generation costs influence the amount of CO_2 emissions displaced by renewable electricity generation.

Peat units and some fossil-fuel units receive fixed price support through the PSO levy, which means their cost of fuel and CO_2 does not affect dispatch decisions. These units thus receive preferential dispatch and tend to run for long periods at high output. Renewable energy will only displace these units in periods where the system is highly constrained and/or periods where wind generation contributes a high proportion towards demand.

3.6 Network constraints

Network congestion adds further constraints to the system operator's dispatch and reserve provision choices, with the dispatch of the generation portfolio departing from the economic ideal. Some generators may have to increase or decrease output to relieve network constraints in a congested area or congested line. Network congestion can also vary across the year as network upgrades take place, generators go offline for maintenance, and there are changes in seasonal demand.

Network constraints can result in renewable electricity generation displacing fossil-fuel generation other than the marginal plant.

3.7 Cross-border trade

Greenhouse gas reduction targets are applied based on national jurisdictional boundaries, but most electricity systems cross numerous jurisdictions. In the All-Island system, the separate jurisdictions of the RoI and NI are part of one synchronous grid that connects to Great Britain through two direct-current (DC) interconnectors. Thus renewable generation in one jurisdiction may offset carbon emissions in another rather than displacing CO_2-emitting generation within the same national boundaries. All consumers in the All-Island system see the benefit of any reduction in CO_2 and fuel costs due to renewable generation offsetting fuel and CO_2 in either RoI or NI, but national emissions reporting methods cannot take these transfers into account. This can result in some emissions reductions due to renewable energy in one jurisdiction being accounted for in the national emission inventory of an interconnected jurisdiction.

National accounting of CO_2 emissions occurs within the boundaries of individual jurisdictions, but electricity is traded across borders. This can result in emissions reductions accruing outside of the country where the renewable electricity is generated.

Part II: Methodology

Part II describes the methodology used in the study. It employs a dispatch model of the All-Island electricity system, built using PLEXOS power market simulation software and validated data which takes account of the extensive range of factors influencing system operation and the impact of wind and other renewable electricity generation. The actual portfolio of electricity generators (including renewables) in 2012 is compared with the outcome from two alternative scenarios to assess the impact of renewable electricity in general, and wind in particular, in displacing fossil-fuel usage and CO_2 emissions.

4. Methodology

4.1 Study approach

By way of further contextual background for the present study, a review is made in Annex 1 of various methods used to estimate fossil-fuel and CO_2 displacement from renewable electricity generation in Ireland and internationally. The strengths and limitations of each are discussed, and a comparison is made of a number of published estimates of CO_2 emissions saving rates in Ireland, the USA and Canada using these different methods.

This study employs the dispatch model method, building on the extensive analysis carried out to date on renewable electricity integration into the All-Island system and other international studies dealing with integration issues. The model uses PLEXOS electricity system simulation software to quantify the fossil-fuel and CO_2 savings associated with the inclusion of renewable electricity generation in the electricity system and is based on the CER's validated model.[42]

The validated CER model is comprised of a comprehensive dataset of generator technical parameters that is tested against historic market outcomes. The generator parameters include: maximum and minimum outputs, generation efficiency at various output points, start-up times, minimum times for which particular generator units must stay on once started, minimum times for which units must remain off once stopped, and how quickly generators can change output.

The CER model is adapted to capture the impacts of reserve requirements, network constraints based on rules defined by the TSO [43] and forecast accuracy for electricity demand and wind output. Further, the demand profiles for both the RoI and NI systems are added. The actual interconnector flows and wind output profiles for both regions in 2012 along with the available energy for hydro power production in each month are also added. Pumped storage is modelled to optimise the pumping/generation cycle each day.[44] The impact of forecast accuracy for wind and demand is included based on forecasts of wind and demand at a 24-hour-ahead time resolution. Forced outages of generators are also included as unexpected events, with scheduled outages input to the model on the basis of occurrences in 2012. The model incorporates uncertainty by basing decisions in advance on which generators are required ahead of time using forecasted values for wind, demand and unit availability, before re-optimising generator output in real time based on these existing dispatch decisions.

This model takes account of the extensive range of factors influencing system operation and the impact of wind and other renewable energy generation as explained in Part 1.

Figure 6 shows the factors taken into account in the model.[45] Full details of the input assumptions are given in Annex 2.

The purpose of the resultant 2012 Base Model is to provide a close representation of the 2012 electricity system and thus provide a benchmark against which the scenario simulations can be compared.

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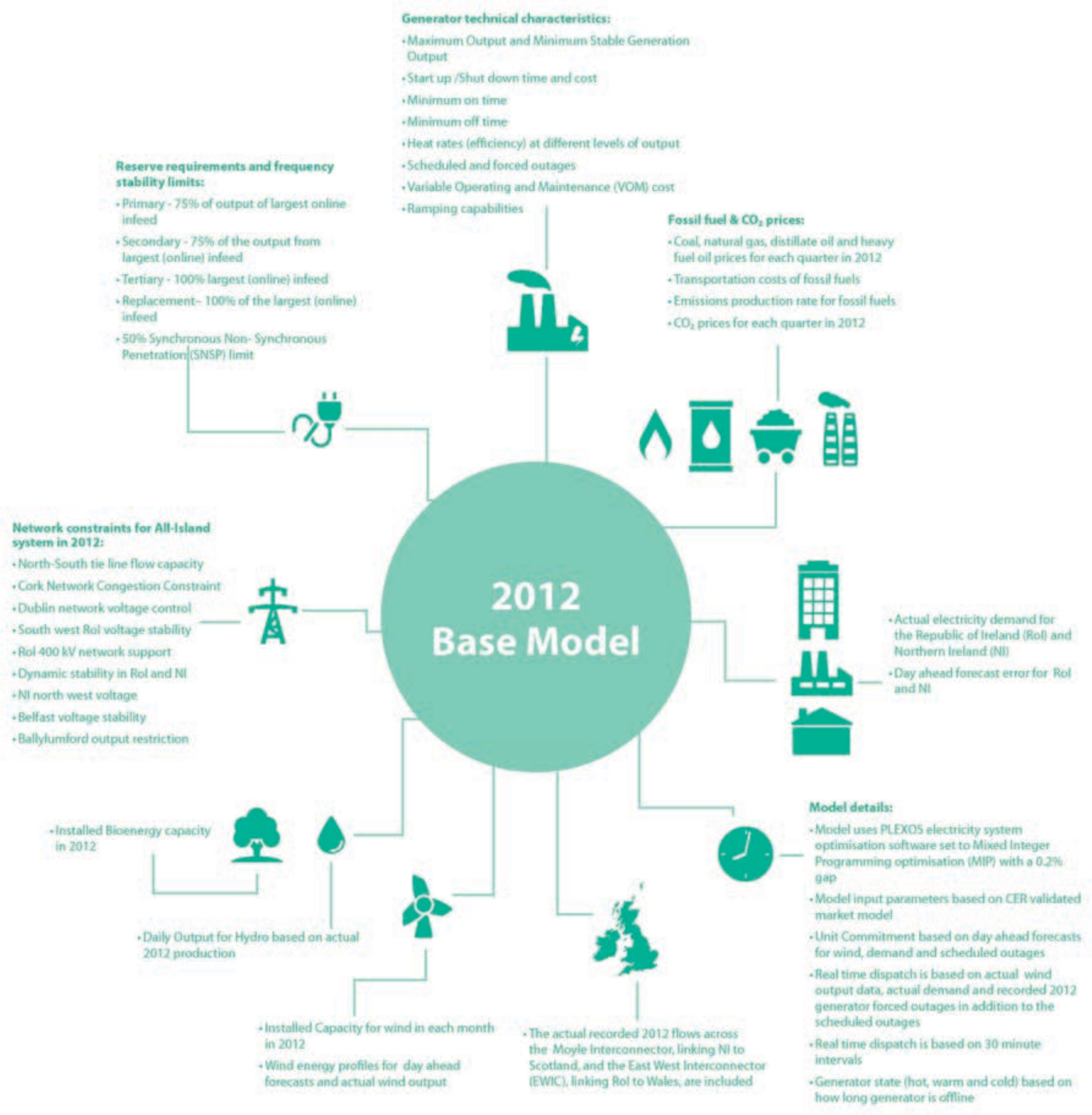
[42] CER (2011), '2011 PLEXOS Validation Reports and Models': http://www.allislandproject.org/en/market_decision_documents.aspx?page=4&article=151a9561-cef9-47f2-9f48-21f6c62cef34

[43] For further details see: http://www.eirgrid.com/operations/

[44] Deane, J.P., McKeogh, E.J., O Gallachóir, B.P., 'Derivation of Intertemporal Targets for Large Pumped Hydro Energy Storage with Stochastic Optimization', *IEEE Transactions on Power Systems*, vol.28, no.3, pp.2147,2155, Aug. 2013.

[45] The model runs at a 30-minute time resolution with 24-hour rolling unit commitment. Some optimisation options in PLEXOS produce a least-cost dispatch by relaxing some of the physical requirements of generators in order to speed up solution times. The Mixed Integer Programming (MIP) linear optimisation method fully accounts for generator start-up times, minimum stable generation levels, generator state (hot, warm or cold)[45] and minimum on and off times. The MIP method is used to capture the full extent of start-up and cycling requirements in the system but at the cost of computational times.

Figure 6: Model details and input assumptions overview



4.2 Scenarios to investigate displacement Impact of renewable electricity

Using as the 'Base Case' the actual system conditions and portfolio of electricity generators (including renewables) in 2012, two alternative scenarios are applied and analysed in order to assess the impact of renewable electricity in general, and wind in particular, in displacing fossil-fuel usage and CO_2 emissions. These consist of:

- No Wind: A scenario that removes all wind capacity from the system;
- No Renewables (No RE): A scenario that removes all renewable (wind, hydro and biomass) generation capacity from the system.

The scenarios are constructed by varying the assumptions on the installed capacity of renewable electricity.

The absence of wind generation in the first scenario and of all renewable electricity in the second would have the potential to reduce the generation system adequacy below the system standard threshold. The 'Loss of Load

Expectation' (LOLE) metric is used to determine if there is adequate generation to meet security standards. The minimum standard is equivalent to 4.9 hours per year for NI and eight hours per year for the RoI.

For this reason, to maintain parity of generation adequacy across scenarios, it was necessary to provide the following additional thermal generation capacity (all gas fired) back into the system to replace the absent renewable capacity[46], as follows:

- No Wind scenario: 180 MW OCGT added in RoI and 58 MW OCGT added in NI;
- No RE scenario: 415 MW CCGT added in RoI along with 88 MW OCGT in RoI and 80 MW OCGT in NI

Table 2 shows the generation portfolio capacities for each scenario in the All-Island system in 2012.

Table 2: Generation capacities for each scenario in the All-Island system in 2012

Generation Type	**2012 Base Model (MW)**		**No Wind (MW)**		**No RE (MW)**	
	NI System	***RoI System***	***NI System***	***RoI System***	***NI System***	***RoI System***
Coal	476	840	476	840	476	840
Gas	1,539	3,684	1,539	3,684	1,539	3,684
Oil-based	362	1,224	362	1,224	362	1,224
Peat	0	340	0	340	0	340
Pumped Hydro	0	292	0	292	0	292
Hydro	4	237	4	237	-	-
Biomass	26	74	26	74	-	-
Wind	467	1,642	-	-	-	-
Replacement Capacity	-	-	58	180	80	503
Total	2,874	8,333	2,465	6,871	2,457	6,883

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[46] The capacity credit for wind is based on EirGrid's evaluations in the Generation Capacity Statement, with 1,800 MW of wind equivalent to approximately 320 MW of dispatchable generation. Other renewable energy is replaced by the same capacity of thermal plant.

Part III: Results

Part III presents the results of the study. It shows the net 'bottom line' effects of renewables in displacing fossil-fuel usage and CO_2 emissions on the system in 2012, for the All-Island system as a whole and for the Republic of Ireland. It also includes a quantification of the individual effects of renewables on the ramping and cycling of fossil-fuel plant, and on the resultant efficiency and CO_2 emissions intensity. These constituent factors are taken into account in determining the overall 'bottom line' fuel and CO_2 savings.

5. Results

The results are presented in two categories. The first category (sections 5.1 to 5.4) deals with the overall 'bottom line' results. These show the net or aggregate impacts of wind and renewable electricity generation on an All-Island system wide basis and for the Republic of Ireland (RoI) in 2012. Total fossil-fuel and CO_2 savings are presented and the displacement intensity of renewable electricity generation is quantified.

The second category (sections 5.5 to 5.7) separates the contributing factors to the overall savings. These include the impacts of wind and renewable electricity generation on fossil-fuel generator emissions intensity though additional cycling, ramping and through reductions in the online capacity factors of fossil-fuel generators. The impact of changing system conditions throughout 2012 are presented along with the impact of electricity trade between RoI and NI through the SEM.

5.1 Summary: Net quantities and values of fossil-fuel and CO_2 emissions savings

Table 3 summarises the high-level results for the two scenarios relative to the 2012 Base Model.

Table 3: High-level results – Net fossil-fuel and CO_2 emission savings impacts

	Wind Savings (Scenario 1 versus Base 2012 model)				Total RE savings (Scenario 2 versus Base 2012 model)			
System	**Fuel Savings (ktoe)**	**Fuel Savings (€m)**	**Emission Savings (m tonnes)**	**Emission Savings (€m)**	**Fuel Savings (ktoe)**	**Fuel Savings (€m)**	**Emission Savings (m tonnes)**	**Emission Savings (€m)**
RoI	586	177	1.51	11	778	245	1.94	15
NI	241	48	0.82	6	265	52	0.91	7
All-Island	826	225	2.33	17	1,043	297	2.85	21

For the Republic of Ireland in 2012 the resultant net savings are as follows:

- Renewable electricity generation is estimated to have saved 778 ktoe of fossil-fuel with an associated CO_2 emissions reduction of 1.94 million tonnes. Wind generation is the largest contributor, with savings estimated at 586 ktoe of fossil-fuel and a CO_2 emissions reduction of 1.51 million tonnes.
- The value of the fossil fuels not consumed in the Republic of Ireland in 2012 as a result of renewable electricity generation is estimated at €245 million, with the value of avoided CO_2 emissions being a further €15 million. Savings from wind generation are estimated at €177 million in fossil-fuel and €11 million in CO_2 emissions. Apart from a small quantity of peat, all of the savings are due to the displacement of imported fossil fuels.
- The fossil-fuel savings are equivalent to the electricity demand of 780,000 Irish households.[47]

On the All-Island electricity system as a whole in 2012:

- Renewable energy is estimated to have displaced 1,043 ktoe of fossil-fuel, valued at €297 million, with an associated CO_2 emissions reduction of 2.85 million tonnes, valued at €21 million.
- Wind generation contributed savings estimated at 826 ktoe (worth €225 million) of fossil-fuel and a CO_2 emissions reduction of 2.33 million tonnes (worth €17 million).

Renewable electricity generation in the All-Island system in 2012 saved fossil-fuels valued at €297 million and 2.85 million tonnes of CO_2 emissions, valued at a further €21 million.

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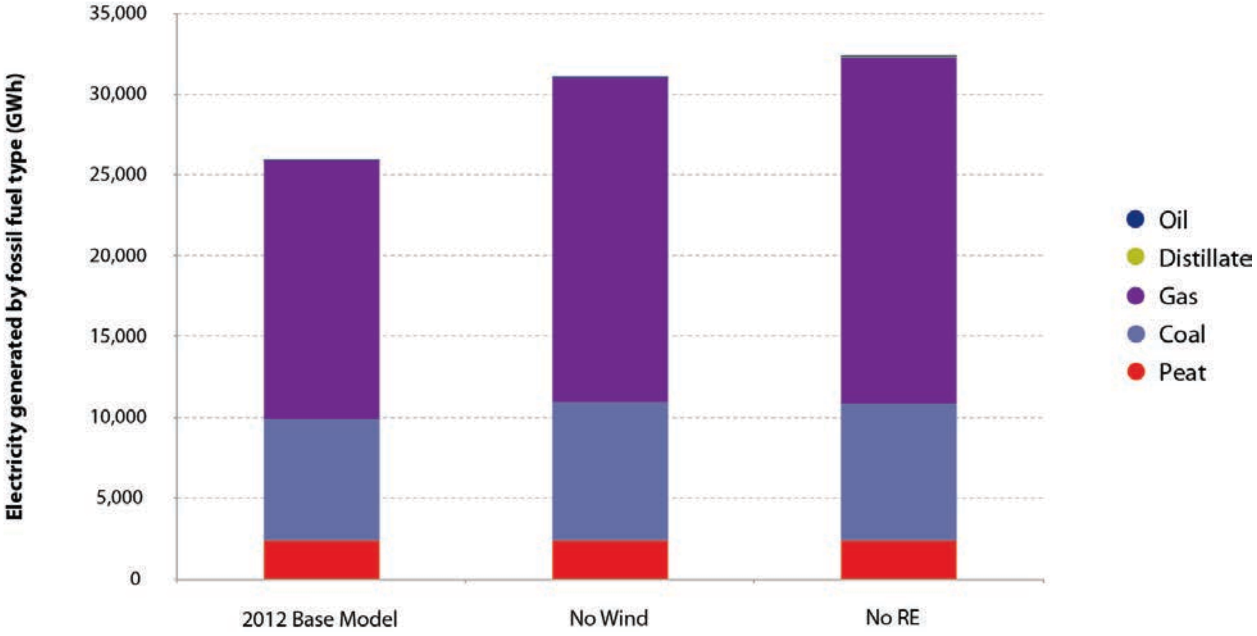
[47] Fossil-fuel average generation efficiency in 2012 is estimated as 40% and would produce 4,071 GWh from the fossil-fuel saved. The average electricity demand of a household is 4,902 kWh. This implies that fossil-fuel savings are equivalent to 784k homes

5.2 Fossil-fuel electricity generation displaced in 2012

The scenario comparisons show that renewable electricity generation is effective in displacing fossil-fuel generation and reducing CO_2 emissions. Figure 7 shows, for the All-Island system, the electricity generated from fossil-fuels in the 2012 Base Model compared with the No Wind and No RE scenarios. With the actual level of renewables on the system in 2012 (the Base Model case), fossil-fuel generation is 17% lower than in the No Wind scenario and 21% lower than in the No RE scenario. Conversely expressed, relative to the actual system in 2012, fossil-fuel generation would have increased by 26% in the absence of renewable electricity generation and by 20% in the absence of wind generation.

Natural gas generation sees the largest displacement but some displacement of coal fired generation is also evident. Each 10 MWh of wind generation output displaced 8 MWh of gas generation and 2 MWh of coal. For every 10 MWh of total renewable electricity generation, 8.3 MWh of gas generation, 1.4 MWh of coal and 0.3 MWh of peat is estimated to have been displaced.

Figure 7: All-Island fossil-fuel generation in 2012 – Base Model and scenarios



Fossil-fuel generation would have increased by 26% in the absence of renewable electricity generation and by 20% in the absence on wind.

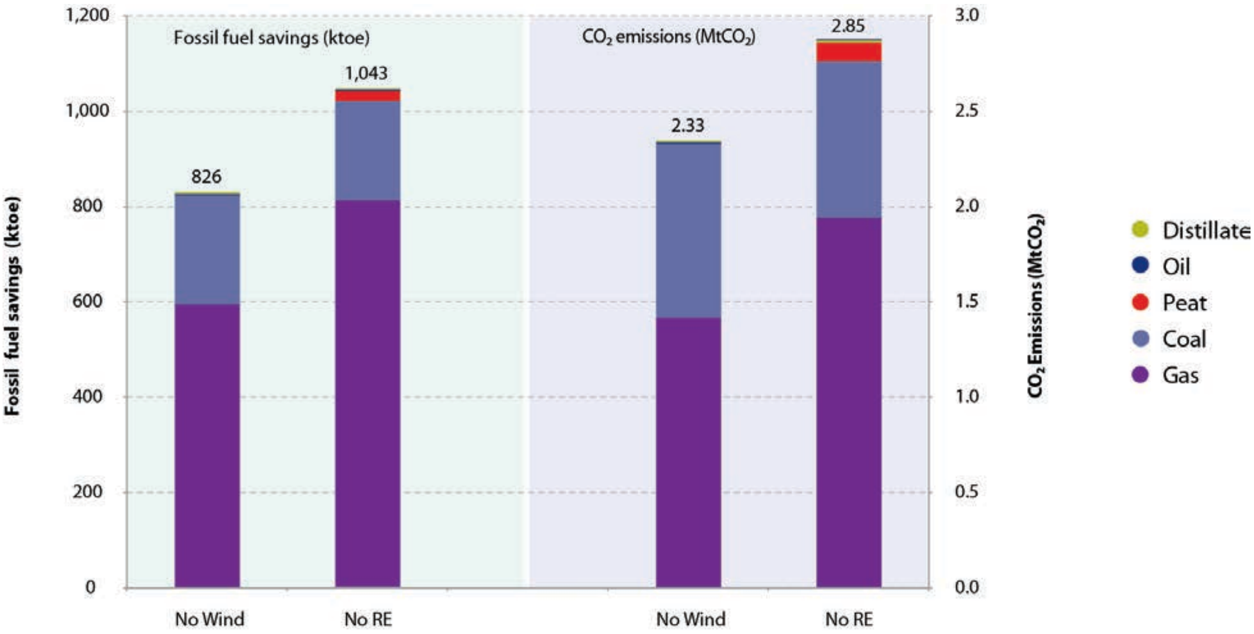
5.3 Displaced fossil-fuel inputs and associated CO_2 reductions

As renewable capacity is taken out of the electricity system, fossil-fuel units must increase output to compensate. In order to produce the same output, this additional fossil-fuel generation requires a higher level of primary fuel input than the level of renewable energy displaced. This is because each unit of output from fossil-fuel generators requires between 1.8 and 4 units of primary fossil-fuel input in steady-state operation due to the efficiency at which these units convert primary fossil-fuel energy to useful electricity output. As wind and hydro power technologies do not generate electricity through combustion, they do not experience these thermal efficiency losses.

Overall in 2012 on the All-Island system, wind energy generation displaced 1.88 units of fossil-fuel input for each unit of electricity produced by wind, whereas total renewable electricity generation displaces 1.53 units of fossil-fuel for each unit of electricity produced by renewable energy. The displacement ratio in the case of total renewable electricity is less than for the case of wind generation alone due to the efficiency losses associated with the combustion of biomass in the former case. The respective emissions displacement intensities were 0.43 tCO_2 /MWh for all renewable generation and 0.46 tCO_2 /MWh for wind generation.

Figure 8 shows the net displacement of fossil-fuels (in ktoe) and CO_2 emissions (in millions of tonnes) on the All-Island system, by type of fuel, in both scenarios relative to the 2012 Base Model with renewable electricity generation.

Figure 8: Fossil-fuel and CO_2 emissions displacement results for the All-Island system, by fuel source, 2012



A total of 72% of the quantity of fossil-fuel savings attributable to wind generation is due to the displacement of gas, and the remaining 28% to the displacement of coal. In terms of CO_2, gas displacement is responsible for 61% of the CO_2 reduction and coal responsible for 39%.

However, in relation to fossil-fuel savings attributable to overall renewable generation, a greater diversity of fuel displacement arises: gas is responsible for 78% of the quantity of savings, coal for 20% and peat for the remaining 2%. The latter figure is due to the displacement of peat through co-firing with biomass.

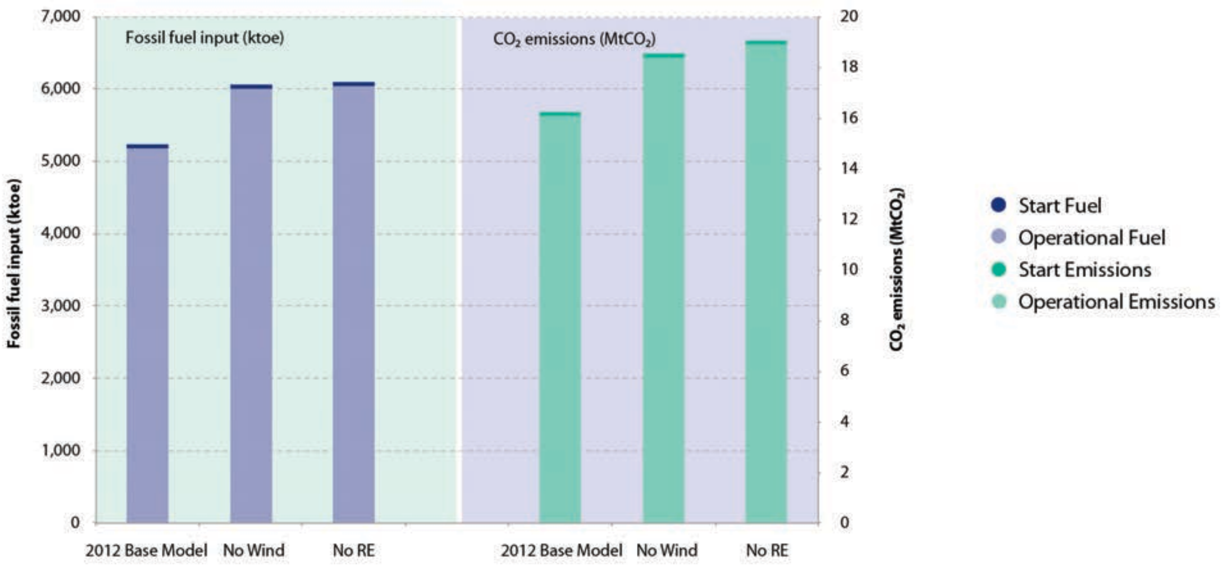
Of the associated CO_2 reduction arising from all renewable generation, gas accounts for 68%, coal 29% and peat 3%.

Each unit of renewable electricity generation displaced 1.53 units of fossil-fuel inputs. Average CO_2 displacement intensity was 0.43 tCO_2/MWh.

5.4 Operational and start-up fossil-fuel use

Figure 9 shows the fossil-fuel use and associated CO_2 emissions in the 2012 Base Model and the No Wind and No RE scenarios. This distinguishes between operational fuel use for electricity generation and fuel use for start-up purposes. It shows that fossil-fuel use due to start-ups is a very small proportion (1%) of overall fossil-fuel use for electricity production in all cases.

Figure 9: All-Island system: Operational and start-up fossil-fuel use and associated CO_2 emissions in the 2012 Base Model and scenarios



In each scenario, fossil-fuel use due to start-ups accounts for 1% of overall fossil-fuel use for electricity production.

5.5 Total electricity system efficiency versus individual fossil-fuel generator efficiencies

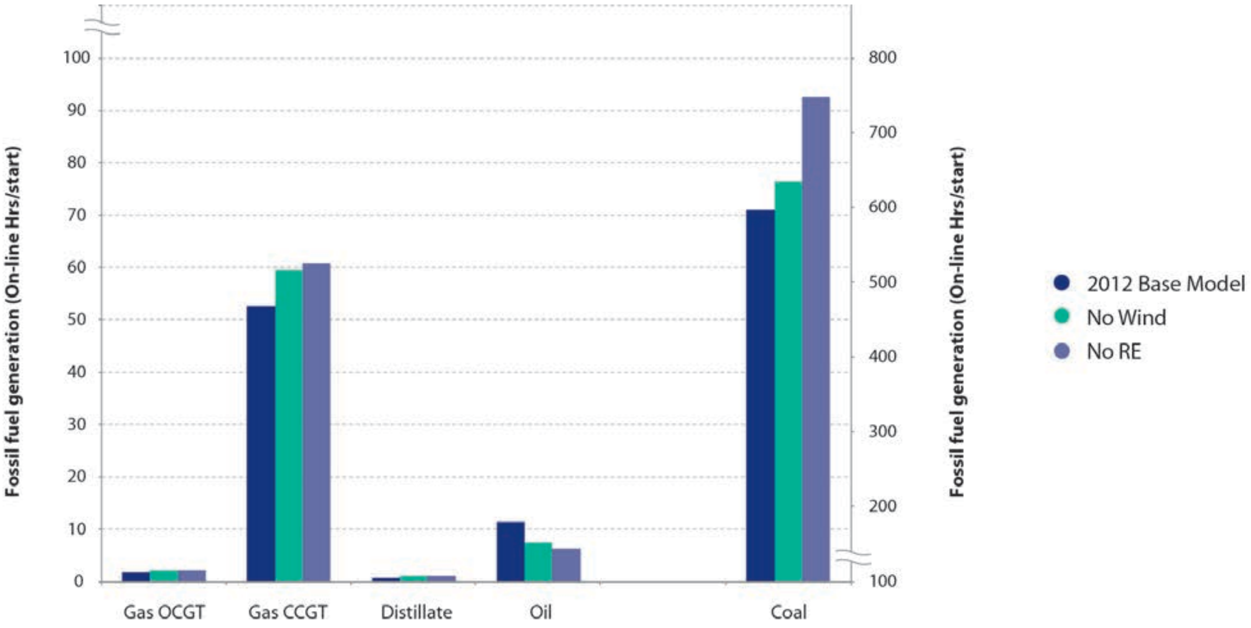
The overall system efficiency indicates how much primary fuel energy input is required to meet electricity demand. Thermal generators (from fossil-fuel or biomass) produce electricity through combustion which entails efficiency losses. In contrast, wind and hydro electricity generators do not produce electricity through combustion processes, and thus increase the overall system efficiency when generating.

Within this overall improvement in system efficiency, the efficiency of individual fossil-fuel generators can be reduced due to renewable sources such as wind as they may spend less time online for each time they start, change output more often and run at less efficient output levels.

Cycling of fossil-fuel generation

Figure 10 shows the amount of time fossil-fuel generators within the All-Island system spent on-line for each start. Wind electricity generation reduces the amount of time coal units spend on-line for each start. As a result coal generators use more fuel for start-ups in the No Wind and No RE scenarios. For each start, gas CCGT units also spend less time on-line with wind generation on the system but the difference is much less pronounced than for the coal units as the marginal gas plant tends to cycle frequently in response to demand variability under all scenarios.

Figure 10: On-line hours per start-up for fossil-fuel generators in the 2012 Base Model and scenarios, for the All-Island system



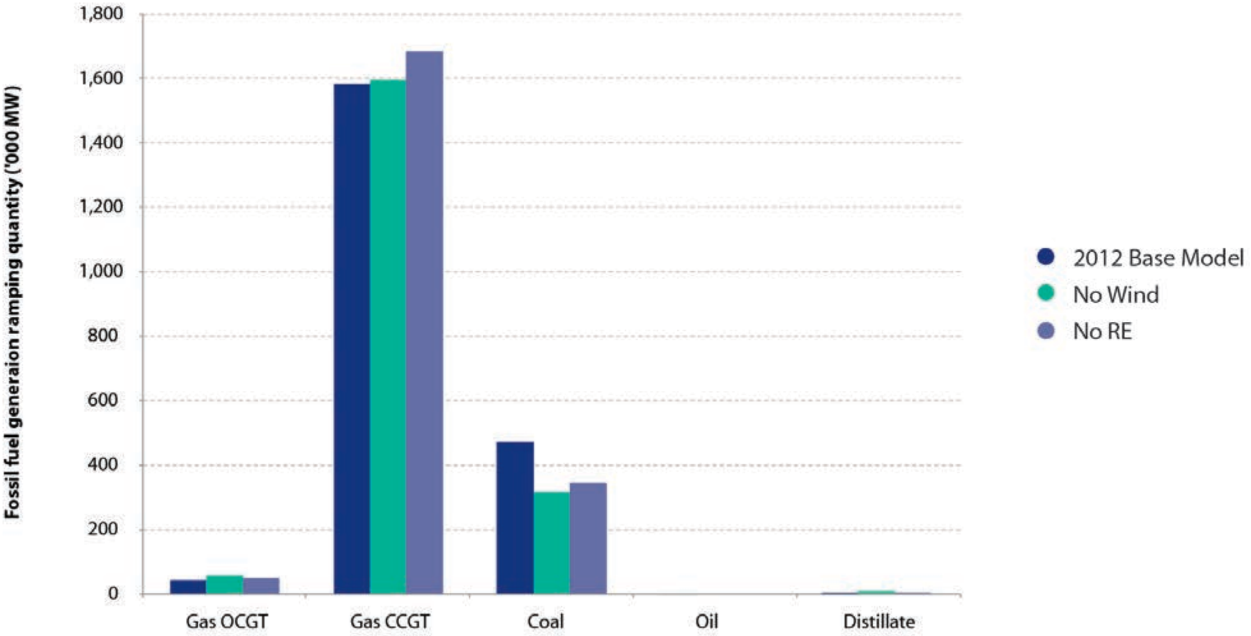
Coal and gas generation spend less time online for each start with renewable energy in the system.

Ramping of fossil-fuel generation

Generators are sometimes required to increase output and at other times to reduce output in response to changing system conditions. Generator response capabilities are known as ramp-up and ramp-down. The different technology types differ in the speed with which they can change output, measured as MW/minute. Output changes require more input fuel to increase electricity output. Figure 11 shows the total cumulative MW of ramping in year 2012 for the All-Island system, for each scenario.

Overall, the total ramping in the No Wind and No RE scenarios is respectively 6% and 1% higher than in the 2012 Base Model. The total quantity of ramping in coal generation is higher with renewable electricity on the system. In contrast, gas CCGTs vary their output by a lesser amount with renewable electricity on the system.

Figure 11: Fossil-fuel generation ramping in 2012 Base Model and scenarios, by generation type



Ramping intensity of fossil-fuel generation

Additional variability over short timeframes can challenge the ramping capabilities of individual generators and result in a requirement for more units to be online to cover difficult ramping periods. Deane et al. developed the 'ramping Intensity' metric that can evaluate this impact.[48] The ramping intensity is defined as the total sum of ramping output throughout the year for all units, divided by the total ramping-up time for those units. A high ramping intensity signifies that fossil-fuel generators change output more rapidly and/or by a greater amount.

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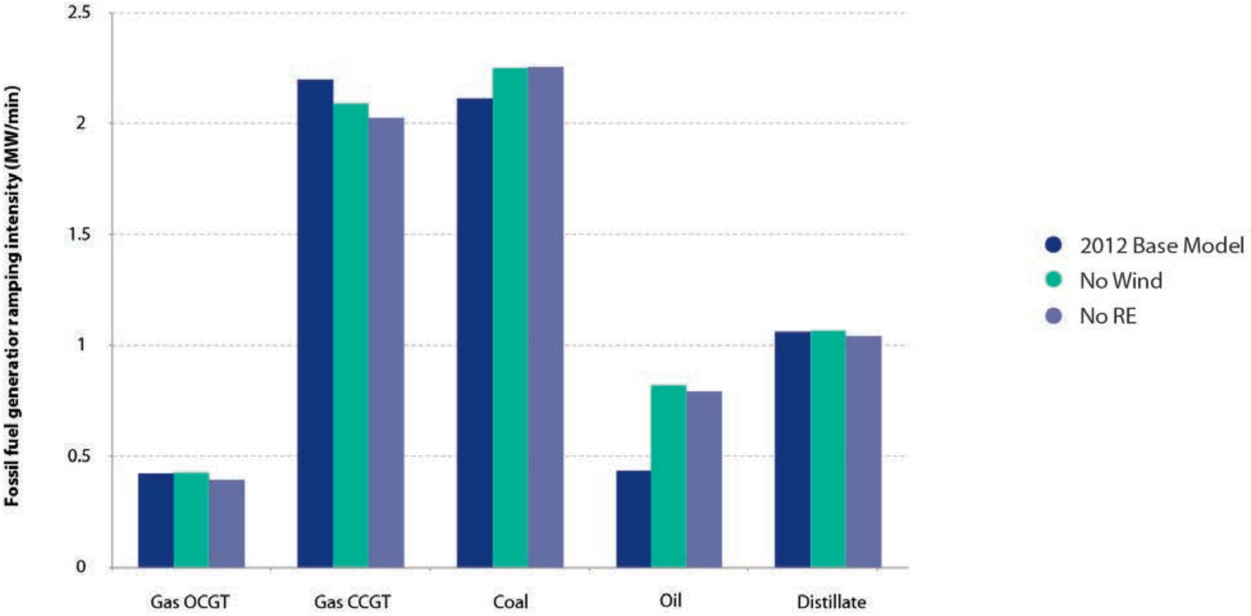
[48] Deane, J.P., Drayton, G. and O'Gallachóir, B.P. (2013), 'The impact of sub-hourly modelling in power systems with significant levels of renewable generation', Applied Energy Journal, Vol. 113, pp.152-158.

Figure 12 shows the ramping intensities across each scenario in 2012.

Figure 12: Ramp intensity by fossil-fuel generation technology for each scenario, 2012

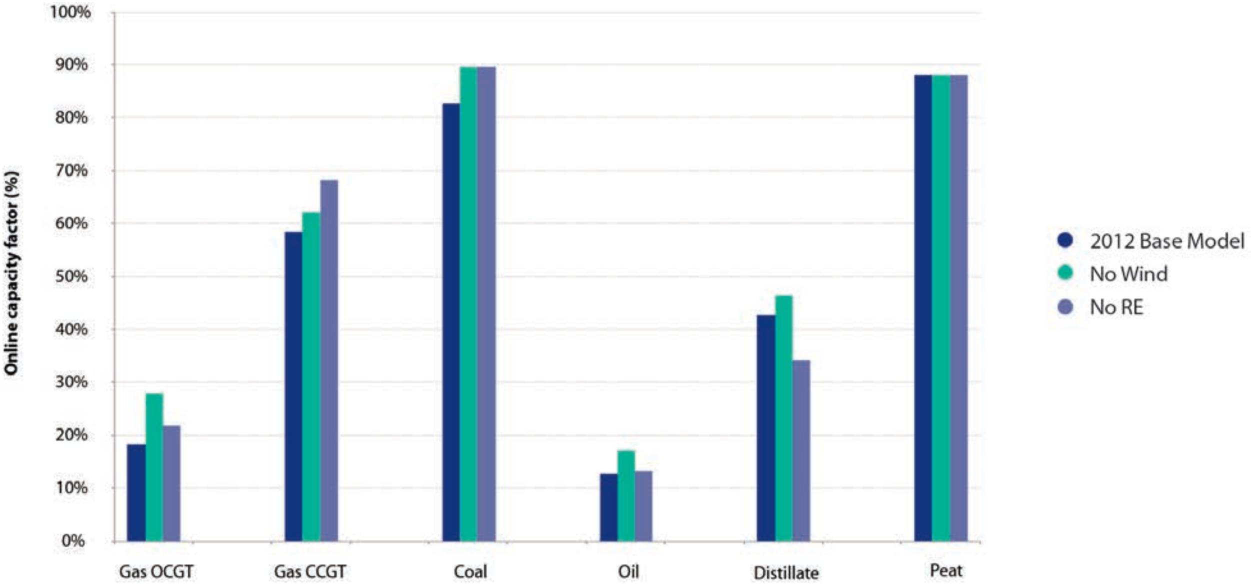


This shows that gas CCGT generators ramp more intensely with renewable electricity on the system whereas coal units ramp less intensely.

On-Line capacity factor of fossil-fuel generators

The operating efficiency of fossil-fuel generators tends to be highest when these units operate close to or at maximum output. At lower outputs such generators tend to see a reduction in their efficiency. Figure 13 shows the average output of on-line generators in 2012 as a percentage of available capacity for each fossil-fuel technology type.

Figure 13: On-line capacity factor of fossil-fuel as % of available output, for each scenario, All-Island system 2012



Gas CCGT and coal generators are responsible for the vast majority of fossil-fuel generation. With renewable electricity on the system these units tend to operate at lower output levels.

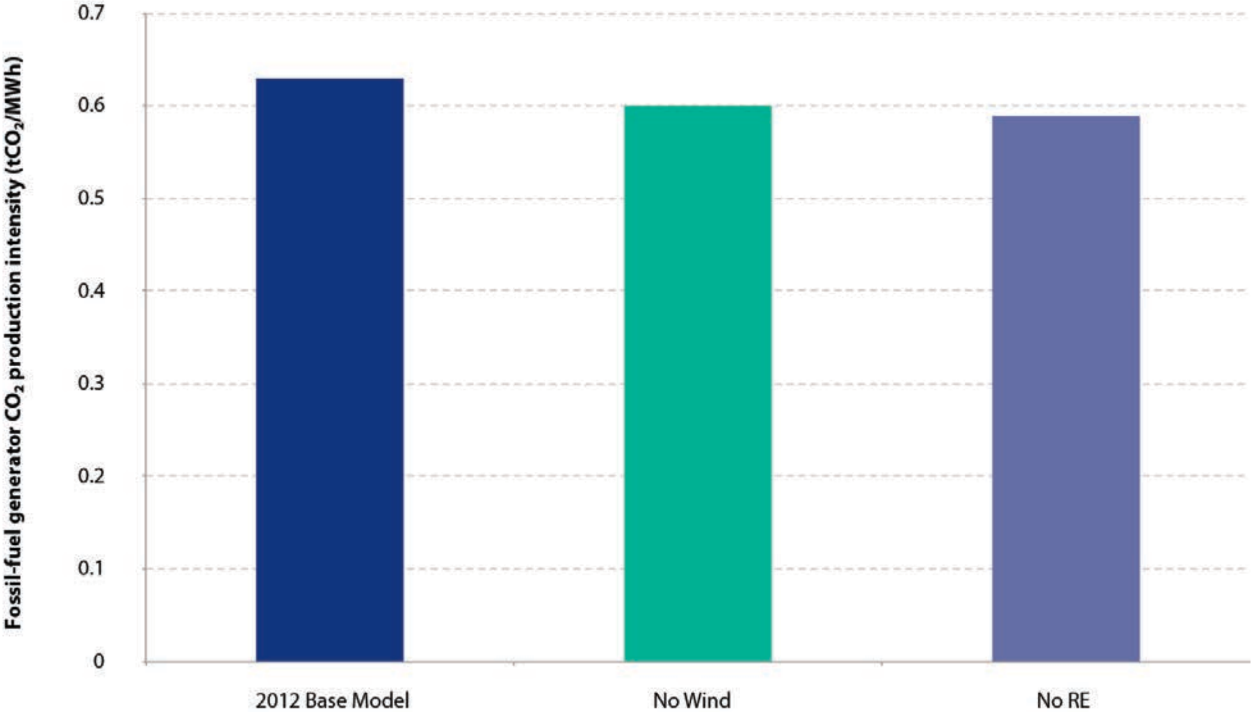
Coal and gas CCGT generator ran at lower outputs with renewable electricity generation on the system

Combined impact on CO_2 emissions

Figure 14 shows the combined impact of cycling, ramping and on-line capacity factors on the average emissions intensity of the individual fossil-fuel units across the scenarios.

With the actual level of renewables on the system in 2012 (the Base Model case), the CO_2 emissions intensity of fossil-fuel generators is 5% higher than in the No Wind scenario and 7% higher than in the No RE scenario.

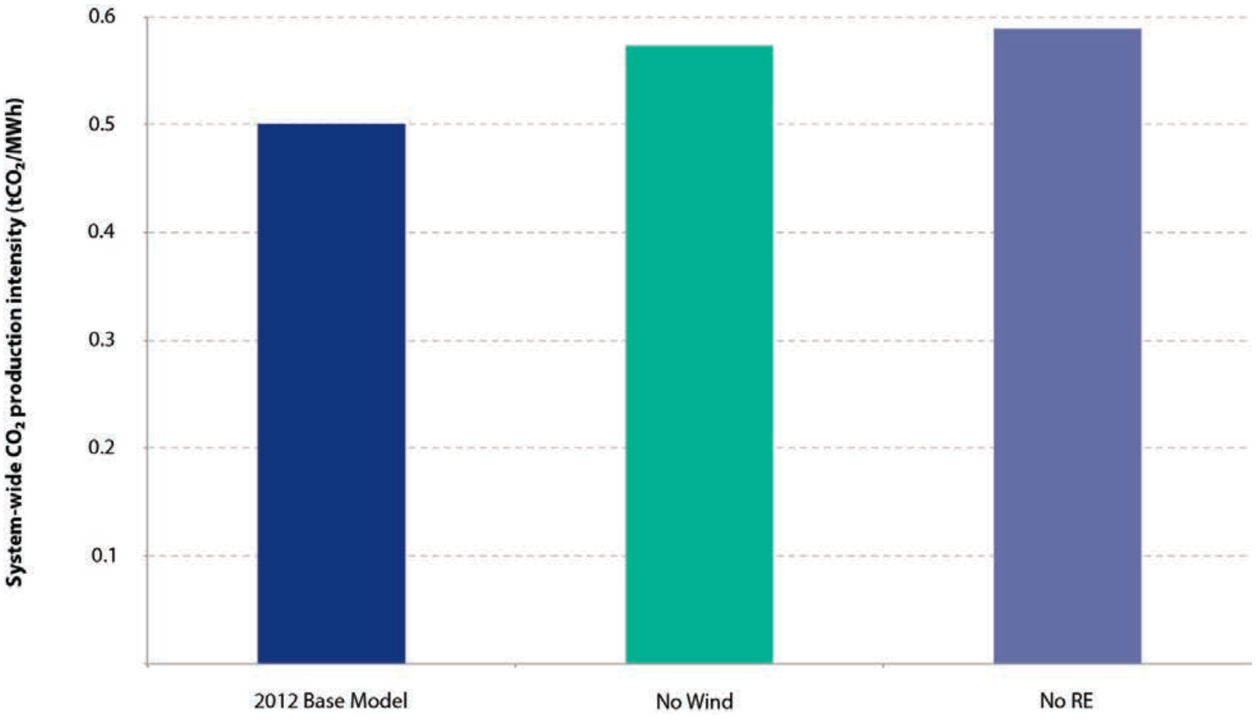
Figure 14: Overall average CO_2 intensity of fossil-fuel units, All-Island system 2012



Despite the increase in emissions intensity for individual fossil-fuel generators, the 20% reduction in total fossil-fuel generation (Section 5.2) means the total 'bottom line' emissions intensity (Section 5.3) is reduced.

Figure 15 shows that the levels of wind on the system in 2012 had the effect of reducing the total electricity system emissions intensity by 12% relative to a case where all wind generation was removed, and the overall level of renewables on the system in 2012 had the effect of reducing the system emissions intensity by 15% relative to a case where all renewable generation was removed.

Figure 15: Total CO_2 emissions intensity for All-Island electricity system (generation from fossil-fuel and renewable sources) – all scenarios



While the CO_2 emissions intensity of fossil-fuel generation, measured as tCO_2/MWh, is 7% higher with renewable electricity generation on the system, the 'bottom line' system wide CO_2 emissions intensity is 15% lower due to renewable electricity on the system.

5.6 Seasonal impacts

The level of fossil-fuel displacement due to renewable energy varies with changes in seasonal demand and system conditions. Lower demand in the summer months lowers the average cost of the generating plant required to meet demand. During these periods in 2012 less expensive units, such as coal in RoI, are more likely to be displaced than at other times of the year. In months with higher demand, mid-merit order gas units are more likely to see lower running duties as a result of renewable electricity generation. In addition, the generator mix is determined by the availability of generators which changes over the year as generators go off-line for planned maintenance or breakdown.

Figure 16: Simulated 2012 All-Island quarterly primary energy requirement, by scenario

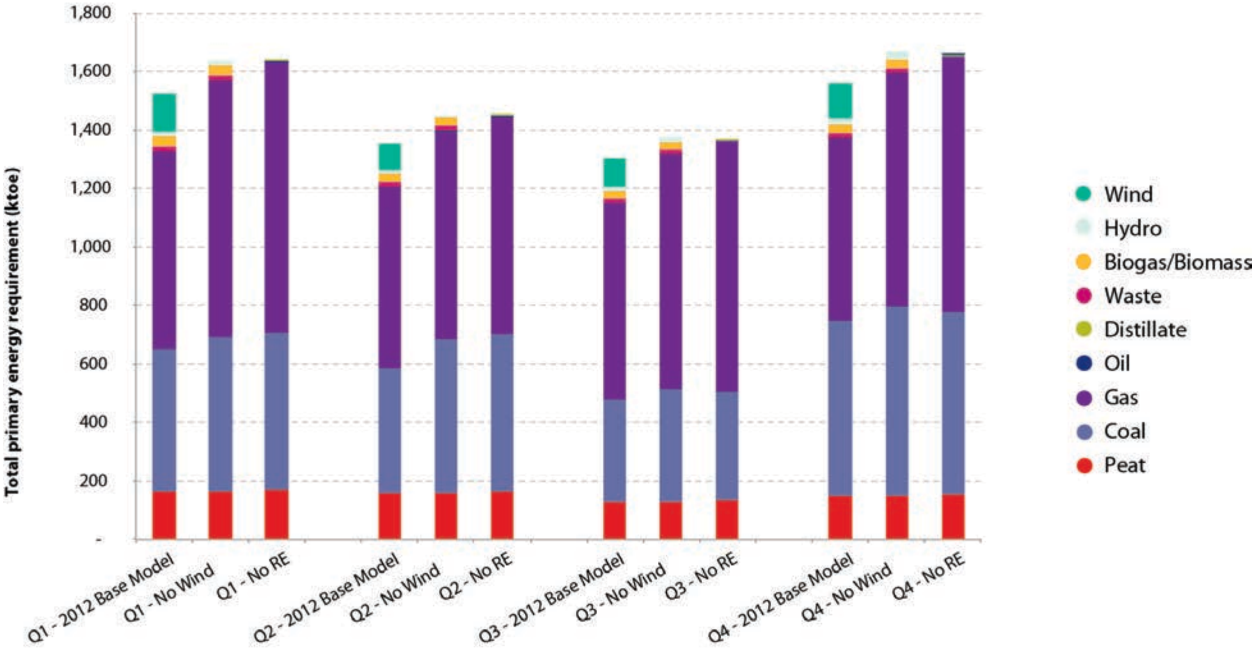
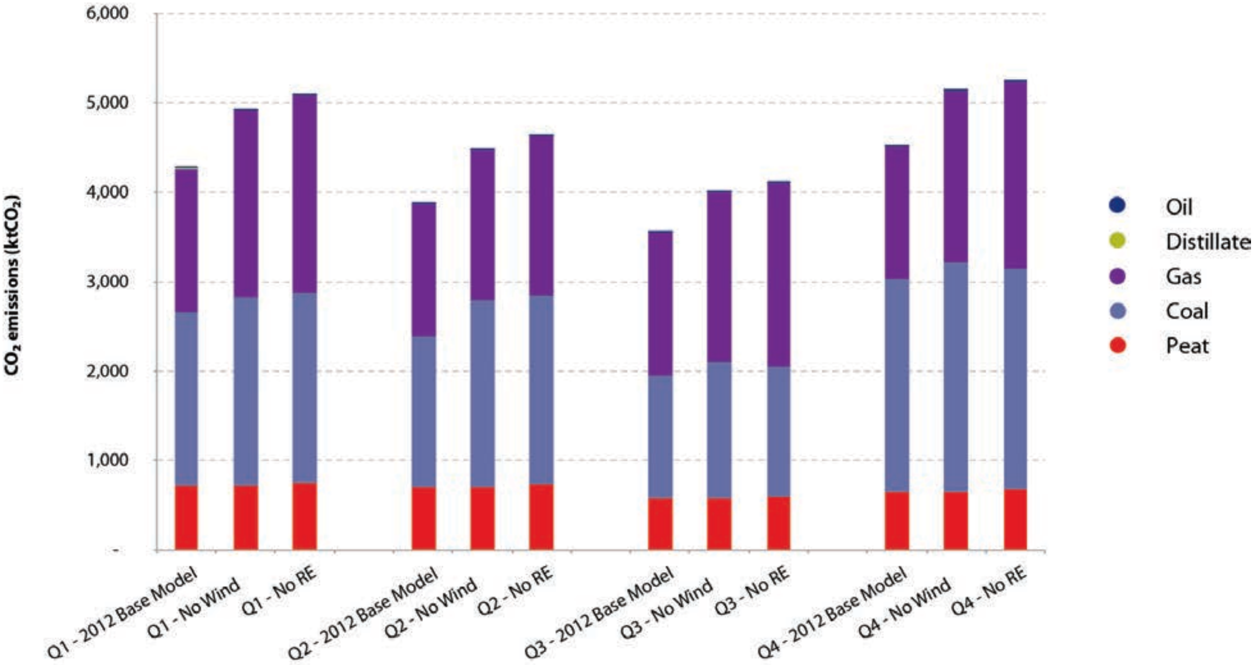


Figure 17: Simulated 2012 All-Island quarterly CO₂ emissions, by scenario



All of the scenarios show higher energy and emissions early in the year when system flexibility was lower and electricity demand was higher. 'Must-run' peat maintains a relatively constant output throughout the year. The electricity generated by renewable energy displaces gas as the marginal fossil-fuel unit, but also some of the lower-cost coal. Coal tends to be displaced at times when the system is too constrained to allow for a further reduction in the output from gas units and at times of high penetrations of wind energy.

Renewable electricity generation has the largest displacement impact at the times of highest demand early and late in the year. The capacity margin of the system in the early part of the year is lowest and the capacity factor of wind generation is highest, averaging over 45% in January and over 33% in February. Likewise, the available hydro resource is highest at these times. During Q2 and Q3 the displacement impact of renewable electricity was lowest when the capacity factor of wind and the available hydro resource was lowest.

As the system conditions change across the year, the amount and type of fossil-fuel displacement varies.

5.7 The Single Electricity Market (SEM) and RoI/NI fossil-fuel generation and CO_2 emissions

Table 4 outlines the CO_2 emission savings associated with renewable electricity generation, allocated between the RoI and NI regions of the All-Island electricity system.

For the All-Island system, the displacement intensity is estimated at 0.46 tCO_2 for each MWh of output from wind, and an average of 0.43 tCO_2/MWh of overall renewable electricity output.

Table 4: CO_2 emissions savings

	Savings from Wind Generation		**Savings from RE Generation**	
System	**CO_2 Savings (tonne)**	**CO_2 Savings (tonne/MWh)**	**CO_2 Savings (tonne)**	**CO_2 Savings (tonne/MWh)**
ROI	1.51	0.37	1.94	0.35
NI	0.82	0.80	0.91	0.81
All-island	2.33	0.46	2.85	0.43

As seen in Table 4, the displacement in 2012 per unit of electricity generation in RoI tends to be lower than in NI. The higher proportion of the less carbon-intensive gas in RoI and the higher proportion of the more carbon-intensive coal in NI are the key drivers for this, but the trade of electricity between the two jurisdictions also has some impact. Examining the CO_2 reduction in NI and RoI separately gives some insight into the impact electricity trade through the SEM on emissions accounting.

Table 5 shows how thermal generation output would change in both jurisdictions, in response to removal of wind generation and of all renewable generation from the system. The removal of 1,028 GWh of wind generation in NI would result in fossil-fuel generation increasing by 1,166 GWh. The additional fossil-fuel generation in NI means that less fossil-fuel generation (3,965 GWh) is required in RoI to replace the absence of 4,094 GWh of renewable electricity.

Table 5: Fossil-fuel generation increase in RoI and NI in 2012 with wind and renewable electricity removed (GWh)[49]

	No Wind Scenario - Change in Generation			**No RE Scenario - Change in Generation**	
GWh	**Renewable**	**Fossil-fuel**		**Renewable**	**Fossil-fuel**
RoI	- 4,094	3,965		- 5,277	5,127
NI	- 1,028	1,166		- 1,125	1,289

In the No RE scenario, the increase in fossil-fuel generation is more in line with the reduction of renewable generation in the relative jurisdictions. The sharing of the displacement benefit is sensitive to the assumptions on the location of the replacement fossil-fuel capacity required to maintain equivalent security standards across scenarios.

The flow of electricity trade between RoI and NI varies from year to year depending on the relative fuel prices and their impact on the merit order, the availability of system assets and the prevalence of network constraints. The simulated outcome is thus specific to the 2012 conditions.

The benefit of the fuel and CO_2 cost savings accrue to all consumers in Ireland's Single Electricity Market (SEM), reflected in the common wholesale market price for consumers in RoI and NI. Emissions are counted from individual generator sites under the emission accounting rules. This means that some of the CO_2 reductions due to renewable electricity generation in one jurisdiction may show up in another. This is the case in the SEM due to the RoI and NI emissions counting towards separate national targets. Trade across the East West and the Moyle

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[49] Differences in pumped storage generation between scenarios results in small differences between the total fossil-fuel generation increases and the total renewable electricity reductions on an All-Island basis

interconnector can lead to the transfer of emission reduction benefits from GB to the SEM area and vice versa. In 2012 the SEM area was a net importer of electricity from GB.

While the flow of electricity trade between RoI and NI varies according to several factors, the benefits of the fuel and CO_2 cost savings accrue to all consumers in Ireland's Single Electricity Market.

6. Summary

This analysis incorporates a dispatch modelling method based on the system conditions that prevailed in the All-Island electricity system in 2012. Two scenarios have been examined, to assess the respective impacts of removing wind and renewable electricity capacity from the system under otherwise the same 2012 conditions.

The overall findings are consistent with the findings of studies of operating conditions in Ireland and elsewhere which have shown that variable renewable generation can be effectively integrated into the electricity system and yield clear energy and emissions saving benefits.

The use of the dispatch model method is the most detailed and comprehensive of the available methods of analysis, in terms of representing real time operation of the electricity system. This has enabled the net displacement effects on fossil-fuel use and CO_2 emissions to be quantified by taking account of all significant dynamic factors and their contributions to these net effects.

The analysis based on this method finds that fossil-fuel generation increased by 26% on an All-Island basis in year 2012 with renewable electricity removed from the system. Of this, the removal on wind accounts for a 20% increase in fossil-fuel generation. Total renewable electricity generation reduced fossil-fuel use by 1,043 ktoe and abated 2.9 million tonnes of CO_2 emissions, with wind responsible for a reduction of 826 ktoe and abatement of 2.3 million tonnes of CO_2 emissions.

Of the saving in fossil-fuel, 78% accrues through the displacement of natural-gas generation, primarily from combined-cycle gas turbines (CCGTs), with 20% fuel savings accruing through the displacement of coal and a reduction in peat use accounting for 2%, arising from biomass co-firing. Of the CO_2 emissions displaced, coal and peat make up a relatively larger share (32%) due to the higher carbon content of these fuels.

Additional cycling and ramping and reductions in online capacity factors due to wind generation in particular reduce the efficiency of individual fossil-fuel generators, and the emissions intensity of these units is increased by up to 7%. However, this reduction in individual efficiency is small in the context of the improvement in overall system efficiency due to the displacement of fossil-fuel generators and their associated combustion efficiency losses.

Total electricity system efficiency decreases by 18% with renewable electricity removed from the system as a result of the increased fossil-fuel combustion and the associated thermal inefficiencies.

The value of the fossil-fuel displacement through the reduction in fossil-fuel generation in the Republic of Ireland is €245 million, with associated CO_2 emissions savings of €15 million. Wind generation displaces fossil-fuel worth €177 million and CO_2 emissions worth €11 million.

Annex 1. Renewable Electricity Displacement Impact Estimation – Methodological Summary

The complexity of the electricity system makes estimation of fossil-fuel and CO_2 emissions an intricate task. The parameters discussed above can vary significantly across short timescales and no 'natural experiment' exists to facilitate analysis. An ideal natural experiment would involve two identical systems having the same generation portfolio, demand profile, forecast accuracy, dynamic fuel price changes, generator and interconnector availability, interconnector trade flows and network constraints in each time period across a year. The CO_2 emissions on the system with renewable energy generation could be compared to the system without any renewable energy in order to determine the impact.

In the absence of this ideal, three main methods have been used to show the impacts of renewable energy on fossil-fuel displacement and CO_2 emissions reduction. These vary in complexity and approach. The methods are outlined below.

Primary Energy Equivalent (PEE) method

The Primary Energy Equivalent (PEE) method equates the energy produced from renewable sources with the amount of primary fossil-fuel energy required to generate the same amount of electricity by making assumptions on the type of fossil-fuel renewable energy is likely to replace and the conversion efficiencies of this electricity generation.

The International Energy Agency defines the primary energy content of fossil-fuels and combustible renewable sources as the calorific content of the fuel.[50] For wind, hydro and solar the primary energy input is equal to the quantity of electricity generated, so expansion of these sources of energy enhance the overall measured fuel efficiency of the electricity system. Other electricity generation types rely on the combustion of fuel to produce electricity, and suffer from conversion losses. Typically, between 25% and 55% of the energy content of the fuel input is converted into useful electricity and the remaining 45% to 75% is lost.

The PEE approach requires an assumption of the efficiency of the fossil-fuel plant being displaced by renewable electricity sources and the type of fuel used. A weighted average approach can be used by assuming that fossil-fuel generation is displaced in proportion to the individual shares in the fossil-fuel mix.[51] This method may over- or underestimate the fossil-fuel and CO_2 displacement as the impact of renewable energy tends to be focused on a subset of the generation portfolio, typically the more expensive or *marginal* generators. As fuel costs are the main contributor to the cost of generation, the marginal units tend to be of the same fossil-fuel type. Using the proportional approach spreads the displacement effect over more fuel types and does not account for the marginal displacement effect.

Kartha et al. suggest three possible options to estimate marginal fossil-fuel displacement: the *operating margin*, the *build margin or* the *combined margin approach*.[52] Low-cost and must-run generators are assumed to be unaffected by the addition of renewable capacity. The system average of the remainder of the generation portfolio determines the *operating margin*. The *build margin* is based on the historical data for the generation – the weighted average of the most recent 20% of plant additions to the portfolio or, if the data is inadequate, using a proxy plant method. Implementation of the proxy plant method in Ireland has tended to assume gas-fired CCGT as the proxy plant.[53] [54] The *combined margin* approach combines the previous two methods.

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[50] International Energy Agency (2007), *Energy Balances of OECD Countries 2004-2005*: http://www.iea.org/

[51] SEAI (2004), *Renewable Energy in Ireland – Trends and Issues 1990–2002*: http://www.seai.ie/Publications/Statistics_Publications/EPSSU_Publications/

[52] Kartha S., Lazarus M. and Bosi M., (2004), 'Baseline recommendations for greenhouse gas mitigation projects in the electric power sector', *Energy Policy* 32, 545-566.

[53] Ó Gallachóir B. P., O'Leary F., Bazilian M., Howley M. and McKeogh E. J., (2006), 'Comparing Primary Energy Attributed to Renewable Energy with Primary Energy Equivalent to Determine Carbon Abatement in a National Context'. *Journal of Environmental Science and Health,* Part A: Toxic/Hazardous Substances and Environmental Engineering, vol.41, No. 5.

[54] SEAI, (2014), *Renewable Energy in Ireland 2013*: http://www.seai.ie/Publications/Statistics_Publications/Renewable_Energy_in_Ireland/

SEAI[54] previously estimated the fuel displacement from renewable electricity generation using the *operating margin approach*. The associated emissions displacement was estimated as 2.42 million tonnes of CO_2. This represents a displacement rate equalling 0.489 tCO_2/MWh[55] of wind-generated electricity.

The data and computational requirements of the PEE method provide a relatively straightforward and understandable way to estimate fuel and emissions displacement. However, the simplifying assumptions can introduce some inaccuracy. The PEE method cannot account for any additional dynamic changes that renewable electricity may introduce into the system. Fossil-fuel units may operate in less efficient modes and may be subject to additional start-ups.

Empirical statistical methods

Empirical methods have applied statistical tools to data on emissions production, changes in electricity demand, renewable electricity generation, and weather conditions. By establishing the marginal reduction in emissions as the share of renewable electricity rises, inferences are made on the displacement effectiveness of renewable electricity.

This method seeks to isolate the impact of renewable electricity generation by accounting for variables that are statistically related to emissions. Kaffine et al. specified a model that controlled for hourly wind energy output, hourly load, average hourly temperature, the expansion of wind capacity and the day-of-the-week changes in electricity demand.[56] They found that marginal emissions reduction due to wind energy in the Texas region was 0.523 tCO_2/MWh of wind generation. The paper highlights the sensitivity of the results to the makeup of the generation portfolio in operation over a given period. In a large system, such as the Texas system, plant and interconnector outages are averaged over a large generation portfolio. In a small system like the All-Island system, an outage of a single plant can significantly alter the generation portfolio and affect system flexibility and the fossil-fuel and emissions displacement estimates for a given period.

A similar method has been used for the Republic of Ireland by Wheatley.[57] This model accounts for wind generation and system demand only and how these relate to changes in plant-specific emissions. This excludes possible influencing factors such as the impact of network constraints, and unexpected generator outages. Excluding these allows the model to interpret changes in plant emissions as being caused by changes in wind output when other dynamic factors may also be influencing emissions at the same time. The 2011 period examined in the analysis was exceptional due to the reduction in system flexibility. The pumped storage capacity was offline for maintenance and the interconnection capacity was offline. The paper suggests that the marginal displacement due to wind energy in 2011 was 0.28 tCO_2/MWh.

O'Mahoney and Denny used similar techniques to estimate the merit-order effect of wind generation in the Irish electricity market. The model specifically seeks to identify the cost reduction due to wind in the Irish market through the offset of thermal price setting generation. The explanatory variables include demand[58] adjusted for interconnector trade and 'must run' thermal units, wind generation, fuel price and the total availability of generators on the system. The paper finds that the savings due to the reduced market dispatch of fossil-fuel plant was €141 million in 2009, including savings due to reductions in CO_2 emissions.[59]

Amor et al. looked at several years of data in Ontario to establish the impacts of wind generation on electricity price and GHG emissions.[60] The model specification accounts for variations in demand, wind output, baseload generation from hydro and nuclear, and output from marginal generators. The impact of network constraints is also included. The study finds that wind displacement effects are strongly influenced by the level of network constraints. The paper estimates GHG displacement in the range 0.283 to 0.394 t CO_2.

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[55] This unit signifies the savings in tonnes of CO_2 for every MWh that would have been produced by the withdrawn generation plant, i.e. wind and/or renewable generation.

[56] Kaffine D.T., McBee B.J. and Lieskovsky J. (2012) 'Emissions Savings from Wind Generation in Texas', *The Energy Journal*, vol.34, No.1. pp.155-175.

[57] Wheatley J. 'Quantifying CO_2 savings from wind power', *Energy Policy Journal*, vol. 63 (2013) pp. 89-96.

[58] Demand and wind generation are specified as quadratic relationship to shadow price.

[59] O'Mahoney A. and Denny E. 'The Merit Order Effect of Wind Generation in the Irish Electricity Market'.

[60] Amor, M. B., Billette de Villemeur, E., Pellat, M. & Pineau, P.O. (2014). 'Influence of wind power on hourly electricity prices and GHG (greenhouse gas) emissions: Evidence that congestion matters from Ontario zonal data. *Energy*, 66, 458-469.

Cullen examined the impact of wind in the Texas system between 2005 and 2007.[61] Wind output, demand, network congestion and changing efficiencies of fossil-fuel generators are included. As the generation output of fossil-fuel generators influences future output, due to the additional costs and inefficacies involved in starting up a generator that has been offline for longer period of time, Cullen includes lagged data for these variables to help explain the generator output. Generator outages and fossil-fuel spot prices are also included as well as controls for generator pricing strategies. The relationship between these variables is expressed as linear and non-linear relationships that can capture some of the more nuanced effects of wind generation of fossil-fuel generator output. The results show that wind tends to displace natural-gas CCGTs but also displace less efficient natural-gas generation from OCGTs. Overall the CO_2 reduction is estimated as 0.43 tCO_2/MWh.

Forthcoming analysis by di Cosmo and Malaguzzi Valeri examines the displacement impact of wind between 2008 and 2012 in the All-Island system. The estimation relates changes in power-plant emissions to variations in the output of wind generators, fluctuations in demand and changes in other influencing factors. Findings show a displacement effect that varied across individual years due to changing system conditions affecting the generation mix and system flexibility.

An empirical method that includes a full specification of the explanatory factors that contribute to emissions of the electricity grid has the potential to provide some insight into the impact of renewable electricity generation on emissions reduction. Historical data is required for several influencing variables over short-time horizons of several years to better understand the historical period examined. The nature of the relationship between the explanatory variables and emissions can be difficult to identify, with the possibility that the influence of some factors is non-linear and lagged in time.

The empirical models tend to focus on what the past displacement impact of renewable electricity was, with models specified to fit the available data as closely as possible. Models capable of predicting and explaining the impact of the various factors require different specifications that include the influence of network constraints, forecasting uncertainty, demand in preceding periods, must-run generators and the availability and flexibility of plant in the generation portfolio. Amour et al. point out that, due to the complexity of electricity systems, empirical methods are unable to fully explain the reasons for observations and that the strength of empirical models lies in their ability to observe an emissions reduction impact in historical data.

Detailed simulation: Dispatch models

The dispatch model method uses detailed information on components of the electricity system to establish a representation of how the electricity system operates. Data and information on the full range of influencing factors prevailing over a particular historic period or that may be in place in the future may be included. Scenario analysis compares identical systems with and without renewable electricity generation. Kartha et al. describe this approach as “the most sophisticated and accurate operating margin approach” for establishing CO_2 displacement impacts.[52] Dispatch models, unlike the PEE and empirical methods, are generally used to investigate possible future effects of changing electricity system conditions, including expansion of renewable generation capacity.

The system characteristics and the prevailing external conditions are identical across scenarios, apart from the level of renewable energy generation. By comparing the fuel use and resultant CO_2 emissions over the scenarios, the effectiveness of renewable electricity generation in displacing fossil-fuel can be estimated. The models typically arrange the generators into a merit order, from the lowest-cost generator to the highest-cost, and dispatch the least-cost arrangement of generators required to meet demand, subject to a range of constraints (system operation requirements, network constraints, generator capabilities). These models can optimise dispatch for a given period by looking at how system conditions are likely to change over the coming periods and can incorporate the impact of any forecasting uncertainty and variability. A number of studies dealing with the All-Island system and other electricity systems have used this method, some of which are discussed below.

EirGrid conducted a study in 2007[62] that updated earlier analysis[63] using the dispatch model methodology applied to future renewable electricity deployment scenarios. Four electricity system scenarios were examined: a

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[61] Cullen, Joseph. ‘Measuring the environmental benefits of wind-generated electricity’, *American Economic Journal*: Economic Policy 5.4 (2013): 107-133.

[62] EirGrid (2007), ‘Wind Powered Generation: An analytical framework to assess generation cost implications’: http://www.eirgrid.com/media/Wind%20power%20generation%20analytical%20report,%202007%20update.pdf

no-wind reference case and three scenarios with increasing levels of wind-power generation. The impact of cycling was examined as part of the analysis. It showed that wind energy displaces between 906 and 974 tCO_2/MW of wind energy installed. This is equivalent to between 0.260 and 0.502 tCO_2/MWh. Denny and O'Malley[64] examined the impact of wind generation on power system operation and emissions reduction over a number of scenarios for installed wind capacity. The analysis showed that the addition of wind capacity reduced emissions. A later paper by Denny and O'Malley[65] confirmed this effect of fossil-fuel and CO_2 displacement, including the impact of any additional cycling, estimating a fuel displacement value of approximately €215 million at today's level of installed wind capacity and 2006 fossil-fuel prices. The All-Island Grid Study examined the impact of five renewable electricity development scenarios for the 2020 power system. The analysis shows CO_2 savings due to renewable energy.[66] Two separate studies by the Economic and Social Research Institute (ESRI)[67] and the Commission for Energy Regulation (CER)[68] examining 2020 impacts found similar CO_2 reduction trends.

The National Renewable Energy Laboratory (NREL) outlined in a recent report[69] a dispatch method used to analyse the effect of renewables (wind and solar) on thermal plant cycling. Using PLEXOS power market simulation software, a dispatch model was created to simulate scenarios with various levels of renewable penetration in the Western Grid.[70] The report found that, in a system with 33% renewable penetration, cycling had a negligible effect on CO_2 emissions, and that the total CO_2 displacement was in the range 0.489 to 0.523 tCO_2/MWh. The report also found that increasing levels of renewable electricity "can displace more traditional low-cost resources (such as coal)" as well as the marginal generation. Valentino et al. examine the emissions impact of incorporating wind energy into the electric power system in Illinois.[71] Their findings showed a reduction in CO_2 emissions for all levels of wind penetration of between 0.672 tCO_2/MWh and 0.847 tCO_2/MWh.

The All-Island and Western Grid have high proportions of less carbon-intensive gas generation. In contrast, the Illinois system is dominated by more carbon-intensive coal combustion. Renewable energy displacing less carbon gas results in a lower displacement impact than when renewable energy displaces coal. Cycling impacts are shown to have a minor overall impact when compared to the absolute 'bottom line' reduction in CO_2 emissions.

The dispatch model approach can allow detailed representation of a system, with the range of considerations relating to that system. The detailed nature of a dispatch model means it can be labour-intensive to build, and the resulting models can suffer from a lack of transparency. The results are highly sensitive to assumptions such as fossil-fuel prices or generator performance. Without an extensive validated database on generator performance and cost data, and information on system operational rules, these models are difficult to develop and review.

The generator dataset underpinning this analysis has been validated by the Commission for Energy Regulation (CER) and is publicly available. The PLEXOS modelling software is widely used in Ireland and internationally and is commercially available (and available free of charge to academic institutions)[72] and all the input data used is published by reputable sources.

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[63] ESB National Grid (2004), 'Impact of Wind Power Generation in Ireland on the Operation of Conventional Plant and the Economic Implications':
http://www.eirgrid.com/media/2004%20wind%20impact%20report%20(for%20updated%202007%20report,%20see%20above).pdf

[64] Denny E. and O'Malley M. (2006), 'Wind Generation, Power System Operation, and Emissions Reduction'. *Journal of IEEE Transactions on Power Systems*, Vol.21, No.1.

[65] Denny E. and O'Malley M. (2007), 'Quantifying the Total Net Benefits of Grid Integrated Wind'. *Journal of IEEE Transactions on Power Systems*, Vol.22, No.2.

[66] Portfolio 4 shows an emissions increase due to the assumption of new coal capacity build.

[67] S. Diffney, J. Fitzgerald, S. Lyons and L.M. Valeri, (2009), 'Investment in electricity infrastructure in a small isolated market: the case of Ireland' in *Oxford Review of Economic Policy*, Vol.25, No.3, 2009, pp.469-487.

[68] CER/NIAUR, *Impacts of High Levels of Wind Penetration in 2020 on the Single Electricity Market (SEM)* (2009).

[69] NREL (2013), 'The Western Wind and Solar Integration Study Phase 2': http://www.nrel.gov/docs/fy13osti/55588.pdf

[70] Involving the USA, Mexico and Canada.

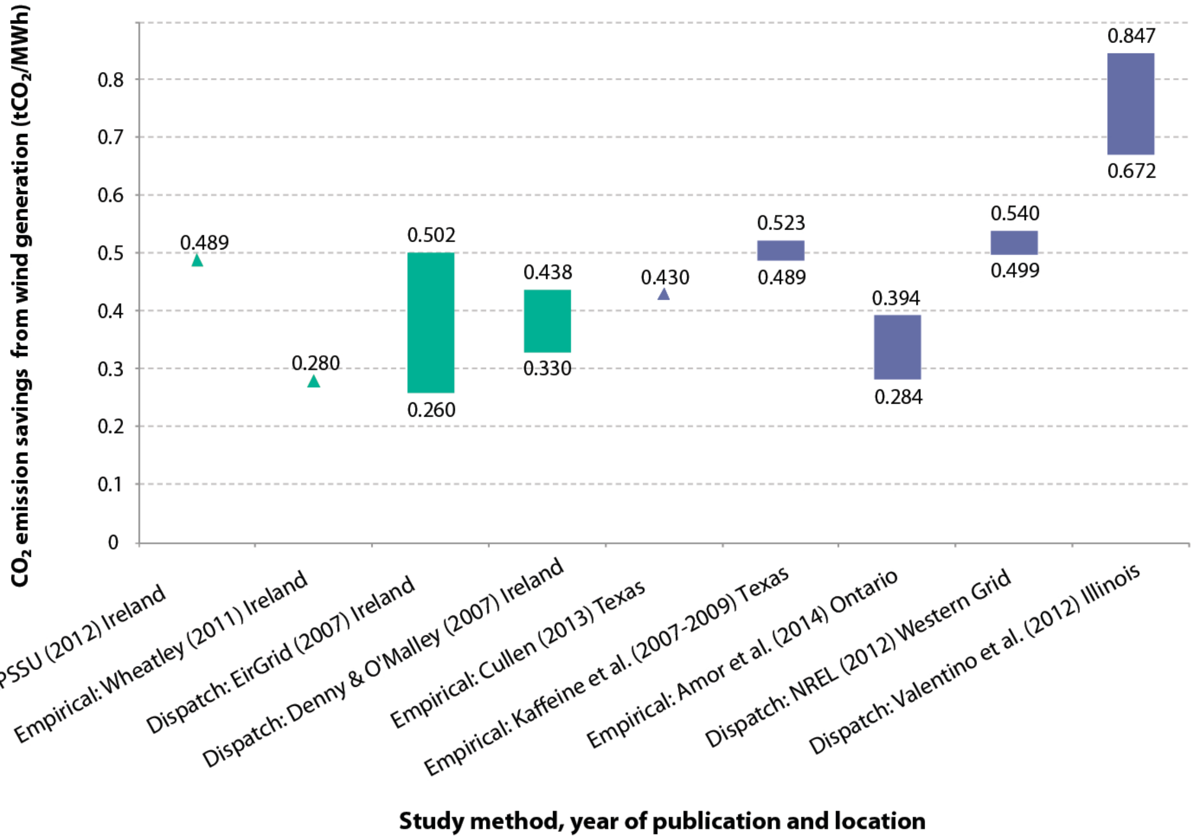
[71] Valentino L,; Valenzuela V,Botterud A,; Zhou Z,; Conzelmann G. (2012) System-wide emissions implications of increased wind power penetration. Environ Sci Technol 46(7):4200–4206

[72] The input assumptions and modelling methodology can be implemented in similar models

Some results compared

Figure A.1 shows the range of results from the various studies (PEE, empirical and dispatch) referenced above for displacement of fossil-fuel generation and associated CO_2 emissions for the All Island electricity system (shown in green) and for systems in other countries (shown in blue). For the studies pertaining to the All Island system, the overall range of emission displacement intensities, for different periods and under different scenarios, extends from 0.260 tCO_2/MWh to 0.502 tCO_2/MWh.

Figure A. 1: Comparison of CO_2 emission savings from wind generation, using different methodological approaches[73]



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[73] The estimate for EirGrid (2007) is inferred from the installed MW in the scenarios operating at a 30% load factor. Estimated from Figure 1 and Figure 4 in Denney and O'Malley (2007).

Annex 2. Input Assumptions

Fuel/CO_2

The fuel price an electricity generator pays depends on the market price of input fuels, the fuel purchasing polices of the individual generators[74] and the transport costs of delivering the fuel to the power station.[75] The fuel prices used are based on the spot market prices in 2012, along with an estimate of the transportation costs.

Transport cost is calculated using a fuel delivery calculator developed by the Commission for Energy Regulation (CER) and Northern Ireland Authority for Utility Regulation (NIAUR),[76] which shows a difference in cost for some fuels between jurisdictions. Quarterly fuel prices for gas, coal and oil 2012 are based on prices provided by SEAI's Energy Policy Statistical Support Unit..[77] Distillate prices are based on prices recorded by DECC.[78]As the All-Island system operates across different currencies, exchange rates were taken into account when using the fuel calculator.[79]

The Emissions Trading Sector (ETS) prices are based on recorded market prices averaged over each quarter of 2012.[80] Table A.1 shows the prices included in the model for fuel and CO_2 in each quarter of 2012.

Table A.1: Quarterly fuel and CO_2 prices for 2012

	Fuel Price (€/GJ)			
	Q1	**Q2**	**Q3**	**Q4**
Gas (NCV) - RoI	7.98	7.69	7.70	8.57
Gas (NCV) - NI	8.01	7.73	7.74	8.60
Coal - RoI	3.1	2.7	2.76	2.65
Coal – NI	3.51	3.11	3.17	3.06
Distillate - RoI	21.99	21.62	22.25	20.86
Distillate – NI	21.63	21.26	21.9	20.5
Oil – RoI	17.55	16.45	17.07	15.75
Oil - NI	17.2	16.1	16.72	15.41
	CO_2 Price (€/tonne)			
	8.01	7.07	7.55	7.18

Demand

The demand for each half-hour period in 2012 for the All-Island system is included in the model. Table A.2 shows the peak and low demands for both the RoI and NI systems, along with the annual demand in 2012. The individual peaks in the NI and RoI occur on different days in 2012, resulting in the All-Island peak being lower than the sum of the maximum demand in each jurisdiction.

Table A.2: System demand characteristics in 2012

System	**Peak Demand (MW)**	**Low Demand (MW)**	**Annual Demand (GWh)**
NI	1,726	516	8,904

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[74] Fossil-fuel purchasing strategies typically use hedging strategies to reduce the risk of fuel price volatility. This can result in short-term differences between the generator price and the spot market price for fuel.

[75] As part of the SEM generator bids are regulated by the CER to ensure the bids reflect the actual short-run marginal cost of generating power.

[76] The fuel transport calculator can be found on the CER website: http://www.allislandproject.org/en/market_decision_documents.aspx?page=6&article=cb4ee33b-a83a-47ce-956a-6cff30900495

[77] EPSSU fuel data for 2012 is based on proprietary data from the IEA on Energy Prices and Taxes .

[78] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65940/7341-quarterly-energy-prices-december-2012.pdf

[79] Euro to USD=1.33, Euro to GBP=0.84.

[80] Sourced from http://www.investing.com/commodities/carbon-emissions-opinion

RoI	4,571	1,624	25,658
All-Island	6,217	2,170	34,562

The impact of demand forecast accuracy is also included based on a typical 24-hour-ahead forecast profile for the RoI and NI system.

Generation availability

Planned and forced outages are included in the model as recorded by the market operator in 2012.[81] Scheduled outages are visible to the model ahead of time, and forced outages visible in real time. Forced outage rates are assumed to be the same across the scenarios, whether with or without variable renewable generation.[82]

Scheduled outages are concentrated over the summer and early autumn months when demand is lowest and capacity margins are highest.

Interconnection

The All-Island system is connected to Great Britain through two separate direct current interconnectors: the Moyle line from NI to Scotland and the East-West line from RoI to Wales. The actual recorded flows across these lines for each 30-minute period in 2012 are included in the model.

The Moyle interconnector capacity decreased in June due to a line fault. The Moyle interconnector can theoretically export 300 MW but is limited in operation to 80MW due to network constraints in Scotland.[83] The East-West interconnector (EWIC) was commissioned in Q4 and began commercial operation in late 2012. The interconnectors tended to import electricity in normal operation in 2012. Overall, the SEM imported 2,199 GWh of electricity from GB across the Moyle and 83 GWh across the EWIC in 2012.

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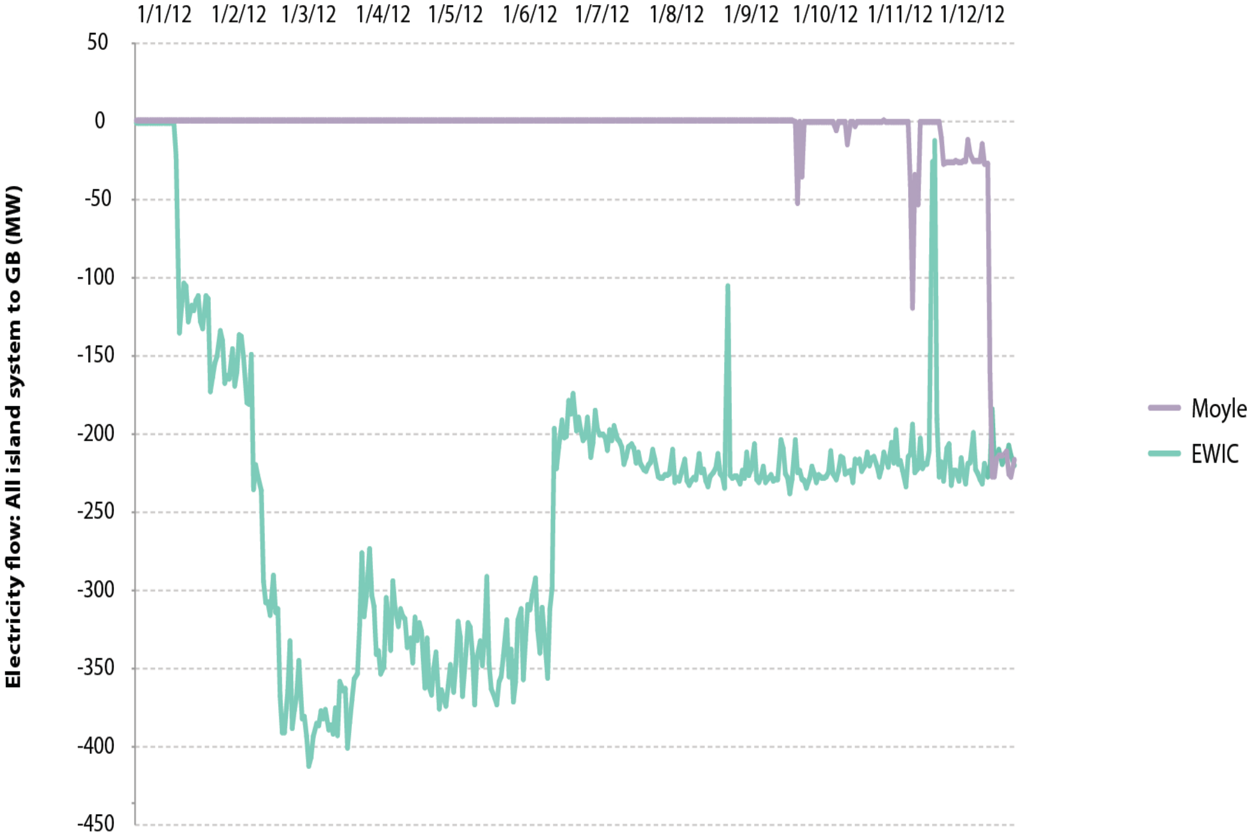
[81] Available from the SEMO website http://www.sem-o.com/Publications/Pages/GeneralPublications.aspx?documentarchivestatus=Active

[82] Evidence from analysis of cycling/ramping impacts in the US shows that median forced outage rates by 0.0086% per hot start. See Lew, D.; Brinkman, G.; Kumar, N.; Besuner, P.; Agan, D.; Lefton, S., "*Impacts of wind and solar on emissions and wear and tear of fossil-fueled generators,*" Power and Energy Society General Meeting, 2012 IEEE , vol., no., pp.1,8, 22-26 July 2012

[83] Moyle Interconnection Limited, (2011), *'Interconnection Capacity Calculation'*. Available from: http://www.mutual-energy.com/Download/110930%20MIL%20SONI%20NG%20Capacity%20Calc%20combined%20Sept%202011.pdf

Figure A. 2: Actual interconnector flows from SEM area to GB in 2012



Wind generation

Actual recorded wind generation data for 2012 is used in the modelling at a 30-minute time resolution.[84] Wind output is determined by the capacity factor and the installed generation capacity.

Seasonal monthly capacity factors demonstrate a variation over the year that is broadly correlated with seasonal demand. The fuel displacement outcome in each month depends on how wind generation coincides with other system conditions. The wind generation capacity factor in 2012 was below the 10-year average of 31.7%,[85] indicating that it was a below average year for wind generation. The lowest monthly factors were recorded in May, June and July, and the highest recorded in January, February and December.[86] The total output from wind energy in 2012 totalled 4,101 GWh in RoI and 1,040 GWh in NI.

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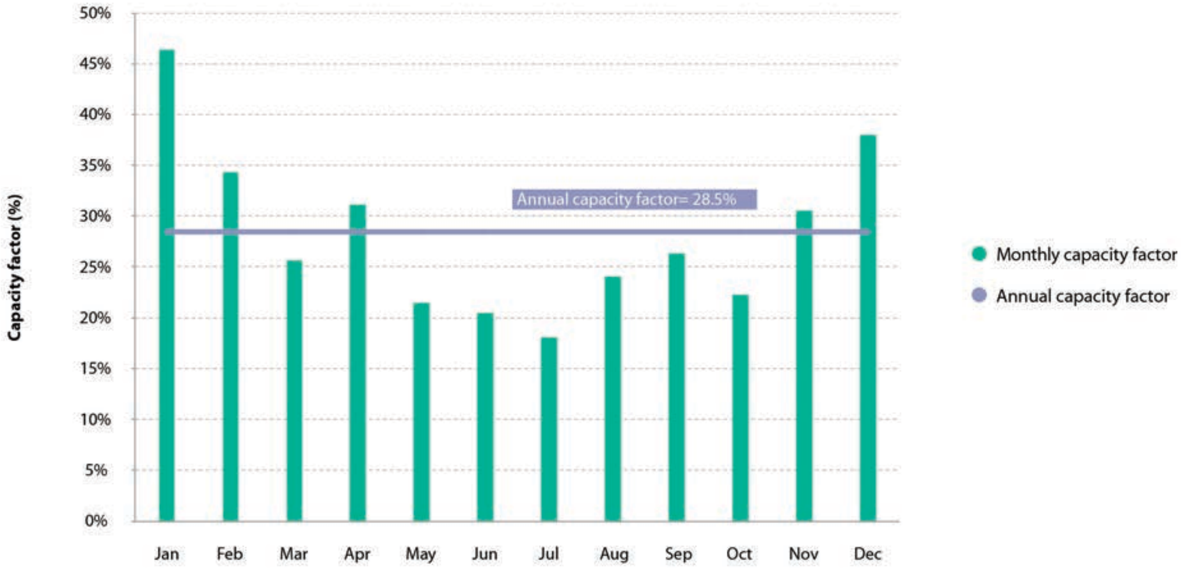
[84] Wind generation and forecast data was acquired from EirGrid and SONI.

[85] EirGrid (2013), 'Generation Capacity Statement 2013-2022': http://www.eirgrid.com/media/All-Island_GCS_2013-2022.pdf

[86] EirGrid (2013), '2012 Curtailment Report'.

Figure A. 3: Actual monthly wind capacity factors and annual average for 2012



Wind forecasts at 24 hours ahead are included for the RoI and NI.[84] he average 24-hour-ahead forecast error for wind in 2012 using the Normalised Mean Absolute Percentage Error (NMAPE) was 5.6%, with the Mean Absolute Error (MAE) showing an average deviation of 92 MW.

Hydro resources

The available hydro resource for each month is calculated based on the output of hydro units in 2012. A daily limit constraint is included in the model that is consistent with the actual energy production in 2012 while allowing the model flexibility to optimise the dispatch of hydro generators.

Constraints and operating reserve

The operational rules that are implemented to manage network constraints in the model detail the maximum and minimum requirements for generator output based on geographical location and operational capabilities. For example, there must be a minimum number of units on-load at any one time in the Moneypoint generation plant and there must be a minimum number of units on-load in the Dublin and Cork areas.

The All-Island system is comprised of the RoI and NI electricity systems connected synchronously through the North-South (NS) tie-line, with a capacity of 450 MW from north to south and 400 MW in the opposite direction. As this is part of the All-Island synchronous transmission grid, the model dispatches the optimal flow across the tie-line as part of normal operation.

A system wide non-synchronous[87] penetration (SNSP) constraint is implemented to ensure system stability at times of high levels of wind penetration.[88] The SNSP constraint ensures that no more than 50% of the system demand can be served from non-synchronous services, which accounts for both interconnectors to Great Britain and wind generation.

Operating reserve maintains electricity system security and stability. Reserves allow for an unexpected change in demand or sudden drop in generation output due to a unit breakdown. The Irish operating reserve protocol requires primary, secondary and tertiary reserves and consideration of the replacement requirements of the largest generation unit on the system. These reserves cover operational horizons from five seconds through to 90 minutes. The constraints and reserve information used in the model are available in the 'Operational Constraints Update 2012'.[89]

Primary and secondary operating reserves are calculated dynamically in the model for each period based on 75% of the largest unit running at that time in RoI and the largest unit running at that time in NI. Tertiary reserve requirements are included as fixed quantities based on the largest single electricity in-feed. These were 425 MW in NI and 480 MW in RoI for the first 9 months of 2012 and 500 MW for the last 3 months of 2012.

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[87] Non-synchronous in electrical terms refers to electricity that is not at the correct frequency or not in sync with the other electricity in the system. In Ireland the standard frequency is 50 Hertz.

[88] EirGrid (2010), 'All Island TSO Facilitation of Renewables Studies': http://www.eirgrid.com/media/FacilitationRenewablesFinalStudyReport.pdf

[89] EirGrid (2013), 'Operational Constraint Update, 7th August 2013': http://www.eirgrid.com/media/OperationalConstraintsUpdate_v1.8_August2013.pdf

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