Applied Energy 305 (2022) 117748

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Wind energy is not sustainable when balanced by fossil energy

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HIGHLIGHTS

- Life-cycle analyses of wind in grids have many significant shortcomings today.
- Wind displaces far less emissions than typically assessed today.
- Wind *does* reduce emissions but insufficiently to qualify as sustainable.
- Policy must focus on developing low carbon dispatchable energy sources.
- Policy must focus on systemic sustainability and less on renewable energy *per se*.

ARTICLE INFO

Keywords:
Levelized Cost of Energy (LCOE)
Life Cycle Assessment (LCA)
Subsidies
Uncertainty analyses
Monte Carlo simulations

ABSTRACT

Ensuring access to affordable, reliable, sustainable and modern energy for all is one of the Sustainable Development Goals. Some countries have therefore invested significantly in wind energy, but emissions, which is a common measure for sustainability in this context, have not fallen significantly. Reductions between 20% and 40% are typical. We therefore test the hypothesis that wind energy reduces emissions compared to using gas turbines when life-cycle emissions are included. The Irish grid is studied due to its record-high wind penetration. The model is based on high resolution grid data covering four years and input from 828 Life-Cycle Assessment cases to allow detailed analysis of demand, supply, life-cycle emissions and their changes due to the increased ramping of gas turbines and increased grid reserves required to maintain grid reliability when wind is deployed. Indirect effects are included to some extent. The model is sampled 10,000 times using Monte Carlo simulations. The results show that emissions are reduced by 10–20%, which supports the hypothesis. However, with an average wind penetration of 34% in 2019, reaching many times the 65% limit for non-synchronous generation set by the system operator to maintain grid reliability, such modest reductions logically imply that achieving an affordable, low-carbon grid using wind together with fossil energy balancing is infeasible with today's technology, emissions and costs. This key finding is transferable to other grids where wind has large penetration and requires fossil energy balancing. Thus, wind energy is not sustainable when balanced by fossil fuel generators.

1. Introduction

UN's Sustainable Development Goals (SDG) encompass a whole variety of issues, but the one most relevant for this paper is SDG 7 which is described as "Ensure access to affordable, reliable, sustainable and modern energy for all" (UN [136]. While 'modern' can be difficult to define, the other three are clearer.

When it comes to 'affordable', it is not just a question of costs but crucially also of value. Despite the fact that an average American consumes 50 times more energy than an average Bangladeshi and 100 times more than an average Nigerian, relatively poorer villagers in Mali and Uganda are willing to pay about ten times higher price than the typical prevailing price in developed countries[15]. The villagers therefore place much more value on the same commodity. Indeed, the cost for an energy source can be mathematically the same while having very different net economic benefits [70].

'Reliable' is perhaps the best defined term in an energy context because grid operators have very clear definitions, and measured by the LOLP and LOLE[5]. LOLP (Loss of Load Probability) is defined as the probability of a loss of load event in which the system load is greater than available generating capacity during a given time period and LOLE (Loss of Load Expectation) is the sum of LOLPs for a given planning

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https://doi.org/10.1016/j.apenergy.2021.117748
Received 18 June 2021; Received in revised form 26 August 2021; Accepted 27 August 2021

horizon, such as a year, and it gives the expected number of time periods in which a loss of load event occurs [85]. Power system planners in the US typically aim at maintaining a LOLE value of 0.1 days/year, or 2.4 h per year based on the target of one outage-day every 10 years [72].

'Sustainable' implies "achieving sustainable development in its three dimensions—economic, social and environmental—in a balanced and integrated manner", which is the prime objective of the SDGs (UN [137]. Furthermore, The European Commission set the target of reducing Greenhouse Gas (GHG) emissions, or 'emissions' in short, to 80–95% below 1990 levels by 2050 in 2009 (European [45]. The power sector is expected to contribute significantly, and the term 'low-carbon electricity grid' is used ('low-carbon grid' in short). Also, the Global Warming Potential (GWP) has been suggested as appropriate for assessing the environmental performance of energy sources, and it has become one of the most commonly used tools [125]. Unfortunately, a clear definition of a low-carbon grid is hard to find, but defining it as a 'grid where 80–95% of the GWP of the emissions are eliminated compared to a grid using fossil fuels' seems meaningful.

Discussing meaningfully the three sustainability dimensions in a single paper, is not possible. This paper therefore focuses on the environmental dimension because it is difficult to improve to the level of a low-carbon grid, as exemplified by the German energy transition.

The German Energiewende (energy transition) has achieved almost exactly what the United States achieved, but at greater expense [121]. Also the federal auditors in German are seriously questioning the transition after spending 160 bn Euros in subsidies during the 2015–2019 period alone with little to show for [33]. Ironically, Germany reduced emissions in 2020 by 80 million tons of CO2 using 31 Billion euros in subsidies, but the same subsidies could have bought 1.24 billion tons of CO2 certificates in the European emissions trading, according to a gas industry representative [154]. In the 2021 report, the Federal Audit Office of Germany go even further: "The Federal Audit Office sees the danger that the energy transition in this form will endanger Germany as a business location and overwhelm the financial strength of electricity-consuming companies and private households" [20], and translated by Wetzel [147]. Moreover, in the first half of 2021, German emissions from electricity generation increased by 25%, where gas-fired power plants increased 15%, coal power plants by 36%, and hard coal power plants by 44%, according to German think tank Agora Energiewende [118]. At the same time, the production of wind energy, or 'wind' in the remainder of the paper, fell by 25%. Hence, the energy transition seems to be neither affordable nor reliable and a long way from a low-carbon grid.

Interestingly, there are plenty of publications arguing that renewables are most effective towards sustainable development. The facts above, however, imply that a thorough investigation is warranted. This paper focuses on wind due its broader geographical applicability on the northern hemisphere where most emissions are located. Indeed, the literature reviews in Sections 2 and 3 highlight significant shortcomings.

Therefore, this paper poses the research question "are wind increasing or lowering climate gas emissions?" where 'emissions' is a shorthand for emissions with GWP. This question seems illogical given that wind turbines are driven by the wind. However, wind requires balancing power. Even with an assumed Power Capacity Factor (PCF) as high as 43%, it still takes 4 windfarms with completely uncorrelated weather systems to guarantee the output of one windfarm[40]. The problem is that uncorrelated weather systems require huge geographical areas. In fact, not even the entire continental USA is sufficient at achievable costs, see Shaner et al. [117] for an excellent analysis. Thus, if the life-cycle emissions of the balancing power are greater than the displaced life-cycle emissions caused by wind, wind will not lead to a reduction in life-cycle emissions when the total system is considered.

Clearly, this paper is only relevant for grids where the balancing power is fossil. This may seem as a strict limitation, but fossil energy has historically been most common balancing power from 1990 to 2013 in the 26 OECD countries studied [142]. The entire European Network of Transmission System Operators for Electricity (ENTSOE) – the largest grid in the world case – is a good example. Thus, this paper is applicable to many large grids in the world.

To improve the reliability and validity of the analysis, the initial question can be rephrased to a comparison between two alternatives so that a comparative analysis can be performed, as described in detail by Emblemsvåg [39],

1. A significant share of wind with gas as backup ('Wind + Gas' alternative). Note that 'gas' is used in the remainder of this paper as a shorthand for gas-fired power plants.
2. Gas replaces the production of wind ('Gas Only' alternative).

A key strength of comparative analyses is that errors can cancel fully or partially out. Note that the focus on gas is simply due to the fact that gas has lower emissions than any other fossil fuel, see Table 2 later, and gas handles well the fluctuations from wind. In a sense, we can argue that the paper discusses an ideal situation comprising of a baseload combined with wind balanced by gas. In most grids, there will be a host of other fossil energy sources, but they do not add any insights to the study because they are technologically inferior to gas when it comes to emissions and handling fluctuation. Hence, the study is conservative.

Anyway, these two alternatives can be tested through a research hypothesis phrased as:

> "*A grid incorporating wind energy balanced by* gas power plants *will have lower emissions than if gas power plants have replaced the wind energy in the same grid*".

To test the hypothesis, the first issue is how to measure the emissions. Estimating the consequences of emissions for a given year is done in a variety of ways, see Thomson et al. [127] for a good review.

Life-Cycle Assessment (LCA) is currently the most accepted tool to assess the environmental performance of products all around the globe and to all stakeholders [48]. A strength of LCAs is that it takes a systemic perspective [99]. Unfortunately, LCAs also suffer from inconsistencies known for more than 25 years as discussed later in Section 3 and exemplified by the significant spread in results documented by Pehl et al. [101]. Summarized, from the literature, there are five major shortcomings of current LCA approaches discussed in Section 3. Understanding these issues is paramount, but first we must also review the literature on wind and balancing, see Section 2. A summary of the approach used in this paper is presented in Section 4. The hypothesis is tested using Ireland as case in Section 5 where all necessary data, assumptions and results are presented in detail. The paper is discussed, including future work, in Section 6.

2. Review of balancing wind in grids with high penetration

There is considerable uncertainty and debate over the effect of wind on the displacement of emissions [127]. Furthermore, they note that it is

Table 1
Descriptive statistics with 15-minute resolution [MWh] of Irish grid data for the years 2016 through 2019. Author calculations using data from http://www.eirgridgroup.com/how-the-grid-works/renewables.

All data are generated with 15 min resolution	SNSP	Demand [MWh/h]	Wind [MWh/h]	Other Generation [MWh/h]	Gas [MWh/h]
Min	0.0%	469.5	0.0	13.6	0.0
Max	66.9%	1,253.5	783.9	321.1	1,085.7
Average	28.9%	804.8	224.4	148.7	432.0
Standard Deviation		151.7	172.0	65.4	200.4
Theoretical min		349.8	0.0	0.0	0.0
Theoretical max		1,259.9	740.4	344.8	1,033.3

Table 2
Emission Factors (EF) for various technologies. Developed from Koffi et al. [75] and some studies added by this author.

Source	References	Case studies	Min LCA EF [gCO2/kWh]	Max LCA EF [gCO2/kWh]	Average LCA EF [gCO2/kWh]
Motor oil	[131]	10	530	900	715
Motor oil	[146]	5	500	1,200	850
Motor oil	[7]	6	780	900	840
Coal	[46]	48	837	1,167	1,004
Coal	[146]	7	950	1,250	1,100
Coal	[7]	6	900	1,200	1,050
Coal	[131]	36	660	1,050	855
Lignite	[131]	7	800	1,300	1,050
Lignite	[146]	3	800	1,700	1,250
Natural gas	[46]	48	407	760	543
Natural gas	[146]	9	440	780	610
Natural gas	[7]	6	400	500	450
Natural gas	[131]	23	380	1,000	690
Waste	[6]	4	97	1,000	549
Peat	[91]	1	1,110	1,115	1,112
Biomass	[141]	5	35	178	107
Biomass	[131]	25	9	130	69
Biomass	[146]	3	35	99	67
Biomass	[90]	25	1	6	2
Biomass	[6]	14	26	550	288
Hydro	[6]	11	2	60	20
Hydro	[7]	6	15	40	28
Hydro	[10]	11	2	75	12
Hydro	[141]	3	4	237	120
Hydro	[46]	48	12	148	41
Hydro	[71]	9	1	609	20
Hydro	[108]	39	0	152	3
Hydro	[131]	12	1	20	11
Hydro	[146]	4	1	34	18
Hydro	[101]	1	78	109	94
Wind	[10]	20	6	46	9
Wind	[17]	34	1	185	11
Wind	[141]	10	0	124	62
Wind	[46]	48	4	84	25
Wind	[83]	72	8	124	66
Wind	[108]	63	5	55	18
Wind	[131]	22	3	41	22
Wind	[146]	8	8	30	19
Wind	[95]	39	0	364	182
Wind	[101]	1	4	12	34
Wind, offshore	[6]	5	5	24	13
Wind, offshore	[9]	13	8	33	16
Wind, onshore	[6]	14	2	81	16
Wind, onshore	[9]	44	7	56	20

currently approximated as the average emissions of the whole system, despite an acknowledgement that wind will actually displace only the generators operating on the margin. Hence, analyses that use average numbers miss critical points, which will evident from the case in Section 5. In this review, the focus is therefore on papers that has a credible handling of fluctuations and the impact on balancing or integration on system reliability.

Furthermore, we must investigate both ‘balancing’ and ‘integration’ when reviewing the literature that has a credible discussion on system reliability. For example, papers suggesting 100% non-synchronous energy sources are excluded because it is technically impossible with today’s grids. It would require a complete overhaul of grids from alternating current (AC) to direct current DC with unforeseeable large costs.

There are not many papers analyzing the environmental impacts of balancing wind in grids, and none that include analysis to the level that ramping and systems reserves are discussed in detail and uncertainty is modelled. However, there are numerous LCAs of wind, see Table 2, that are used in this study to estimate the emission data. Interestingly, the literature analyzing costs is far richer, which is why it is useful to investigate some of this literature first.

The challenge is that the intermittency, undispatchable feature, and variable and uncertain energy output make the integration of Variable Renewable Energy (VRE) currently unsatisfactory [153], which impact both costs and emissions. In fact, if the integration cost of VRE is taken into consideration, the optimal shares of VRE in the grid will decline significantly [11,156]. The analysis of Verdolini et al. [142] points to the substantial indirect costs of VRE integration and highlights the complementarity of investments in different generation technologies for a successful decarbonization process. Indeed, the proper measurement of integration costs is a hotly debated subject in academic and policy-making circles (Agora [2], which means that this paper is very relevant for both the academic discourse and for policymaking.

Interestingly, this debate is far less pronounced when it comes to emissions. This may be due simplifications made either intentionally or unintentionally driven by data availability or methodological limitations. Anyway, this leaves considerable room for improvement that this paper addresses, as discussed more in Section 5.

A good exception is Thomson et al. [127], but they ignore the LCA perspective altogether. Uncertainty is also ignored alongside ramping and system reserves. The actual accuracy of the analysis is also unclear since there are a number of linear approximations, and the analysis is based on regression. However, their analysis offers a good starting point, and later in Section 6 their findings will be discussed. Two other studies – Tsagkaraki and Carollo [130],Udo [133] – are also worth noting, and Tsagkaraki and Carollo [130] actually uses LCA. However, none of the papers offer the level of detail provided here.

It should be noted that using Battery Energy Storage Systems (BESS) is also discussed in the literature. Due to the fluctuations of the wind, a minimum of 3 weeks storage is identified by Shaner et al. [117], and only Grams et al. [52] have such a perspective. However, their study has low resolution (6 h), which introduces significant inaccuracies as shown in Section 5. Furthermore, they ignore a number of practicalities such as the fact that intertrade in Europe is a meager 13.6% [14], which means that spatial differentiation would require huge investments in infrastructure in addition to new wind capacity.

The analysis of Bouman et al. [18] is also relevant, but as noted by the authors; "It is unsure what role compressed air technology will play in securing baseload renewable power generation in future electricity generation systems. The capital investment required, in combination with finding a suitable geological location, might prove to be a significant impediment for large scale implementation".

It should be noted that BESS together with Solar Photovoltaic (PV) differs substantially from wind together with BESS because dimensioning the BESS can be done far more reliably due to the higher regularity of the sun on suitable latitudes compared to the wind [42]. For example, Raugei et al. [105] have performed a LCA study of using Solar PV in conjunction with BESS in California. They find that such a strategy would be effective at curbing California's domestic electricity grid mix carbon emissions by 50%, and reducing demand for non-renewable primary energy by 66%. This is encouraging results. Unfortunately, a 50% reduction does not constitute a low-carbon grid, and it is unclear whether the same approach is scalable to a true low-carbon grid at reasonable costs.

Then we have two papers that deal with balancing wind using BESS in the day-ahead (24 h) forecasting error market [12,155]. This is a good idea irrespective of wind. Using BESS as peak shavers to handle small variations in the grid brings many advantages, see Uddin et al. [132], including lower costs [21], less emissions [109]and better quality [128].

Unfortunately, most studies only consider investment costs for BESS [111]and costs is also a dimension of sustainability. These authors calculate the Levelized Cost Of Storage (LCOS) for 9 technologies in 12 power system applications from 2015 to 2050 based on projected investment cost reductions and current performance parameters. A major driver is the number of charging cycles. For applications with more than 300 annual cycles, LCOS reduce from 150 to 600 US$/MWh (2015) to 130–200 US$/MWh (2050), for between 50 and 100 annual cycles from 1,000–3,500 (2015) to 500–900 US$/MWh (2050), and applications with less than 10 annual cycles never cost below 1,500 US$/MWh. Hence, the excellent study of Schmidt et al. [111] illustrates that BESS must be attuned to applications and which performance parameters that are important. Furthermore, for large-scale application the costs are still prohibitive, especially when taking into account the geophysical constraints of wind [117].

Thus, with the current technologies, balancing wind over days and weeks will be predominantly performed by other generators, which is what we witness in real life and studied in this paper. Finally, none of the studies directly relevant to this paper analyze how wind can achieve a low-carbon grid with fossil balancing, and none discuss the shortcomings of LCAs. Hence, the results found in the literature are most likely too optimistic in favor of wind.

3. Shortcomings with LCAs

There are several shortcomings with today's LCAs that must be discussed to improve accuracy. The shortcomings are:

1. Methodological uncertainty.
2. Data availability. This shortcoming is well known in the literature, but the extent of the problem is unclear due to the lack of an accounting system.
3. Failure to incorporate indirect effects.
4. Subsidies, which is a special type of indirect effects, are ignored in LCAs.
5. LCAs ignore overcapacity and overproduction.

These issues are discussed in the subsequent sections.

3.1. *The methodological uncertainty of ISO LCAs*

The leading LCA framework is provided by ISO, and they state that 'Life-Cycle Assessment (LCA) is a tool for identifying and evaluating the environmental aspects of products and services from the "cradle to the grave": from the extraction of resource inputs to the eventual disposal of the product or its waste'[63]. The idea is simple, but there are many gaps when putting it into practice.

The most comprehensive review this author has identified is the excellent review by Finkbeiner et al. [48] where 34 gaps and issues are identified, emphasizing that "A recurrent topic for many challenges identified is the need for additional, robust and relevant data". Unfortunately, they do not challenge the framework despite acknowledging that "A number of challenges, e.g. 'allocation', 'functional unit' or 'uncertainty analysis', is inherent to the LCA method as such".

Other studies show that in the context of emerging technologies, the problems are even greater. Three main challenges exist when conducting LCAs of emerging technologies [129]: Comparability, data, and uncertainty. Unfortunately, none of the 65 papers reviewed addressed the challenges comprehensively.

Basically, there are three fundamental issues that have persisted for more than 20 years since there has been no significant improvements of the LCA framework if we compare [65,66]to [64] and the findings from the more recent studies discussed previously. Any changes are mostly refinements, which explains why researchers still discuss the shortcomings or some variants thereof. Therefore, we must address the fundamental issues, which is done in the three subsequent sections, see Lee and Inaba [81] for a well described process including examples.

3.1.1. *The problem of functional units*

ISO through ISO/ TC 207/SC 5 (2006) promotes the usage of functional units, defined as 'quantified performance of a product system for use as a reference unit'. For example, 'systems A and B perform functions × and y which are represented by the selected functional unit, but system A performs function z which is not represented in the functional unit. As an alternative, systems associated with the delivery of function z may be added to the boundary of system B to make the systems more comparable'. For industrial products that fulfill a specific function, this approach is workable. However, when products have different functions, have multiple functions or no functions at all, the approach becomes troublesome. Furthermore, if nonlinear relations exist between the functional unit and the function, like fuel consumption of a ship and the mass of cargo, then the functional unit is highly misleading as a basis for comparison[37]. Furthermore, ISO/ TC 207/SC 5 (2006) states that '…alternative design solutions can often be represented by various function structures, which by default require different functional units, the result is incomparability'. Hence, functional units may be useful at certain applications but as a general approach it can be problematic.

This is also the case of permanent magnets in wind turbines. As Wulf et al. [150] note; "Comparison with other LCA studies is quite difficult because of the use of different functional units (1 kg of REO, 1 kg of REO equivalents, 1 kg of metal, and 1 kg of magnet) as well as life cycle impact assessment methods".

3.1.2. *The problem of unit processes*

A unit process is defined as 'smallest element considered in the life cycle inventory analysis for which input and output data are quantified' (ISO/ TC 207/SC 5 2006), or 'the basic building blocks within the system boundaries'[68]. In today's highly complex world of manufacturing, this approach is unrealistic; 'taken into account that there are more than eight million chemical compounds and materials in commercial usage today (see the Beilstein and Gmelin databases) out of which 60,000[93] were toxic substances commonly used in 1984, establishing unit processes seems a rather daunting, if not impossible approach'[37]. The only thing that has changed since then, is that the number of chemical compounds and materials have become even larger. Indeed, as Watari et al. [145] note in the context of Rare Earth Elements (REE); because of the complex nature of many supply chains, it is difficult to directly link specific mining impacts to end-uses, particularly if these minerals are used in many applications.

3.1.3. *The problem of impact categorization*

One major problem with impact categorization is that it leads to political debate [68]as people disagree which emissions affect which impact categories and to what extent. A second topic of debate is how various impact categories are to be weighted towards each other. Unfortunately, even if the impact categories are similar/the same, there are still plenty of room for debate [37–38]:.

1. Due to the fact that various emissions can affect several impact categories, the emissions have to be accounted for several times. Thus, there is a risk that it may be over-accounted or under-accounted and it is up to the practitioners to decide.
2. During characterization we try to assign the relative contribution of the relevant environmental processes. This is largely based on scientific knowledge. However, value-choices are also made, which opens up for politics.
3. The last step is weighting or valuation. The purpose is to rank, weight and possibly aggregate the results to arrive at the relative importance of the results [60]. Unfortunately, stakeholders are allowed to impact the weighting scheme ruining comparability. Methods for weighting are presented in [84].
4. Impact scales such as 'Global', 'Continental', 'Regional' and 'Local' are also difficult to compare.

Clearly, achieving reliable and comparable studies is challenging, which lay the foundation for the issues discussed next.

3.2. *The problem of poor data quality*

The ISO 14,040 standard defines data quality as: 'characteristics of data that relate to their ability to satisfy stated requirements'[62]. There are ten criteria for information quality [61], but how to address this is left to the practitioners. The result is a wide range of quantitative and/or qualitative approaches for capturing data quality [44].

LCA models are commonly built using existing databases and datasets with Life Cycle Inventory (LCI) data that can be coupled to primary data collected by the research team. Unfortunately, research articles, government documents and other sources of cited LCI data are often not the primary source for the data, and variability and uncertainty are often confused and/or misused [44]. For emerging technologies, uncertainty exists as an overarching challenge [129].

Uncertainty is defined as a lack of knowledge, or the level of confidence in a value being true or false and while variability refers to the observed differences due to diversity, and is represented with a frequency distribution derived from the observed data and can usually not be reduced with further measurement or study [43]. This can be further broken down, and Huijbregts et al. [57] differentiate between three different types of uncertainty in LCAs; 1) parameter uncertainty, which is due to uncertain input data, 2) scenario uncertainty, which occurs because LCA outcomes are based on normative choices in the modeling, and 3) model uncertainty, which arise due to the mathematical models. The pedigree matrix, see e.g. Ciroth et al. [23], is often used to manage the quality. However, this tool is highly subjective and more a tool for organizing researchers' thoughts. Hence, the handling of uncertainty is often simplistic, as all the single-point estimates presented in Table 2 show.

When it comes wind, LCAs rarely include the impacts of REE required for the permanent magnets used. But there are some LCAs on the magnets themselves, see Arshi et al. [8],Marx et al. [86], although they admit that data quality is very poor in China. This is not strange since even the majority of Original Equipment Manufacturers "don't have good visibility as to the source of their REEs", as claimed by Ryan Castilloux and quoted by Dodd [30].

It should be noted that permanent magnets are primarily used in direct-drive wind turbines used for offshore and larger onshore installations [122], which is where the main growth of the wind industry takes place. In the US alone, the expected demand for REE related to wind is about 4,600 million tonnes [59]if growth targets are met.

Although there are different types of permanent magnets, NdFeB magnets are the most used because of their outstanding properties, and they usually contain four different REE: neodymium, praseodymium, terbium and dysprosium [4]. Dysprosium and terbium are both costly and poorly available [107]. An average permanent magnet contains 28.5% neodymium, 4.4% dysprosium, 1% boron and 66% iron and weighs up to 4 tonnes [104]. While much progress has been made towards reducing the use of the different REE, competitive REE free magnets are far away [24]. Moreover, there are considerable uncertainties concerning reuse and recycling [4]. Furthermore, the problem with REE is mining and processing often under terrible conditions. Indeed, the BBC described the Bayan Obo area that contains approximately 70% of global REE deposits as 'Hell on earth'[87]. While not all mining is performed in China, separation and refining is performed almost exclusively in China, and this situation is unlikely change in foreseeable future [4]. There are also radioactivity concerns as REE ores often contain thorium and uranium, which has been a major deterrent to starting REE mines outside China [115].

Clearly, currently nobody who knows the extent of underestimation that takes place in LCAs for wind. In this paper, we must contend with knowing that there are major uncertainties, which is exacerbated by the next issue.

3.3. *Ignoring indirect effects*

The main indirect effects of VRE are largely driven by their low energy density and fluctuating nature. Wind is problematic as there have been insignificant improvements over decades from an already low energy density [139]. When VRE therefore takes a large share of the grid, we have for the first time in history an energy density reversal so that society might have to devote 100 or even 1000 times more land area to energy production than today [120], which can have enormous negative impacts on agriculture, biodiversity and environmental quality [144]. It should be noted that the discussion of land use is a topic where we can find large discrepancies in the results, as shown by [49]. We believe that one reason for this is the different conceptions of electricity. If electricity is merely electrons over a period of time, people will get a much more optimistic result than if electricity is electrons that must be available with a certain reliability.

For example, habitat loss and degradation currently threaten over 80% of endangered species, while climate change directly affects 20% [88], and the mining of REE is a major culprit [124]. When IEA [58] calculates a 20–40 fold increase in material usage of critical materials to achieve the climate goals, we can only fathom the consequences even with a large increase in recycling. In the case in Section 5, the usage of peatland adds additional issues.

Unfortunately, LCAs normally lack the data to factor in all these issues. In fact, these hidden material flows are largely unevaluated in material flow analyses, despite the high correlation with environmental burden [53,76].

A second issue that could further distort LCAs, is the lack of incorporating indirect resources used on corporate level. Indeed, writing some decades ago [89]found that overhead costs constituted roughly 35% of an average American corporation. Arguably, similar overhead environmental impact related to the indirect resources should have been included in LCAs, but they are not. When we discuss indirect effects, we have to respect that they are many and some are very difficult to handle without an accounting system found in cost accounting. The reason we cannot merely add 35% to current LCA estimates is that the overhead resources – and hence the overhead environmental impact – do not follow direct resources. Just as the true costs can be hundred percent off the calculated costs [97], we can only speculate how much the true environmental impact is off. What is certain is that the more overhead resources, the higher the risk for significant mistakes.

The lack of data also forces this study to simplify indirect effect modeling and focus primarily on indirect grid effects. These effects arise from the fact that prior to the liberalization of electricity markets and the rapid expansion of VRE, electric power system operators only had to match generation to a demand which was relatively predictable over daily, weekly and seasonal cycles [73], with only occasional shutdowns for maintenance or technical problems. However, today the situation is dramatically different [19,31,135]. Moreover, VRE is given dispatch priority [73]despite the fact that the impact of mandatory requirements to dispatch VRE resources on emissions is poorly understood [31,127]. Indeed, in their analysis of the Irish grid, Tsagkaraki and Carollo [130] note that wind balancing is far more costly than is generally believed at high wind penetration.

The result is that all other energy sources have to 'cycle' or 'ramping' (up/down) – start up, shut down and run part load cyclic operations. For example; in Germany the share of VRE is expected to grow from 14% in 2013 to 34% in 2030, which will result in an overall growth of 81% in the numbers of startups, while respective costs increase by 119%[110]. The authors note that this effect is ignored in most studies, but it is included here.

Indeed, the number of scientific articles on indirect effects is limited; much more attention is paid to the optimization of full load operation than to part load operation of a combined cycle [140]. When it comes to the LCA literature, we have not seen a single study that includes ramping. The reason is perhaps that LCA focus on years while ramping is found by the minutes and hours, which would create a very complex LCA model. In this paper, however, ramping is included.

Another problem with increased ramping, is that operators are putting their assets increasingly at risk of outages and High Impact Low Probability events that they wish to minimize and avoid if possible [77]. The risks are related to increased costs, increased emissions, reduced lifespan and even technical failures. New coal fired plants can have failures as early as 5 to 7 years into operation; for older plants it could be nine months to two-years after start of significant ramping [82]). Furthermore, there can be significant negative impact on emissions when ramping coal plants to follow wind [31]; an additional 6,340 lbs of SO_2 and 10,826 lbs of NOx were released while 246 fewer tons of CO_2 were released when wind entered the grid and the coal power plants had to ramp down.

The general approach adopted throughout the industry, although there are variations, is that a hot start of a turbine represents an overnight shutdown or less than 8 h offline (turbine metal temperatures greater than 400 °C); a warm start reflects a weekend shutdown of up to 64 h (greater than200 °C); and a cold start anything greater than 60 h offline (less than200 °C) [82]). The overall ratios in the US were calculated to be 61% hot, 24% warm and 15% cold [73]. Peakers, however, have a peaking duty cycle role. Specifically, they are called upon to meet peak demand loads for a few hours on short notice, often in the 15-minute or 5-minute-ahead real-time market. In 2001 there were 29 peaker plants in California; by 2015 the number grew to 74 facilities [96].

Gas turbines are more robust and typically handle cycling and load following well. The issues involved with gas turbines are the emissions [31]. When the engines are base loaded, the combustion system operates at high firing temperatures and most of the CO is oxidized to CO_2. But at partial loads, when the firing temperature is lower, this oxidation reaction is quenched by the cool regions near the walls of the combustion liner. This results in increased CO emissions at low loads [92]. The impacts of ramping on component life, maintenance cost, emission compliance, unit reliability and availability are also significant [77].

It is difficult to estimate fully the consequences of ramping, and by excluding the most difficult part – the aging itself – the estimated cost is about 600 kEUR per year for a 300 MW CCGT, but a conventional HP turbine has double the cost [73]. Thus, it is important to be asset specific. Using numbers without accounting for actual asset operations can result in significant under-/over estimation of ramping effects [77], because there are several key drivers that cause the ramping to vary among different units such as [78]: 1) Maintenance related activities, 2) equipment design and manufacturer, 3) vintage of technology, 4) turbine design and pressure, 5) fuel type and quality, 6) MW capacity, 7) age, 8) time between an off and on cycle, and 9) plant configuration, size, economies of scale, and scope.

Depending on the unit, Intertek APTECH regards all cycles of range greater than 15–20% gross dependable capacity (GDC) as significant [77]. Given the information on ramping costs, most utilities are using ramping costs in the range of 10% to 30% of what Intertek APTECH has found to be the "true" cost of ramping. Thus, most utilities may be in a high-cost penalty regime [77]. The literature is more or less absent concerning the effects on emissions.

The lifespan issue is related to the fact that design standards of many currently operational units required only that they should be able to withstand creep at their full-load operating conditions for 100,000 h [143]. This is particularly a problem for large thermal units, but despite the dramatic changes in operational profiles, VRE integration studies have so far tended to overlook the impact of off-design operation on large thermal units [73].

Although creep damage is known to occur even though the design lifetime of the component includes this expected damage. Fatigue damage, however, becomes more relevant as the component is ramped up and down and can lead to premature failure especially if the component is near the end of its creep life [31]. Thus, fatigue is more dominant problem than creep [73]. However, the creep-fatigue interaction is the most dominant failure mode [77].

As we understand, ramping is a complex issue that requires very detailed modeling on asset-level to give correct results. Furthermore, it is impossible to simulate since it involves weather forecasts and ongoing human decision-making related to such forecasts, operational issues on assets, etc. Regrettably, these effects cannot be fully included in this paper, but they should not be forgotten when interpreting the results because the ramping effects imply that consequences of wind on ramping are underestimated in the model.

3.4. Subsidies have environmental impact often ignored

Subsidies are not difficult to understand conceptually, but because terms and definitions across various policy communities differ, confusion is virtually guaranteed, which is why the World Trade Organization (WTO) has resisted defining the term [149]. However, the WTO provides internationally accepted criteria [126], that can be summarized into a sentence as 'a subsidy is a financial contribution by a government, or agent of a government, that confers a benefit on its recipients'. There is no straightforward definition of subsidy in the Agreement on Subsidies and Countervailing Measures ("SCM Agreement"), see https://www.wto.org/english/tratop_e/scm_e/subs_e.htm. Irrespective of how subsidies are structured, they involve a transfer of real resources, and all resources in an economy are associated with environmental impact [47] including emissions – directly or indirectly.

One paper that address subsidies is Jansen et al. [67], and they claim that the first 'negative subsidy' windfarms are here. This is an interesting study that warrants a detailed argument to position it more correctly than the authors have done.

First, they use a narrow definition of costs, which means that Jansen et al. [67] fail to take into account systemic costs despite the importance of using System LCOE, see Emblemsvåg [40],Reichenberg et al. [106], Ueckerdt et al. [134]. This means that opportunity costs are ignored, but the opportunity costs are large – about 2–3 times larger than the narrowly defined LCOE [40]. This corresponds very well with the German experience – the cost of maintaining two energy systems [121]is large.

Their narrow understanding of subsidies is the second major issue, and Jansen et al. [67] argue that subsidies constitute the difference between the harmonized expected revenues (including the support payments expected under each windfarm's CfD contract) and the expected revenues generated from the wholesale market alone. This is a reasonable statement mathematically speaking, but it hides a number of caveats.

First, while their definition of 'harmonized expected revenues' as discounted average revenue per MWh of electricity generated over the lifetime of the project is sound, it embeds the fact that the cost per MWh electricity is rising. The authors do not discuss why – it is because of renewable electricity has entered the grid, see Fig. 1. Their argument is therefore circular.

Second, many windfarms are set up as Special Purpose Vehicle companies to manage risks. By using publicly available, audited accounting information Aldersey-Williams et al. [3] find in the UK that open domain data are unreliable. Furthermore, they find that new wind farms are achieving a LCOE of around 100 GBP/MWh which is considerably higher level than implied by CfD bids in 2019 of 57.50 GBP/MWh. Therefore, there is a big difference between what is presented and reality. Indeed, after studying audited accounts of virtually all the windfarms in both the UK and Denmark, Hughes [55–56] argue that the trends are rising costs as windfarms age to such an extent that the whole 'falling cost argument' used by many is fundamentally flawed. Therefore, it seems that the falling auction costs are more an expression of expectations.

Finally, the third major issue is that Jansen et al. [67] discuss subsidies in isolation, but subsidies cannot be viewed in isolation from performance because electricity generated from dispatchable energy sources cannot be readily compared to electricity from VRE – there is a huge difference in reliability and dispatchability as discussed next. For example, the German power grid repeatedly faced critical situations in June 2019: significant shortfalls in available power were detected on three separate days [102], and California has been running rolling blackouts [13].

3.5. *The problem of overcapacity and overproduction*

Wind varies from zero to nameplate capacity, which represents a challenge. Dispatch-down of VRE refers to the amount of VRE that is available but cannot be used by the system. This is because of broad power system limitations, known as curtailments, or local network limitations, known as constraints [36]. In 2019, the total dispatch-down energy from wind in Ireland was 711 GWh, up 254 GWh since 2018. This is equivalent to 6.9% of total available wind in Ireland. This is overproduction, but the much larger type of overproduction is not discussed.

In 2000, Germany had an installed capacity of 121GW and it generated 577TWh, which is 54% as much as it theoretically could have done (that is, a CPF of 54%). In 2019, the country produced just 5% more (607 TWh), but its installed capacity was 80% higher (218.1GW) because it now had two generating systems [121]. This means that most of the increased installed capacity is unnecessary had it not been for the fact that VRE leads to hugely varying output. Thus, when all VRE sources produce with high output, they are overproducing, but politically they are allowed to transfer this overproduction to the grid at the expense of the dispatchable energy sources resulting in large alternative costs. The impact is real. For example, since 2010, system operation costs have increased by 62% in Britain [69]. This means that wind is neither carrying its true costs nor assigned its true emissions.

To resolve this, we must require comparable performance, as the

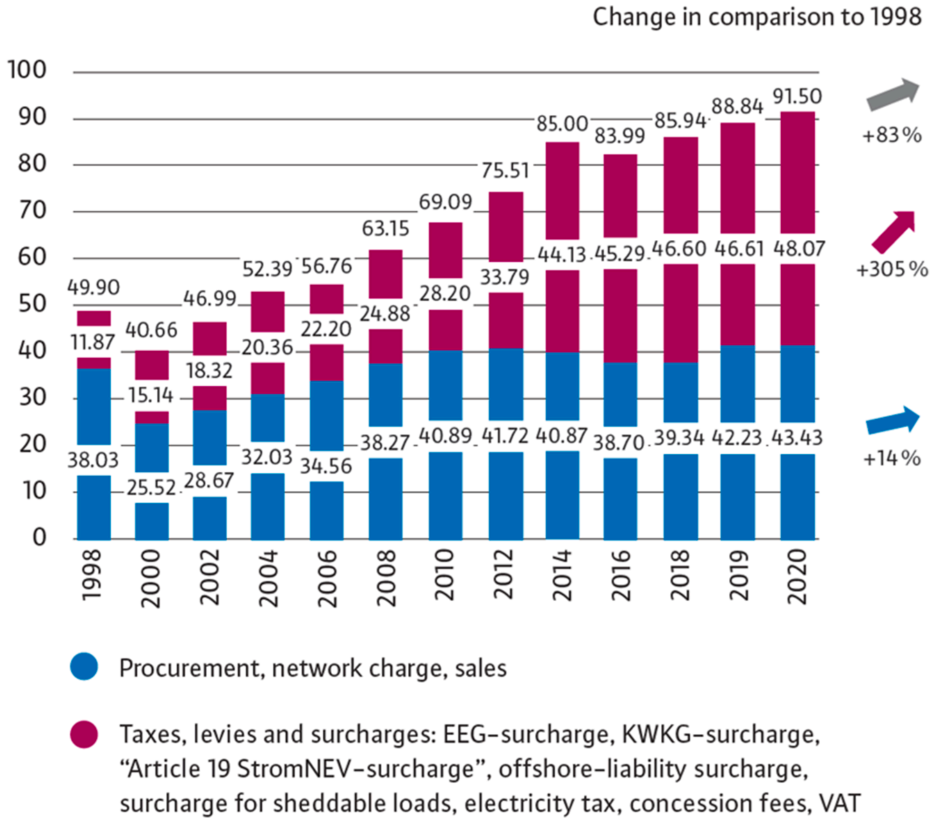

Fig. 1. Average, monthly electricity bill [EUR] for a German household with an annual consumption of 3,500 kWh. Source: BDEW [16].

research hypothesis alludes to. Hence, overproduction can be defined as all electricity generated above the electricity production from a system that can guarantee an output with the minimum amount of balancing and reserves. This will be illustrated and estimated in the case as presented shortly.

4. The approach used in this paper

After this review, a summary of the chosen approach is useful before presenting the case in the next section. Clearly, there are many caveats and shortcomings to be aware of, and the steps chosen that will reduce them to a minimum are;

- Perform a detailed grid analysis using historical data. The analysis must be complete and detailed enough to explain all observations including ramping, grid reserves and so on.
- Gather LCA data. To achieve a robust analysis, this study uses 18 studies incorporating 828 single LCA cases to estimate average numbers and uncertainty, see Tables 2 and 4.

Table 3

Dispatchable Power Plans in Ireland 2019. Source; EirGrid Monthly Availability Reports (except specific emissions, which comes from Table 2 using the Emission Factors [gCO2/kWh]).

Company	Power plant name	Technology	Primary Fuel	Installed capacity [MW]	Opening year	Close before	Specific emission [gCO2/kWh]
Aughinish Alumina Ltd	Seal Rock - SK3	CHP	Gas	85	2005		573
Aughinish Alumina Ltd	Seal Rock - SK4	CHP	Gas	85	2005		573
Bord Gáis	Whitegate - WG1	CCGT	Gas	444	2016		573
Dublin Waste to Energy	DWTE - DW1	OCCT	Waste	62	2018		549
Edenderry Power Ltd	Edenderry - ED1	CST	Peat	118	2008		1,112
Edenderry Power Ltd	Edenderry - ED3	OCCT	Distillate Oil	58	2010		802
Edenderry Power Ltd	Edenderry - ED5	OCCT	Distillate Oil	58	2010		802
ESB Energy Ireland	Aghada - AD1	CST	Gas	270	1980	2023	573
ESB Energy Ireland	Aghada - AD2	CCGT	Gas	431	2010		573
ESB Energy Ireland	Aghada - AT1	CCCT	Gas	90	1980	2023	573
ESB Energy Ireland	Aghada - AT2	CCCT	Gas	90	1980		573
ESB Energy Ireland	Aghada - AT4	CCCT	Gas	90	1980		573
ESB Energy Ireland	Ardnacrusha - AA1	Hydro	Water	21	1929		36
ESB Energy Ireland	Ardnacrusha - AA2	Hydro	Water	22	1929		36
ESB Energy Ireland	Ardnacrusha - AA3	Hydro	Water	19	1929		36
ESB Energy Ireland	Ardnacrusha - AA4	Hydro	Water	24	1929		36
ESB Energy Ireland	Erne - ER1	Hydro	Water	10	1950		36
ESB Energy Ireland	Erne - ER2	Hydro	Water	10	1950		36
ESB Energy Ireland	Erne - ER3	Hydro	Water	22	1951		36
ESB Energy Ireland	Erne - ER4	Hydro	Water	22	1951		36
ESB Energy Ireland	Lee - LE1	Hydro	Water	15	1957		36
ESB Energy Ireland	Lee - LE2	Hydro	Water	4	1957		36
ESB Energy Ireland	Lee - LE3	Hydro	Water	8	1957		36
ESB Energy Ireland	Liffey - LI1	Hydro	Water	15	1949		36
ESB Energy Ireland	Liffey - LI2	Hydro	Water	15	1949		36
ESB Energy Ireland	Liffey - LI4	Hydro	Water	4	1949		36
ESB Energy Ireland	Liffey - LI5	Hydro	Water	4	1949		36
ESB Energy Ireland	Lough Ree - LR4	CST	Peat	91	2004		1,112
ESB Energy Ireland	Marina - MRC	CCCT	Gas	123	1954	2023	573
ESB Energy Ireland	Moneypoint - MP1	CST	Coal / HFO	285	1985	2025	1,002
ESB Energy Ireland	Moneypoint - MP2	CST	Coal / HFO	285	1986	2025	1,002
ESB Energy Ireland	Moneypoint - MP3	CST	Coal / HFO	285	1987	2025	1,002
ESB Energy Ireland	North Wall - NW5	OCGT	Gas	104	1982		573
ESB Energy Ireland	Poolbeg - PBA	CCGT	Gas	231	1998		573
ESB Energy Ireland	Poolbeg - PBB	CCGT	Gas	231	1998		573
ESB Energy Ireland	Turlough Hill - TH1	Hydro	Pumped Water	73	1974		Total mix
ESB Energy Ireland	Turlough Hill - TH2	Hydro	Pumped Water	73	1974		Total mix
ESB Energy Ireland	Turlough Hill - TH3	Hydro	Pumped Water	73	1974		Total mix
ESB Energy Ireland	Turlough Hill - TH4	Hydro	Pumped Water	73	1974		Total mix
ESB Energy Ireland	West Offaly - WO4	CST	Peat	137	2004		1,112
Indaver	Indaver - IW1	OCCT	Waste	16	2011		549
SSE Generation Ireland	Great Island - GI4	CCGT	Gas	461	2015		573
SSE Generation Ireland	Rhode - RP1	OCCT	Gas/Distillate Oil	52	2004		573
SSE Generation Ireland	Rhode - RP2	OCCT	Gas/Distillate Oil	52	2004		802
SSE Generation Ireland	Tarbert - TB1	CST	HFO	54	1970	2022	802
SSE Generation Ireland	Tarbert - TB2	CST	HFO	54	1970	2022	802
SSE Generation Ireland	Tarbert - TB3	CST	HFO	241	1970	2022	802
SSE Generation Ireland	Tarbert - TB4	CST	HFO	243	1970	2022	802
SSE Generation Ireland	Tawnaghmore - TP1	OCCT	Gas/Distillate Oil	52	2003		802
SSE Generation Ireland	Tawnaghmore - TP3	OCCT	Gas/Distillate Oil	52	2003		573
Synergen	Dublin Bay - DB1	CCCT	Gas	405	2002		573
Tynagh Energy Ltd	Tynagh - TYC	CCCT	Gas	384	2006		573
Viridian	Huntstown - HN2	CCGT	Gas	342	2002		573
Viridian	Huntstown - HNC	CCCT	Gas/Distillate Oil	400	2007		573

Table 4
Summary of Tables 2 and 3 and actual generation in 2019.

Emission Source Type	Case studies	Min LCA EF [kgCO2/MWh]	Max LCA EF [kgCO2/MWh]	Average LCA EF [kgCO2/MWh]	Total generation 2019 [MWh/yr]	Total emissions in 2019 [tonne/yr]
Motor oil	21	603	1,000	802	124,740	100,000
Coal	97	837	1,167	1,002	574,710	576,003
Lignite	10	800	1,500	1,150	0	0
Gas	86	407	760	573	14,815,700	8,493,100
Waste	4	97	1,000	549	546,800	299,974
Peat	1	1,110	1,115	1,112	2,105,800	2,358,496
Biomass	72	21	193	107	0	0
Hydropower	144	12	148	36	877,600	31,993
Pumped hydro, pumping	NA	314	555	432	−478,500	206,572
Pumped hydro, generating	NA	12	148	36	243,000	8,859
Wind	393	4	90	37	9,967,400	365,198
SUM	**828**				**29,734,250**	**12,423,349**

- Build a model to test the hypothesis that incorporates the uncertainty for a large array of grid configurations to simulate possible future situations including both overcapacity and overproduction.
- The model also incorporates indirect effects and subsidies, although it is very uncertain. It is used primarily when interpreting the results.

Indeed, all the issues discussed in Sections 2 and 3 are required for interpretating the results, which is why they are included in the paper.

5. The Irish case

Ireland (IE) is an interesting case to study because it has minimal export/import – about 1.6% from July 2019 to June 2020, according to EirGrid. Furthermore, the Irish system has significant capacity surplus which will be eroded as demand increases and some generation plants are assumed to shut [35], but Demand Side Units (DSU) are improving the situation. Ireland also has the highest share of non-synchronous VRE on a single synchronous power system, which makes it one of the most challenging grids to operate in Europe [50]. Crucially, Ireland publishes grid data with 15 min resolution, which allows detailed analysis. However, first some basic facts.

5.1. Description of the Irish grid

A broad overview of the last ten years starting from 2010 (and ignoring 2020 due to COVID-19) is found in Fig. 2. We see that changes came in 2015 as gas started to increase after years of reduction. Therefore, by starting in 2015 we get more resolution, see Fig. 3.

Linear curves have been fitted using Excel, to indicate trends. We see immediately that coal has fallen while gas and wind have increased almost with the same gradient (85% similarity). Peat, the fourth major energy source of Ireland, has remained relatively constant.

Using the SCADA (Supervisory Control And Data Acquisition) readings provides a very good overview, and in Fig. 4 the grid data is presented. Note that on less than 15 days out of 4 years, the readings for 01:00, 01:15, 01:30 and 01:45 was either missing or duplicated – the duplicated were deleted and those missing were approximated using linear interpolation. This approximation is inconsequential to the results.

We see that over a 4-year period, the buildup of wind capacity is significant from 2,457.3 MW to 4,127.6 MW – 1,670.4 MW or 58.57 TWh with 100% PCF. In 2018 and 2019, the actual demand flattened despite a significant increase in wind capacity, see Fig. 4. The data points for wind and gas correlate at negative 90.3% whereas the trend curves for wind and gas correlate perfectly at 100%. Hence, the fall of coal is associated with an increased in wind, as expected, but it may be more

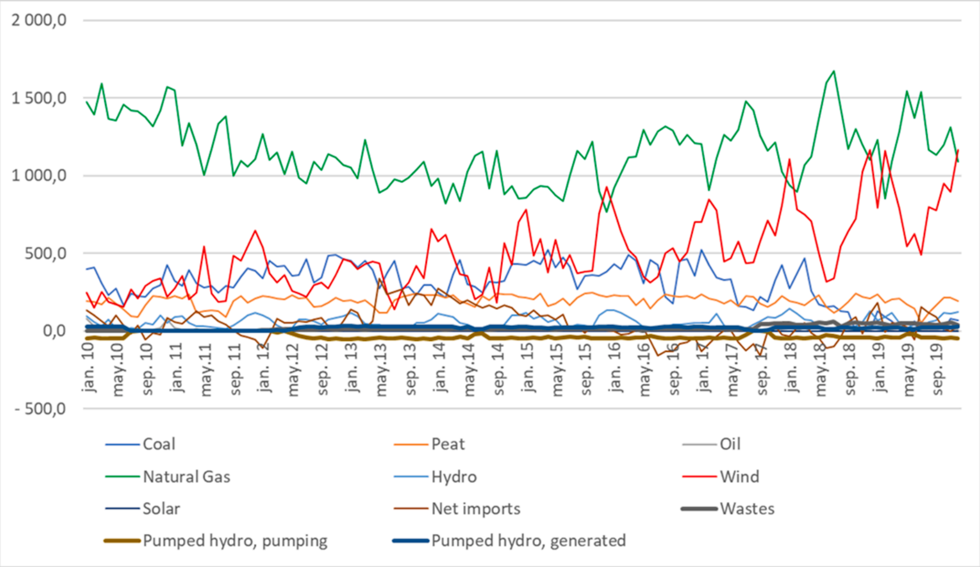

Fig. 2. Monthly Irish grid generation [GWh] 2010 through 2019.
Source: https://www,seai,ie/data-and-insights/seai-statistics/monthly-energy-data/electricity

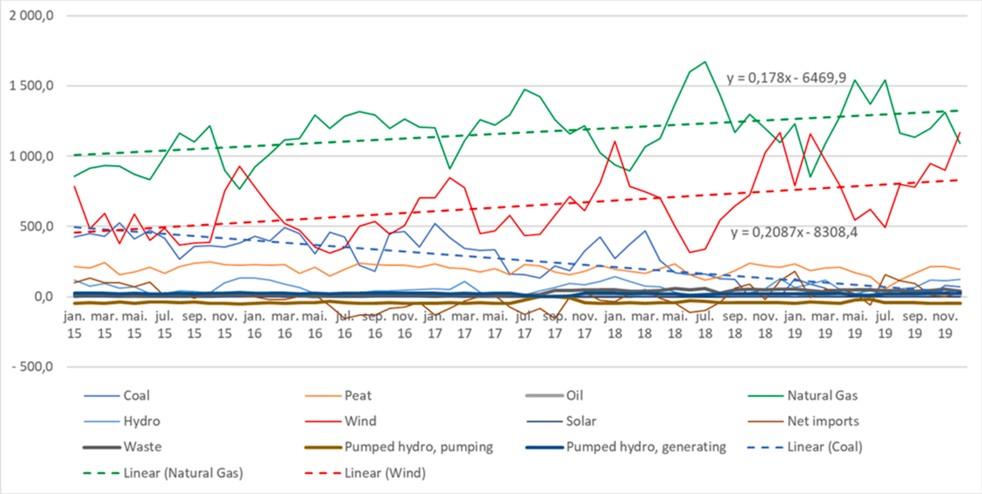

Fig. 3. Monthly Irish grid generation [GWh] 2015 through 2019.
Source: https://www,seai,ie/data-and-insights/seai-statistics/monthly-energy-data/electricity

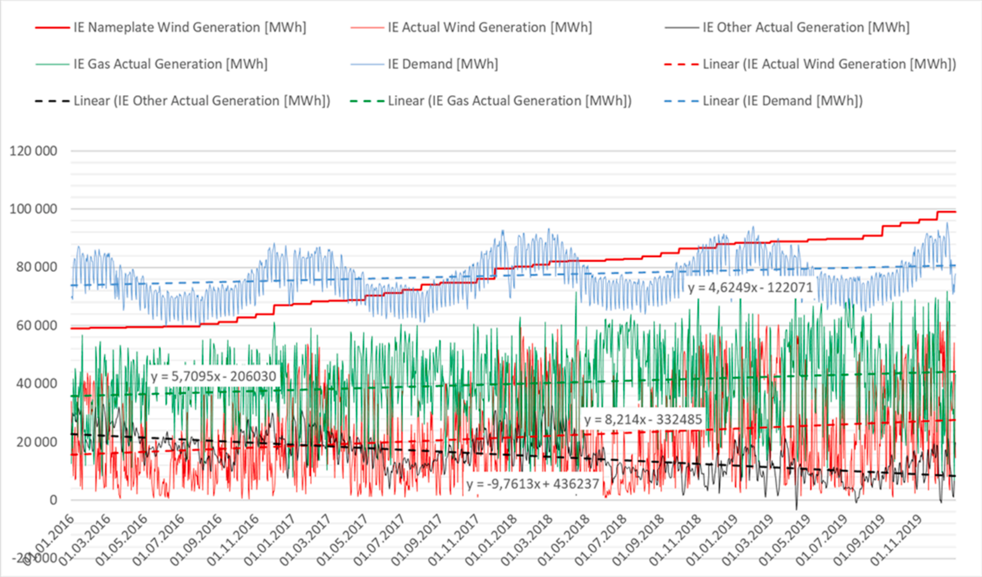

Fig. 4. Daily Irish grid data [MWh] 2018 and 2019. Authors calculations of data from http://www.eirgridgroup.com/how-the-grid-works/renewables.

surprising that the average gas consumption has equally increased. As Devlin et al. [29] note, gas and wind are unlikely allies in the UK and Ireland.

From Fig. 4 we can obtain several interesting observations for Ireland. First, the overall trendline for the demand is relatively stable, i. e., flat despite the fact that electricity consumption is expected to increase significantly [35]. The reason can be primarily warmer weather, which results in less electricity for heating, over these 48 months and/or management of DSUs, which consists of one or more individual demand sites that can be dispatched by the Transmission System Operator (TSO) as if it was a generator [35]. Second, the wind nameplate capacity has risen markedly in the period, 783.6 MW, although the actual wind production has only risen slightly, 3.6 GWh using the trend line for estimation. This gives a yield compared to additional capacity of merely 19%. Note that weather differences will impact this number too, so it should be interpreted as a guesstimate.

In Table 1 some descriptive statistics are presented. The SNSP (System Non-Synchronous Penetration) is the sum of VRE and HVDC (High Voltage Direct Current) imports as a percentage of total demand and exports. With the insignificant net import, the SNSP is essentially the ratio of VRE over total demand. Through the successful completion of the DS3 Program (Delivering a Secure, Sustainable Electricity System) the operational limit on non-synchronous generation may be increased to 75% (SEM [116]in an effort to reach the 70% renewable by 2030 target [114]. In 2019, the annual average was 33.9%.

However, it started out much lower. In March 2016, the SNSP level was reassessed concerning the reliability of the grid and the limit was raised from 50% to 55%, then to 60% in March 2017, and to 65% in April 2018 [36]. Above this limit, the VRE must be constrained/curtailed or exported. With an adequacy standard of 8 h LOLE per year [35], wind can never deliver reliably without incurring significant curtailment costs or costs for BESS.

Despite the massive increase in wind capacity, we see from Fig. 5 that the mode is merely 21 MWh/h, but the median is 184 MWh/h and the average is 224 MWh/h. Fig. 5 is a histogram of all the 15 min actual production data from wind, which results in an overall probability density function for the wind production. There is 0.2% probability for no output whatsoever. Hence, Ireland relies on fossil balancing. When it

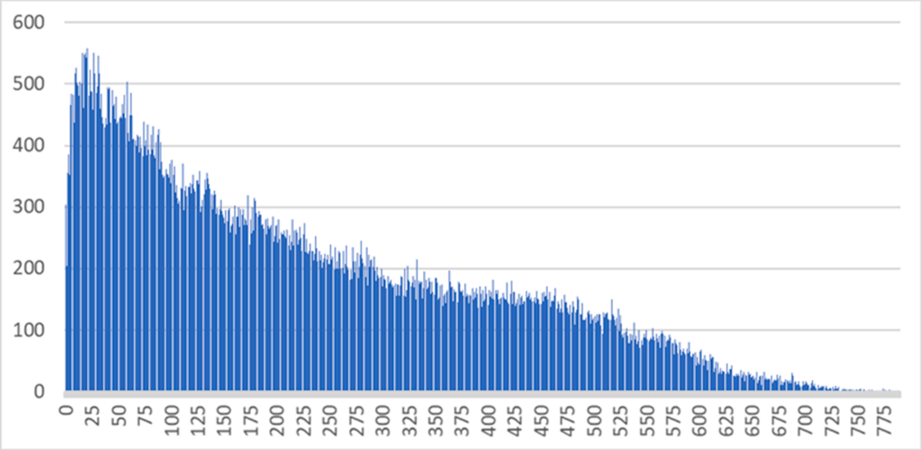

Fig. 5. Hourly wind generation probability distribution including capacity buildup without making seasonal adjustments, Ireland 2016 – 2019.

comes to the demand, a normal probability distribution using the parameters in Table 1 works. However, to reduce the uncertainty in the model, it is best to follow the seasonal variations which are relatively reliable – although somewhat uncertain.

A more interesting graph to present is the one in Fig. 6. Here, the production for the years of 2016 through 2019 is sorted from largest production of wind to the lowest using the same 15-minute resolution, which results in almost 35,000 data points per year. Clearly. irrespective of the 1,670.4 MW increase in installed wind capacity, every year the lowest production is almost unchanged and it concerns roughly 100 days per year (some 20%). Hence, the Irish grid is very dependent on fossil balancing, and a large share of annual demand can never be handled by wind. In fact, in 2018 there were 11 h with absolutely no production.

It is easy to assume that this situation arises due to Ireland being a small grid, but a similar situation is found everywhere. Even for ENTSOE the same curves emerge, see Fig. 7, despite the large investments in wind over these years. Note that some smaller countries have been excluded from Fig. 7 due to data quality, but all major grids are included – Austria, Belgium, Cyprus, Germany, Denmark, Estland, Finland, France, UK, Greece, Italy, Latvia, the Netherlands, Norway, Poland, Romania and Sweden.

Thus, we see from Fig. 7 that even across the entire ENTSOE, a third of the year has roughly a third of the production of maximum production, and over the aggregated time of a month, the production is very low (less than 20% of maximum production). Hence, with large geographical diversification, the curves become flatter, but the necessity of balancing power is not significantly reduced. Indeed, if the transmission limitations were included, see Batalla-Bejerano et al. [14], the ENTSOE situation is possibly worse than for Ireland. Hence, ENTSOE also relies on fossil balancing.

So far, we understand that increased wind clearly implies increased gas consumption, which is explained in greater detail later. Note that some of this increase is also due to increased demand. Furthermore, since gas is used as balancing, gas faces volatility from two sources; 1) from the demand itself, and 2) from the fluctuations of the wind. The question relevant for this paper is whether or not this situation is better than handling the entire production using gas alone. Interestingly, Simla and Stanek [119],Stanek et al. [125] carried out a similar study for Poland, except it concerned coal and not gas and the approach was different, but they also identify clear adverse effects of wind on thermal generators.

There are a number of assumptions that must be made to analyze the

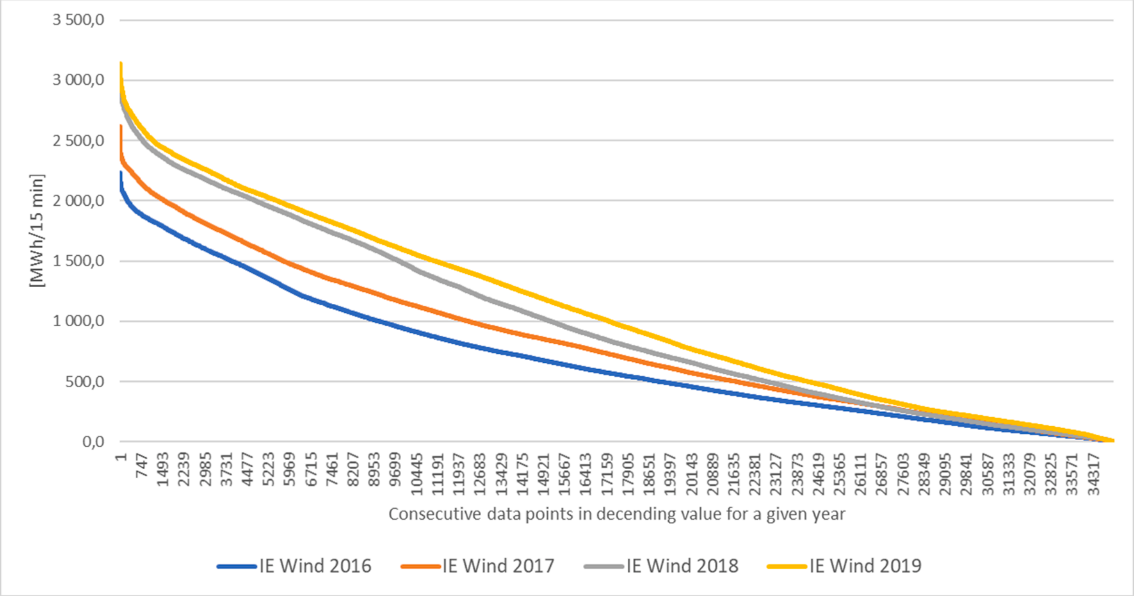

Fig. 6. Wind profile for Ireland (IE) per year using 15 min data resolution. Author calculations using data from http://www.eirgridgroup.com/how-the-grid-works/renewables.

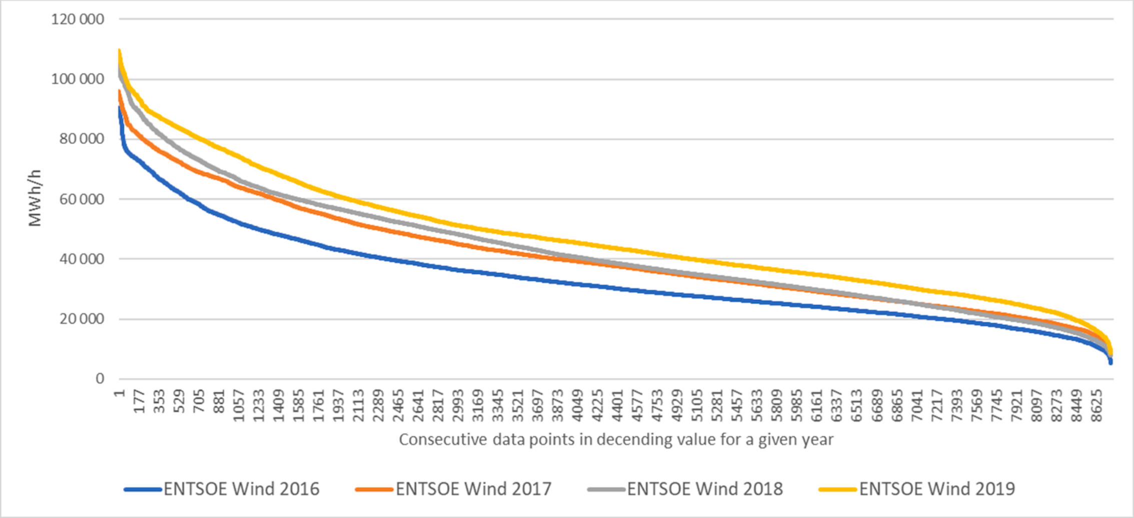

Fig. 7. Wind profile for ENTSOE per year using 1 h data resolution. Author calculations using data from https://data.open-power-system-data.org/time_series/2020-10-06.

case and avoid specific circumstances such as the weather pattern in 2019. In the model, it is assumed that gas is being ramped up and down once the wind has supplied what it can – excluding curtailment and constraints losses. Base load therefore consists of the rest of the grid, and it is changed slowly on a monthly basis to fit seasonal variations.

5.2. Data and assumptions

The SCADA data obtained from EirGrid are extremely valuable, but we also need environmental data. Since this paper takes a systemic view, the uncertainties of the various LCA estimates are used as uncertainty distributions to indicate where the 'true' LCA estimates can be found. The work of Gonzalez-Salazara et al. [51] illustrates the variability for coal- and gas turbines. Another good study is Pehl et al. [101] concerning the future low-carbon grids. They also provide data with variability, but in less details.

Starting with wind, Pehl et al. [101] estimate that nuclear, wind, Solar PV and concentrating solar power (CSP) have specific emissions of 3.5–11.5 gCO2eq per kWh while hydro has 78–109 gCO2eq per kWh. Given, the discussions earlier, it is clear that these numbers are most likely too low, which is also evident when comparing these results to the best compilation of data found during the research provided by Koffi et al. [75], see Table 2. Note that EF in Table 2 is an abbreviation for Emission Factor.

To increase the weight towards future performance, the Pehl et al. [101] study is included. Furthermore, some of the data did not include averages and minimum-/maximum values, but by using the other sources, highlighted in grey, minimum-, maximum- and expected values are approximated to complete the data set. For example, the coal data in Evans et al. [46] did not offer minimum- and maximum values so the average minimum values and average maximum values of Ardente et al. [7],Turconi et al. [131],Weisser [146] were computed and used as approximations. In total, the LCA data used in the model is derived from 828 cases, which is a significant number of cases but also necessary to capture the uncertainties in LCA estimates.

It is striking how estimates differ between various sources, which clearly support the issues discussed in Section 3. In the analysis of this paper, the uncertainty is modelled using triangular distributions using the minimum-/maximum values together with the average values as expected values. This concerns not only Table 2, but all data presented in this paper unless specified otherwise.

To provide a more accurate analysis, we also need data from all the dispatchable power plants that must step in when wind produces too little, see Table 3. Note that many plants are dual fuel power plants to secure back-up opportunities, such as the Rhode and Tawnaghmore peaker plants. Gas has large enough capacity (ca 34 TWh in 2019 at 90% PCF) to replace the wind (ca 10 TWh in 2019) completely. We also note that Ireland is in the process of closing power plants due to age and/or technology. The pumped hydro emissions at pumping have been calculated based on the total mix in the grid at the time of operation. The resulting data, based on the data in Table 2, are presented in Table 3.

Then we have peat, which requires some extra elaboration. Approximately 17% of the Irish landscape is covered in peatlands, and Ireland is one of the largest users of peat [91]. These peatlands store a significant amount of carbon, estimated at 1502.6 MT of Soil Organic Carbon (SOC), which represents 36% of total SOC stock in Ireland [34]. The problem is that peat is the least carbon efficient fuel source when compared to other fossil fuels [80], and its combustion can emit over 90% of total CO_2 emissions of the full peat energy chain [74].

A serious omission of the model is that the emission effects of puncturing peatland by the foundations of windmills is ignored. As Smith et al. [123] find, wind built on undegraded peatland is unlikely to ever reduce carbon emissions. The biochemist Mike Hall stated it bluntly in 2009; "wind farms (built on peat bogs) may eventually emit more carbon than an equivalent coal-fired power station" if drained [100]. However, this is ascribed ignorance and not inherent to wind as technology. Obviously, peat is something that must be discontinued at some point.

A summary, organized according to emission source type, is provided in Table 4. The emissions from plants without considering the supply chain is provided by SEAI [113]. Their numbers are peat at 1,065 gCO2/kWh, followed by coal at 886 gCO2/kWh, oil at 771 gCO2/kWh and gas at 366 gCO2/kWh. The total emissions, found in SEAI [113] are estimated at 10.3 million tonnes, whereas the sum of Table 4 is about 20% higher. The difference lies primarily in the life-cycle perspective, as discussed in more detail next.

5.3. Life-Cycle emissions compared to local emissions

The aforementioned 20% difference in the data has several components primarily due to the life-cycle perspective versus a purely local perspective. Clearly, when SEAI [113] has no emissions for wind and hydro, indirect emissions and emissions earlier on the supply chain are ignored.

Arguably, the 20% difference is probably too small. With the growing realization that investments in technologies that use resources more efficiently are beneficial to the economy (lower costs) as well as the environment (lower environmental burden per product unit) [148], a comparison to costs is useful. In many manufacturing industries, direct material purchases constitute up to 70% of total costs [27]. Indeed, energy- and material costs generally form the main cost category for industrial companies [148]. In Germany, which is a major manufacturing hub, material cost shares varied from 35% to 55% for individual industrial sectors in 2008 [112]. Hence, it is clear that the aforementioned 20% is probably far too little difference in the local emissions versus the total life-cycle emissions. The real supply chain emissions are probably as large as those taking place locally in Ireland, which implies that 30% is perhaps ignored.

Due to the importance of reserves and ramping in balancing, special attention is provided next.

5.4. *Modeling reserves and ramping*

When it comes to grid reserves and ramping, the time-related definitions in Fig. 8 are used in the model. With an installed wind capacity of 1,500 MW, Doherty and O'Malley [32] found that the best-case scenario is a 12% increase in the amount of reserve needed above the case with no wind, while the worst-case scenario is a 44% increase. They also estimate the actual reserve needs stating that 'For a reliability criterion of three load shedding incidents (LSI) per year and a forecast horizon of 3 h, the reserve needed on the system with no wind capacity is 470 MW'. With 1,000 MW installed wind capacity the system requires 516 MW; a 10% increase [32]. At the end of 2019, the installed wind capacity of Ireland is 4,127.6 MW. Hence, with a linear interpolation the model presented here needs a system reserve of 660 MW.

When it comes to the ramping margins, a detailed analysis by CER [22] shows that portfolios that are capacity adequate are unlikely to be adequate in terms of ramping over all the necessary timeframes to efficiently and effectively manage the VRE and changes in interconnector flows while maintaining system security. This means that having enough capacity is insufficient to maintain grid reliability. Hence, rules for ramping must be implemented to provide buffers to the system. Therefore, the rules in Table 5 are implemented, also in this study, and ramping margin is defined as 'the increased MW output that can be delivered by the service horizon time and sustained for the product duration window'.

Note that to perform the Monte Carlo simulation, which is described at the end of this section, a minimum ramping increment/block must be defined, and it is set to the smallest gas turbine or pumping hydro capacity, which is 52 MW in this case. Obviously, this is a crude approximation with respect to a single facility, but when implemented across all the dispatchable assets in Ireland, it is accurate enough given the accuracy of the emission data.

Table 5
Ramping margin services. Source: CER [22].

Ramping Margin Service	Ramp-up Requirement	Output Duration
RM1	1 hr	2 hrs
RM3	3 hrs	5 hrs
RM8	8 hrs	8 hrs

Emissions are typically estimated as specific EFs per megawatt-hour [kg/MWh] [51]), and fuel consumption is related to ramping and Minimum Environmental Load (MEL) of the balancing fossil energy sources. The MEL is also called the minimum emissions-compliant load because it is the lowest output at which the generating unit can operate and still meet environmental limits for nitrous oxides (NOx) and carbon monoxide (CO) emissions, and typically it is about 50% of full load [151]. Ramp rates of most industrial frame gas turbine models are advertised as 10 MW/min up to 100 MW/min, with an average of about 25 MW/min, and the ramp rate depends on generating unit capacity, operating conditions and optional technologies for reducing startup time and increasing ramp rate and the number of units and their configuration [152]. Unfortunately, the starting loading capability is often quite different than the advertised ramp rate for gas turbines; ramp rates of 35 to 50 MW/min are achievable only after the unit has reached self-sustaining speed.

More important than the ramp rate, however, is the minimum operation load [54]. Below 50 percent, most plants increase their emissions to the point that they violate air permits, according to the industry expert Harvey Goldstein [94], although some can go down to 40% [151]. Indeed, at their respective MEL, gas is less flexible and produced more NOx and CO emissions than coal [51]. As Abudu et al. [1] illustrate, ramping and its consequences is a complex field. Therefore, in this paper it must be simplified using Table 5 and NOx and CO emissions are ignored.

However, we can estimate the increase in emissions during ramping by using the averages of the normalized ratios between high load and Minimum Complaint Load (MCL), which is the minimum load at which the turbine is complaint either with emissions or other restrictions [51]. MCL is assumed to be the same as MEL in this paper and in Table 6. Then, we get a Fuel Ramping Factor (FRF) of 1.36 for gas ranging from 1.24 to 1.73 and for coal we get 1.14 with no variation. The FRF is the ratio between the full load and the MCL. The number from coal is used as approximations for all fossil sources, except for gas. This introduces extra uncertainty which is modelled as 1.14 ± 10% using a triangular distribution.

The actual, ideal ramping profile for 2018 and 2019 is shown in Fig. 9, and polynomial curves have been fitted. The ramping is the difference between gas load from one 15-minute interval to another with- and without wind. 'Other' is the sum of all other dispatchable energy sources. For 2018 and 2019 this gives 70,079 15-minute intervals, which in Fig. 9 is aggregated to day level for presentation.

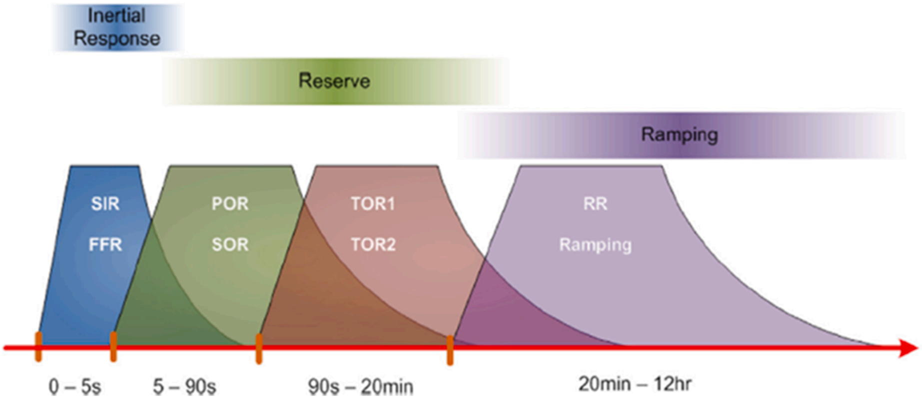

Fig. 8. Frequency control measures in Ireland. Source: CER [22].

Table 6
Emissions as a function of load. Data from Gonzalez-Salazara et al. [51].

Load	Type of plant	Min Effect	Max Effect	CO2 emissions [kg/MWh]			High vs MCL		
		[MWe]	[MWe]	Average	Min	Max	ratios		
Full load	HDGT Simple Cycle	269	334	500	482	529	1	1	1
Full load	HDGT Combined Cycle	398	475	345	334	359	1	1	1
Full load	Aero Gas Turbine	14	58	495	418	565	1	1	1
Full load	Small Coal	3,5	21	1072	951	1202	1	1	1
Full load	Mid-sized Coal	27,5	165	869	771	974	1	1	1
Full load	Large Coal	100	250	775	688	869	1	1	1
MCL	HDGT Simple Cycle	269	334	711	640	801	1,42	1,33	1,51
MCL	HDGT Combined Cycle	398	475	417	340	591	1,21	1,02	1,65
MCL	Aero Gas Turbine	14	58	715	572	1153	1,44	1,37	2,04
MCL	Small Coal	3,5	21	1252	1111	1404	1,17	1,17	1,17
MCL	Mid-sized Coal	27,5	165	984	873	1103	1,13	1,13	1,13
MCL	Large Coal	100	250	866	768	971	1,12	1,12	1,12

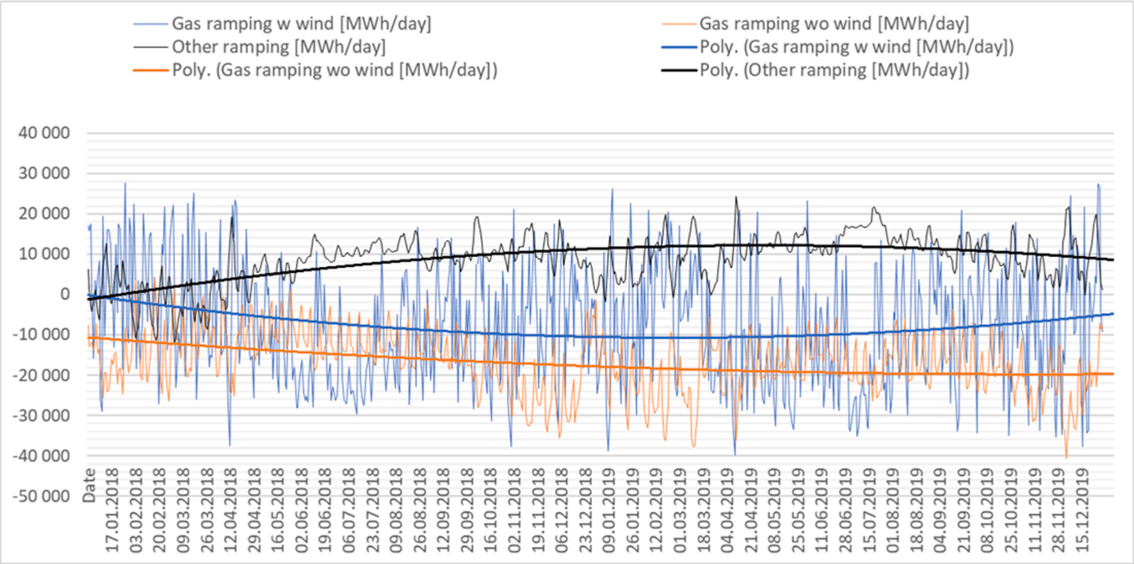

Fig. 9. Actual ramping requirements in 2018 and 2019. Authors calculations of data from http://www.eirgridgroup.com/how-the-grid-works/renewables.

We see that the ramping of gas would have been less if there were no wind at all, i.e., the demand was met using only gas. In fact, if we calculate the standard deviations of the ramping, it is 14.6 GWh when wind is in the grid, but only 6.9 GWh without wind. The difference of this in terms of challenges to the grid is significant, as illustrated graphically in Fig. 10.

The ramping profile then becomes as shown in Fig. 11. The model is an approximation, but it clearly illustrates that Gas Only leads to less ramping, which the real-life data in Fig. 10 shows. Hence, the model is quite realistic. The increased aging of assets due to the increased ramping in the Wind + Gas alternative is ignored. By removing the demand and generation curves, only the ramping is left in Fig. 12. The

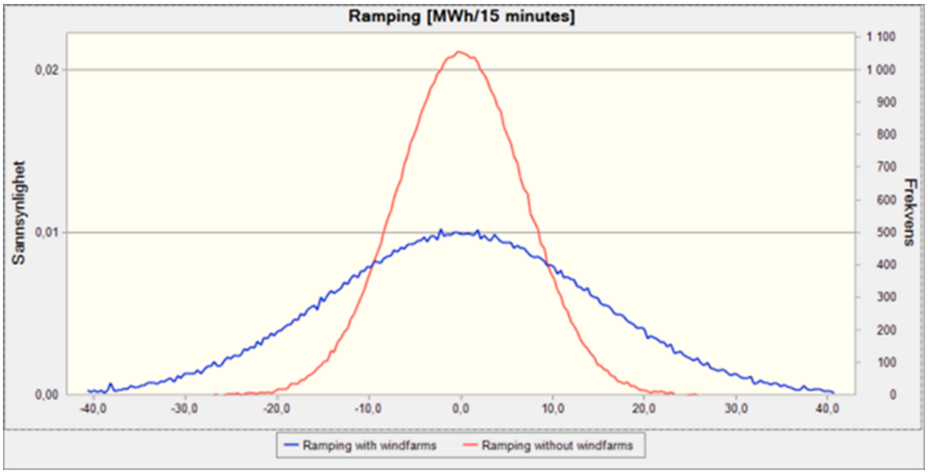

Fig. 10. Ramping with, or without, wind in the Irish grid. Author's calculations of data from http://www.eirgridgroup.com/how-the-grid-works/renewables.

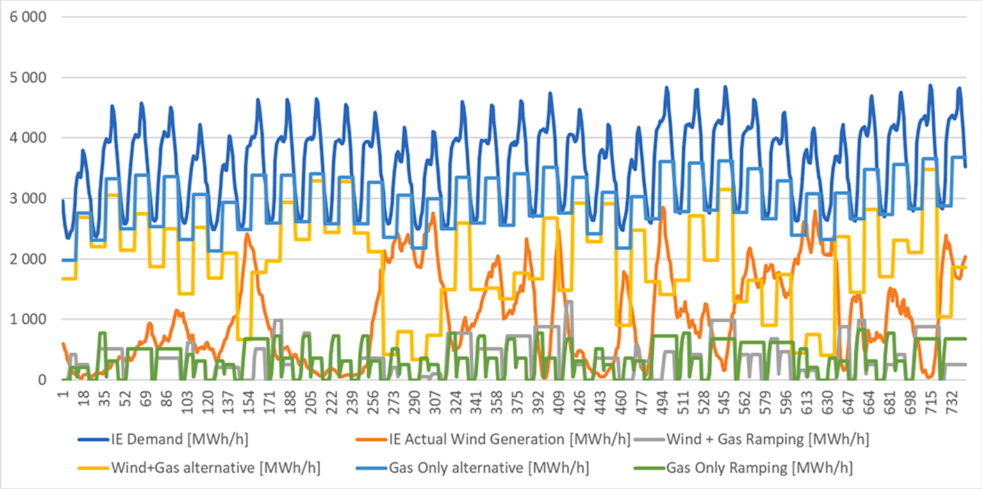

Fig. 11. January 2019 demand, generation and ramping in the model with 15 min resolution.

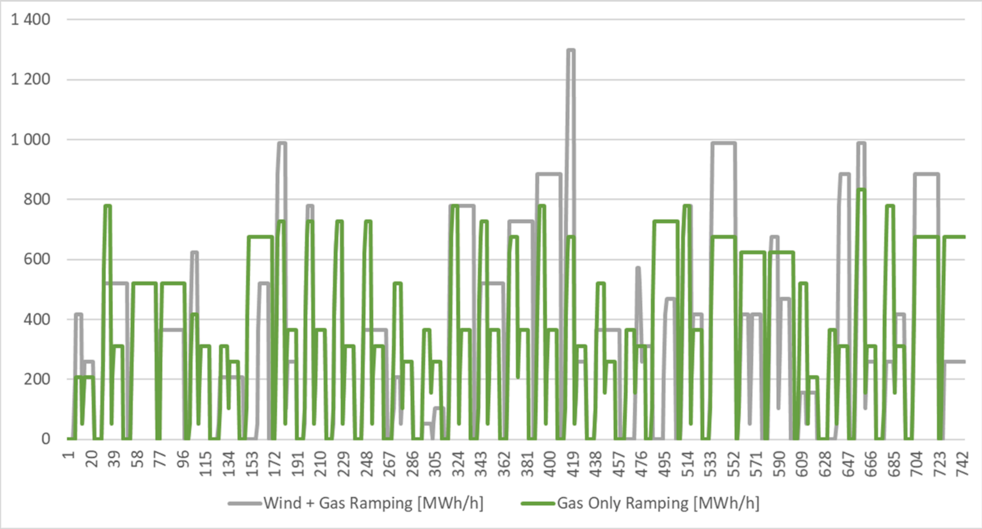

Fig. 12. Ramping profile in the model for one month.

statistics show that Wind + Gas introduces far more ramping by the numbers while the Gas Only alternative has less ramping but somewhat longer periods, as expected.

The final element of the model is to guesstimate the indirect effects. Using inflation and current electricity prices we find that small businesses and households in Ireland has an electricity price about 73 EUR/MWh higher electricity price than inflation would imply. Industry has the price implied by inflation. However, in the Gas Only alternative, gas must replace wind. The LCOE for electricity from gas is around 67 USD/MWh ranging from 58 to 81 (US [138], or roughly 57 EUR/MWh ranging from 49 to 69 using the exchange rates for 2019 found from the World Bank.

If Ireland used gas instead of wind, the savings would have been approximately 116 EUR/MWh for the share of the wind, compared to the current 245.6 EUR/MWh price in Ireland. With approximately 10.0 TWh of wind in 2019, that costs about 73 EUR/MWh more than inflation, this would have given a total energy, economy wide saving of about 389 MEUR compared to today. Since subsidies in 2018/2019 ran at 209 MEUR [25], the Gas Only alternative would have eliminated all subsidies and reduced the overall annual cost by 180 MEUR. Since, the total cost of Ireland's energy imports in 2018 was 5.0 billion Euros[114]and total emissions from all energy usage in Ireland are about 38,6 million tonnes (SEAI 2020a), then this relatively small saving would imply about 2.0 million tonnes less emissions due to a more cost effective solution. In the deterministic case, the total emissions avoided in the Wind + Gas alternative compared to Gas Only alternative would then become 1.6 million tonnes.

Due to the fluctuations of the wind, we must model the uncertainty for every data category (demand, wind production, gas, etc, and the data in the tables presented earlier), for every 15 min. Then, 10,000 Monte Carlo trials are run, using Latin Hypercube sampling for best possible accuracy, for the two alternatives to test the hypothesis. Unless otherwise is mentioned, triangular uncertainty distributions with ± 10% variation are used. Since the model contains 17,652 assumptions and 9 forecasts, this gives a total data sample of 176,5 million datapoints, which with 15 min resolution corresponds to 5,000 years of sampling with the 2019 configuration of the Irish grid. The interested reader in Monte Carlo simulations can find very detailed descriptions with basic examples in Emblemsvåg [39].

5.5. *Results*

The main results are shown in Fig. 13. The model has remarkably similar (3.5 million tonnes) baseline to the official figures which are 3.1

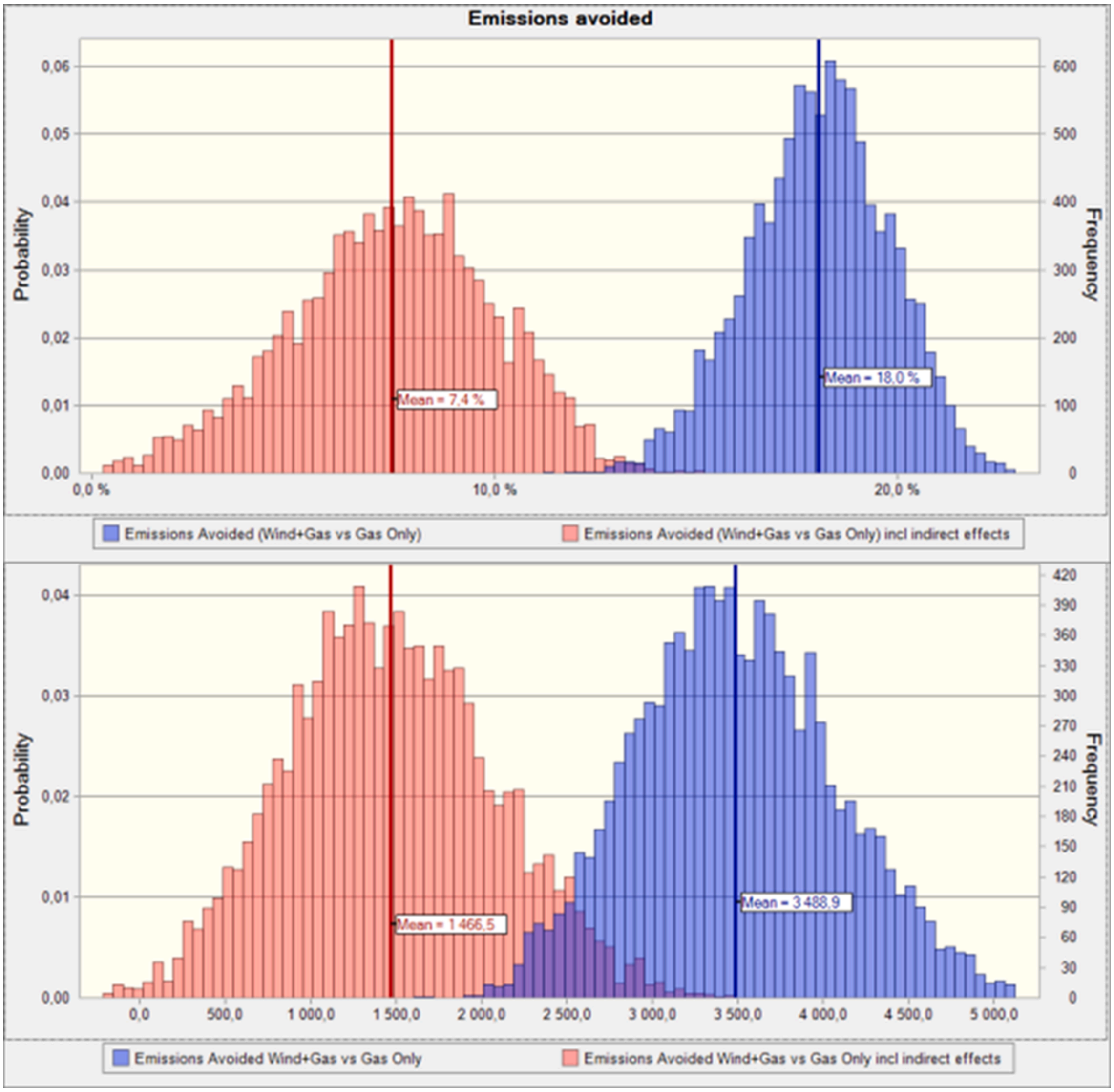

Fig. 13. Life-Cycle Emissions [kilotonnes/yr] for both alternatives in the lower panel and percentage change in top panel and with and without indirect effects.

million tonnes avoided (SEAI 2020a) by wind.

The reason for the difference is that the model takes a life-cycle perspective, has generalized a year using statistics, electricity demand was 2.1% higher in 2019 than in 2018 and the model is a simplification of reality concerning the actual mix in the grid of various dispatchable energy sources. Furthermore, some of these energy sources have been used less and less, see Fig. 3. Therefore, a direct comparison is only indicative.

The upper panel in Fig. 13 shows the percentage change in emissions avoided whereas the lower one displays the absolute numbers of emissions avoided. In line with Tsagkaraki and Carollo [130],Udo [133], which also studied the Irish grid, we see that the emission savings of having wind into the grid is relatively limited and far less than what many believe.

The impact of indirect effects, the red graphs in Fig. 13, such as subsidies shifts the avoided emissions downward by approximately 1.5 million tonnes. This effect is uncertain and should therefore be interpreted with care. Then, we must add the issues excluded from the model such as 1) the increased aging of the assets, 2) the likely underestimation of emissions upstream in the supply chain with respect to all technologies involving large amounts of REE, i.e., wind and 3) the puncturing of peatland. The total impact of data uncertainty and indirect effects is extremely difficult to estimate. However, it is unlikely that wind does not contribute positively at all, or even negatively. Hence, the research hypothesis is supported particularly if we ascribe the puncturing of peatland as ignorance and avoidable.

Nevertheless, the title of this paper is clearly supported. In 2019 the SNSP was 33.9%, but it varied substantially and reached the 65% limit many times. To reach 70% on average, including hydro, requires massive amount of curtailment. Furthermore, with the many days of low wind production, see Fig. 6, and the relationship between wind and gas documented in Figs. 3 and 4, the inescapable conclusion is that Ireland will continue to depend on fossil fuel and cannot build a low-carbon grid with the current approach. This conclusion is also strongly supported by the sensitivity analysis performed of all the parameters in the model, see Fig. 14. This conclusion is even more robust if we take into account setback distances of up to 2000 m, depending in wind turbine height, which alone would result in 95% of the country being excluded for the development of new onshore wind [26].

Unfortunately, expanding offshore wind and also curtailing the wind indirectly by producing hydrogen through electrolysis is extremely costly. The reason is that the costs for offshore wind are even higher than onshore and emissions are higher due to infrastructure such as service vessels. In fact, Japan discontinued their only floating wind experiment after almost 10 years of operations due to poor profitability [79].

But regardless of wind levels, the fact is that the grid stability

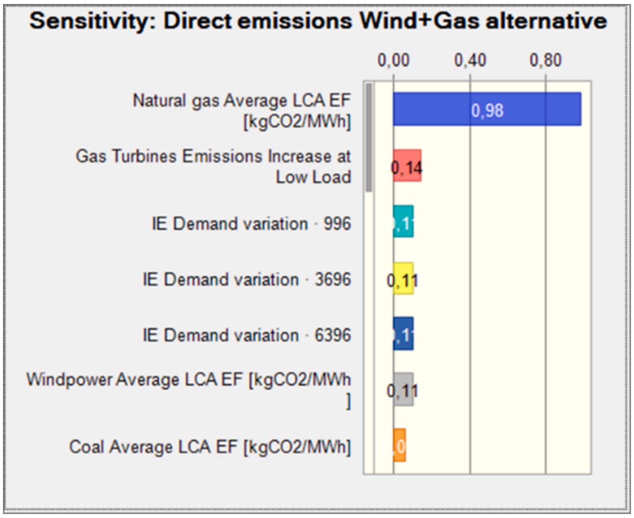

Fig. 14. Sensitivity analysis of Wind + Gas alternative.

requires synchronous energy sources. With a SNSP limit of even 70%, it is hard to see how any grid can ever become low-carbon with foreseeable technologies unless low-carbon synchronous energy sources are developed. What approach Ireland chooses is not relevant for this paper, so the discussion about Ireland ends here after critically revieing the case in the next section. Thereafter, we discuss the implication of the case for the broader topic of wind.

5.6. *Critical evaluation of case study*

Although the greatest efforts have been made to model the emissions from the grid accurately using historical data with high resolution, 828 LCA cases to provide the best possible emission inputs, ramping and grid reserves are included – even some indirect effects and subsidies are incorporated – the model is admittedly a simplification of reality that ignores aging, human decision-making and more. By analyzing two alternatives up against each other, however, some of the consequences of these simplifications cancel out although the LCA data quality remains an issue along with the simplistic modeling of indirect effects and subsidies.

Nonetheless, the Monte Carlo simulation performed with high resolution and a large number of trials, gives robust estimates. It is therefore unlikely that the true results are found outside the total solution space presented in Fig. 13.

Emission analyses have been performed countless times, but as we see from the literature review, these studies have many limitations. The presented analysis is possibly one of the most comprehensive analysis of its kind, which is why it is original. It has many technical improvements over earlier analyses, it has a larger LCA data base, it discusses LCA shortcomings and try to rectify some of them, and it is the only analysis including indirect effects, subsidies and analyze how wind can achieve a low-carbon grid with fossil balancing by ramping and grid reserves. Given that the high penetration of wind in Ireland results in such small improvements, 10 – 20%, this observation begets whether or not this is a generalizable finding. This is discussed next.

6. Discussion and future work

Based on the German situation discussed earlier, and Fig. 7 for ENTSOE, the modeling and empirical findings from the model, support the title of this paper in cases where fossil energy balances wind. However, if load-following energy sources with very low emissions can be found, the conclusion will also change. For example, researching how wind can work together with hydroelectric power should be prioritized. Another option is related to the possibility of using load-following nuclear reactors, see [98], and molten-salt reactors is one such avenue [41].

To be more specific, its main contribution is that it provides insights concerning how wind impacts emissions in grids, which is poorly understood [31,127]. Basically, wind can provide some reductions in emissions, but only to a certain level due to diminishing returns economically and environmentally. As we see in 2021 in Germany, despite all the subsidies and the 80% expansion of total grid capacity by renewables [121], wind production fell by 25% and climate gas emissions have the greatest rise since 1990 [118]. As mentioned earlier, there are several studies pointing to the fact that the emission reductions caused by wind are far less than many think. The results of this study make this finding even clearer. However, Thomson et al. [127] also find that “Furthermore, it was also identified that wind is almost as technically effective as demand-side reductions at decreasing GHG emissions from power generation.”

This sentence is too broad. It seems that their model does not have sufficient granularity to answer such questions because it ignores curtailment effects and reliability issues (including grid reserves and ramping) related to the SNSP ratio, and it ignores the life-cycle emission perspective. In real life, as in the model presented here, it is critical how demand side effects materialize. If they are very short-term (less than 3 h), they have no impact whatsoever because the grid reserve will not change. If the demand is reduced for longer time periods (at least 12 h) resulting in a net reduction in generation without idle cycling of fossil energy sources, however, then demand side reductions are the most effective approach because it cuts emissions directly at the root. In the intermediate interval, emission reductions depend on a number of factors such as ramping, reserve changes, grid mix, fossil energy source mix, etc. The strength of using the Monte Carlo simulation, as done in this paper, is that we can sample the entire solution space accurately and hence analyze the impact of simultaneous changes (combined effects).

In fact, Denny and O’Malley [28] find that some of the environmental benefits of wind generation may be reduced by an increase in emissions from combustion plants accommodating wind. Additionally, wind reduces CO_2 emissions, but it is not effective in curbing SO_2 and NOx emissions. Hence, they conclude that a short-term policy promoting the reduction in system demand through energy efficiency (demand management) and consumer awareness may prove both more economical and more emission efficient than a short-term policy promoting large-scale investment in wind.

Nevertheless, wind will have some positive effect on emissions, but the reductions will not sufficiently lead towards a low-carbon grid when wind is balanced by fossil energy. In their study after the blackout in Turkey in 2015, Project Group Turkey [103] argues that “A large electric power system is the most complex existing man-made machine”. Then, exposing the grid to the fluctuations of the wind is not the way forward neither economically nor environmentally. Thus, low-carbon grids must be developed using energy sources that are predictable, safe, economical with near-zero life-cycle emissions.

The primary, direct applicability of this paper is to show that the current path of using wind to achieve the SDGs, will not work in grids where the balancing power is fossil. Policy today should therefore primarily focus on developing balancing power that have low-carbon footprint otherwise the investments in wind will not produce the intended effects. Academically speaking, its value lies in its originality discussed in Section 5.6.

To improve the usefulness of the work further, there are three main avenues to pursue. Firstly, expand towards Solar PV to include the other main VRE. In this case, batteries are important components to discuss, as shown by Emblemsvåg (2021b); Raugei et al. [105]. Secondly, model a different balancing power approach such as hydro or load-following nuclear power. Thirdly, develop more accurate models concerning the indirect effects and subsidies.

It should be noted that improved data quality will always be interesting. It is particularly important to estimate the true emissions in the Chinese supply chain of REE. With the poor data quality associated with REE production, it is likely that the reduction in emissions from wind reported in the case will move towards 10% as suggested in the model, and perhaps even 0% when indirect effects are included.

7. Conclusions

The paper has analyzed in detail the impact of high wind penetration in grids with fossil balancing using both simulation and empirical data. The Irish grid was chosen due to its high-penetration of wind, isolation and high-resolution data. The hypothesis that “A grid incorporating wind energy balanced by gas power plants will have lower emissions than if gas power plants have replaced the wind energy in the same grid” was tested and accepted.

However, both the simulation and the empirical data unequivocally support the key finding that wind is dependent on balancing power to such an extent that wind cannot be analyzed independently. Furthermore, due to the fluctuations of the wind, grid operators cannot accept high penetrations of wind and at the same time expect to build a low-carbon grid unless large alternative costs are to be introduced and potentially system reliability compromised. Therefore, wind is renewable, but it does not provide an economical approach towards low-carbon grids. In smaller grids, such as the Irish, it is even technically infeasible because irrespective of installed wind capacity, the wind production will too often be too low. The exception occurs when the balancing power is dispatchable and not based on fossil fuels.

At a policy level, the paper suggests that policymakers should become less preoccupied by what is renewable and focus more on what is sustainable. The assumption underlying much rhetoric today, that VREs are per definition sustainable, is incorrect because VREs are not independent source of energy – its impact on the grid is crucial to understand. Concerning wind, it fluctuates and requires balancing power to such an extent that it is incompatible with a low-carbon grid unless it is combined systemically with balancing power that is low-carbon or groundbreaking improvements in BESS are found. When fossil fuel is the balancing power, wind is not sustainable per today.

Declaration of Competing Interest

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

Acknowledgements

I would very much like to thank EirGird for making excellent SCADA data available, and to Eric Lambert in particular for providing detailed data for each power plant in Ireland. I would also highlight the useful feedback from both the editor and two anonymous reviewers.

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