International Journal of Sustainable Energy

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/gsol20

Wind power with permanent magnets is not sustainable with today's *modus operandi* but a number of changes can improve this situation

Jan Emblemsvåg

To cite this article: Jan Emblemsvåg (2025) Wind power with permanent magnets is not sustainable with today's *modus operandi* but a number of changes can improve this situation, International Journal of Sustainable Energy, 44:1, 2452847, DOI: 10.1080/14786451.2025.2452847

To link to this article: https://doi.org/10.1080/14786451.2025.2452847

Published online: 16 Jan 2025.

INTERNATIONAL JOURNAL OF SUSTAINABLE ENERGY
2025, VOL. 44, NO. 1, 2452847
https://doi.org/10.1080/14786451.2025.2452847

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Wind power with permanent magnets is not sustainable with today's *modus operandi* but a number of changes can improve this situation

Jan Emblemsvåg

Department of Ocean Operations and Civil Engineering, NTNU Ålesund, Norway

ABSTRACT

The presented research rejects the typically held view that wind power is a sustainable energy source. Two key insights support this position. First, the manufacturing of permanent magnets required by most wind turbines today, emits large amounts of greenhouse gases. Second, wind power requires balancing- and backup power and increased grid reserve to reliably secure power to customers. Typically, gas power is used. Combining these two insights, and using the Republic of Ireland as a case study, this paper submits a novel study. The conclusion is that wind power with permanent magnets will not meet the 'low carbon' target of 100 kg CO_2-eq./MWh set forth as an operational target for sustainability. The wind industry can improve the situation substantially by reusing permanent magnets at least 4 times and balancing wind power with non-fossil, dispatchable power such as nuclear power, hydroelectric power, geothermal power or bio energy.

ARTICLE HISTORY
Received 29 July 2024
Accepted 7 January 2025

KEYWORDS
Balancing- and backup power; life-cycle assessment (LCA); life-cycle GHG emissions; low carbon; rare earth element (REE)

1. Introduction

Providing 'low carbon' electricity for all people is an essential characteristic of a 2°C-compatible energy system (Rogelj et al. 2018), and the most ambitious climate mitigation scenarios require electrification of most of our economy. Life-cycle assessment (LCA) is used to inform the sustainable pathways for 'low carbon' energy system development and consideration of the available natural resources and regulatory, social, technical, environmental and economic aspects of programmes (UNECE 2021). Furthermore, the life-cycle global warming potential (GWP) has become one of the most commonly used tools for assessing sustainability of energy sources (Stanek et al. 2018).

The 'low carbon' development concept has its roots in Rio 1992, generally expressed in the context of the term low-emission development strategies (LEDS) used to describe forward-looking national economic development plans or strategies that encompass low-emission and/or climate-resilient economic growth (Clappi, Brineri, and Karousakis 2010). The term 'low carbon', however, lacks a clear definition. The European Commission (2018) sets the target in 2009 of reducing Greenhouse Gas (GHG) emissions to 80–95% below 1990 levels by 2050, but it did not specify the target clearly. Therefore, after discussing this target and contextualising it using EU data, Emblemsvåg (2022) suggests a definition of a 'low carbon' energy source as an energy source with a life-cycle GHG emission of 100 g CO_2-eq./kWh (or 100 kg CO_2-eq./MWh) or lower. With reference to Figure 1, this definition seems useful because it also corresponds to energy sources we commonly

CONTACT Jan Emblemsvåg emblemsvag@yahoo.com

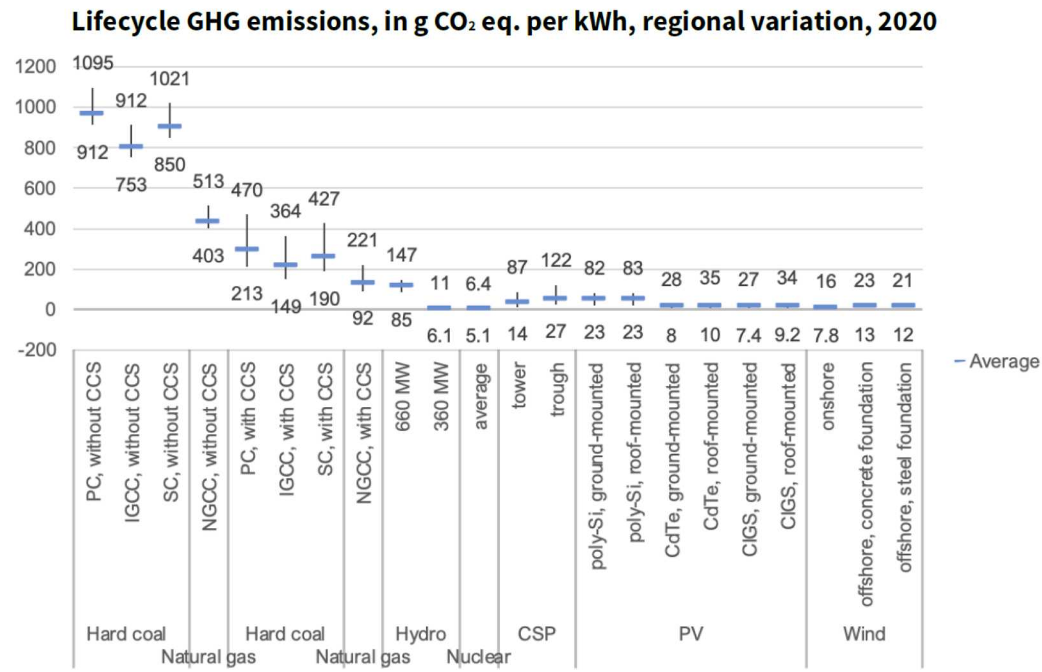

Figure 1. Life-cycle GHG emission in g CO_2 equivalents per kWh including regional variations, 2020. Source: UNECE (2021).

refer to as 'clean', and it is therefore adopted in this research as well. It is noteworthy that hydroelectric power (dubbed Hydro in the rest of the paper) does not necessarily meet the 100 g CO2-eq./kWh limit.

It is important to note from Figure 1 that there are spreads in the life-cycle GHG emissions for all technologies. Generally, the fossil energy sources display the greatest spread. However, several energy intensive materials needed for wind turbine designs, such as Rare Earth Elements (REE) for example, are not accounted for in the life-cycle inventories used for calculating the life-cycle GHG emissions, due to the absence of several processes/parts in the 'minerals and metals' indicator (UNECE 2021).

Thus, LCA estimates come with a large number of caveats and shortcomings (Emblemsvåg 2021a; Finkbeiner et al. 2014). For example, LCAs of wind power, dubbed Wind in the rest of the paper, rarely include the impacts of REE associated with the permanent magnets used in most wind turbines, and the LCAs that *do* include the permanent magnets admit that the data quality on the Chinese part of the supply chain (where REE is introduced) is very poor (Marx et al. 2018). Even the majority of original equipment manufacturers 'don't have good visibility as to the source of their REEs', according to Ryan Castilloux (Dodd 2018).

LCA has historically been a bottom-up approach, but a recent top-down assessment shows that an increase of 1% of green energy production represents roughly a 0.90% increase of GHG emissions in the exploitation phase including mining, processing, and production stages (Golroudbary et al. 2022). This finding is derived using the life-cycles GHG emission rates from energy sources that are adapted from the GREET model (Wang et al. 2021) and previous studies (Jin et al. 2018). GHG intensities are calculated by using IPCC AR5 100-year GWP values (IPCC 2013) where 1 is used for CO_2, 36 is used for CH_4 and 298 is used for N_2O, respectively. The research of Golroudbary et al. (2022) concerns the 'permanent magnets' type called Neodymium magnets (NdFeB) frequently used in wind turbines and direct drive motors in electric vehicles (EVs) (Fishman and Graedel 2019).

The novelty of this case study consists in conducting a holistic assessment of the quantitative impact of green energy technologies on other natural resources, i.e. REE, and assessing the side effect and dynamic changes over time in the period 2010–2030 (Golroudbary et al. 2022). The study considers 16 types of ores existing in the deposits (Bastnäsite, Monazite, Xenotime, Euxenite, Apatite, Gadolinite, Loparite, Uraninite, Brannerite, Dolerite, Pyrochlore, Perovskite, Zircon, Clay, Synchysite, and Parisite) while analyses offered by other publications are limited mainly to 1 or maximum 3 types of ores (usually Bastnäsite, Monazite, or ion-adsorption clays). Although, several technologies are currently being developed to reduce the use of REEs in permanent magnets, they will remain far from competitive with the existing wind technologies even until the next decade (Bobba et al. 2020). Thus, permanent magnets are most likely here to stay for a long time, which raises the following research question:

Can Wind using permanent magnets meet the 'low carbon' target?

This research question refers to Wind in its ideal application. For example, Wind built on undegraded peatland is unlikely to ever reduce carbon emissions (Smith, Nayak, and Smith 2014). As the biochemist Mike Hall bluntly stated in 2009; 'wind farms [built on peat bogs] may eventually emit more carbon than an equivalent coal-fired power station' (Pearce 2009).

Furthermore, Emblemsvåg (2021a) demonstrated through a detailed simulation of the Irish grid that Wind will never meet the 'low carbon' target, as long as it is balanced by fossil fuels. Ireland is particularly interesting as a possible window into the future. The country has the highest share of non-synchronous Variable Renewable Energy sources (VRE), such as solar photovoltaics (PV) and Wind, on a single synchronous power system combined with minimal export/import (about 1.6% from July 2019 to June 2020 according to EirGrid), which makes the Irish grid one of the most challenging grids to operate in Europe (Gaffney, Deane, and Gallachoir 2019). Yet, despite the high share of VREs, the life-cycle GHG emissions in Ireland had fallen by merely 20% due to an almost perfect correlation between Wind and gas power (dubbed Gas in the remainder of the paper) for balancing despite significant increase in Wind capacity, see Figure 2.

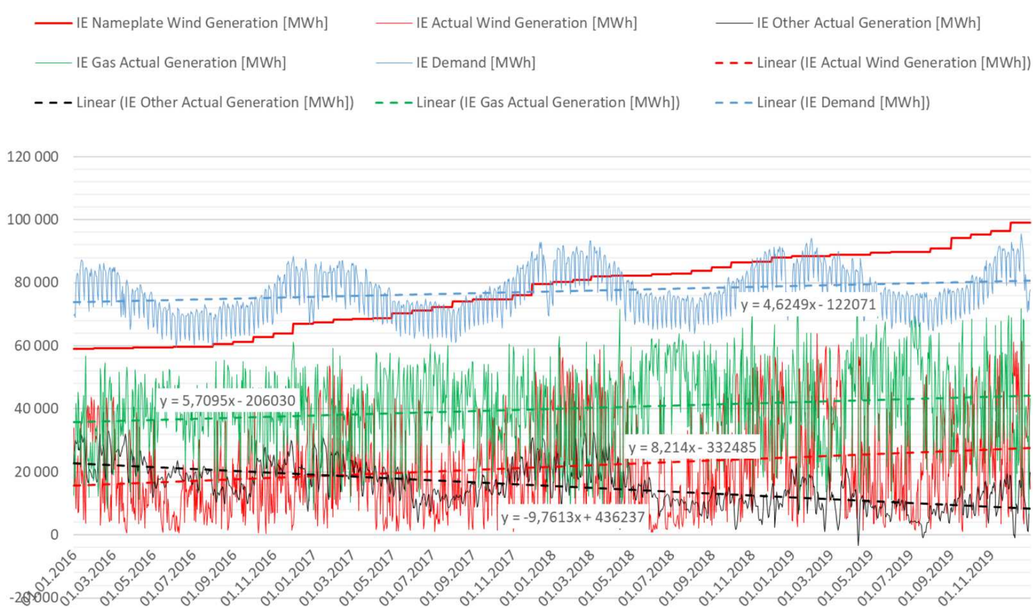

Figure 2. Daily Irish grid generation [GWh] 2015 through 2019. Source: Emblemsvåg (2021a) using data from https://www,seai,ie/data-and-insights/seai-statistics/monthly-energy-data/electricity.

It is important to understand grid stability where synchronisation determines the control of frequency and voltage stability in the grid. The SNSP (System Non-Synchronous Penetration) in Ireland 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 Committee 2017) in an effort to reach the 70% renewable by 2030 target (SEAI 2020). In 2019, the annual Power Capacity Factor (PCF) for Wind was 28.4%. That is, Wind produced 28.4% of its nameplate capacity, but the SNSP limit was reached frequently and on annual basis it ended at 33.9%. The difference between 28.4% and 33.9% is due to other VRE and import from the UK. Ireland had essentially almost reached its grid technical decarbonisation limit given today's technologies.

Using grid forming inverters (and not grid following inverters like today), there may be a technological solution to the limit of the SNSP so it conceivably can be lifted to 100%. There are, however, major technical hurdles as such inverters have never been used at scale before. It is also costly and would lead to very large amount of curtailment or storage needs, which both cost money. Therefore, Wind without balancing is not economically feasible due to grid technical issues (Emblemsvåg 2021a). Since 26 OECD countries use Gas as the primary balancing power for Wind (Verdolini, Vona, and Popp 2018), this finding applies to most OECD countries also. However, the study of Emblemsvåg (2021a) was incomplete by the difficult access to emission data from China concerning the production of permanent magnets for the wind turbines. Thus, there is a need to amend the study. Two alternatives that may work for *any* country are proposed – (1) 'Wind + Gas' where Gas is used for balancing- and backup power and (2) 'Gas Only' as a reference. In this paper, these two alternatives are analysed.

Note from Figure 2 both the seasonal- and daily demand variations with a rising trend curve from year to year. The expansion of Wind has resulted in less usage of other energy sources such as coal power (dubbed Coal in the remainder of the paper) and peat power (dubbed Peat in the rest of the paper), but their usage has reduced. Gas has, on the other hand, expanded in line with Wind.

Three qualifications must be addressed before continuing. First, some countries are endowed with clean, natural resources that translate into dispatchable power with very low life-cycle GHG emissions such as Norway (Hydro) and Iceland (Geothermal power; or Geothermal in the remainder of this paper), but these countries are outliers. Moreover, countries that have this possibility are always small. There are no large countries running on Hydro or Geothermal. The dispatchability of Hydro and Geothermal makes these energy sources highly beneficial, but of limited interest globally when the large share of fossil power and fuels are to be replaced due to geographical constraints.

Second, while this paper focuses on Wind, many of the arguments also apply to Solar PV because Solar PVs also provide non-synchronous and non-dispatchable electricity. However, Solar PV power has much less variability in the availability and is therefore easier to forecast and subsequently balance. The issues surrounding Solar PV power are most likely less pronounced than for Wind, but outside the scope of this paper.

Third, this paper ignores hybrid grid solutions involving different mixes of clean energy sources such as Wind, Solar PV, Geothermal, Hydro and nuclear power (referred to as nuclear in the remainder of this paper). The reason is that we have to understand each source individually before a detailed analysis of a hybrid grid solution makes sense. For example, if it turns out that the life-cycle GHG emissions of Wind are too high to meet 'low carbon' objectives, then we can remove Wind from the portfolio of clean energy sources unless countermeasures can be found, which would lead to a different conceptualisation of a hybrid grid.

To assess the life-cycle GHG emissions of Wind, this study combines the insights of UNECE (2021), Golroudbary et al. (2022) and the system simulation of Emblemsvåg (2021a) to realistically model grid performance and its impact on the life-cycle GHG emissions. The results indicate whether or not Wind meets the targets for a 'low carbon' grid, and can therefore be labelled as 'sustainable'.

The translation of life-cycle GHG emissions to sustainability rests on the assumption that sustainability can be realistically measured using the GWP as mentioned earlier. This study will therefore become the first LCA analysis of Wind based on permanent magnets that includes the entire life cycle, realistic grid modelling and includes all the uncertainties.

Next, the method is discussed in greater details before the results are presented in Section 3. A discussion in Section 4 puts the results into a broader context. Limitations and future work are addressed in Section 5. Concluding remarks are found in Section 6.

2. Method and data

This study improves Emblemsvåg (2021a) by replacing the life-cycle GHG emission data for the Chinese part of the supply chain with the recent data offered by Golroudbary et al. (2022). This replacement introduces some methodological challenges discussed here.

2.1. Converting macro-level GHG emission data to life-cycle GHG emission data for a wind turbine

Breaking down the macro level data of Golroudbary et al. (2022) to an individual wind turbine is the first challenge. The results indicate that the amount of primary REEs available for the global production of permanent magnets is about 24 thousand tonnes in 2020 and will reach around 50 thousand tonnes in 2030. They report that the estimated emissions in 2020 for mining of REE alone were 153 thousand tonnes CO_2-eq. while the processing emissions were 3.1 million tonnes CO_2-eq., and during the manufacturing stage of the magnets another 3119 million tonnes of CO_2-eq. emissions were emitted (Golroudbary et al. 2022). Hence, for every tonne of permanent magnet delivered from China, 130 tonnes CO_2-eq. emissions were emitted. Whether or not shipping of the permanent magnets is included is unclear.

Since a 2 megawatt (MW) wind turbine contains around 350 kg REEs (Nugent and Sovacool 2014), and Wind in Ireland had a PCF in 2019 of 28.4%, this will give over 25 years about 354 kg CO_2-eq./MWh life-cycle GHG emission for the REE in the turbine. Compared to the estimates in Table 1, we note that Wind has roughly speaking half of the average life-cycle GHG emissions compared to Gas, but almost ten times higher than the average life-cycle GHG of Wind used by Emblemsvåg (2021a).

Table 1. Life-cycle GHG emission factor (EF) for energy sources and their actual generation in Ireland in 2019. Source: (Emblemsvåg 2021a).

Emission source type	Case studies	Min LCA EF [kg CO_2/MWh]	Max LCA EF [kg CO_2/MWh]	Average LCA EF [kg CO_2/MWh]	Total generation 2019 [MWh/year]	Total emissions in 2019 [tonne/year]
Motor oil	21	603	1000	802	124,740	100,000
Coal	97	837	1167	1002	574,710	576,003
Lignite	10	800	1500	1150	0	0
Gas	86	407	760	573	14,815,700	8,493,100
Waste	4	97	1000	549	546,800	299,974
Peat	1	1110	1115	1112	2,105,800	2,358,496
Biomass	72	21	193	107	0	0
Hydropower	144	12	148	36	877,600	31,993
Pumped hydro, pump.	NA	314	555	432	−478,500	206,572
Pumped hydro, gen.	NA	12	148	36	243,000	8859
Wind	393	4	90	37	9,967,400	365,198
SUM	**828**				**29,734,250**	**12,423,349**

Ideally, similar conversions should be performed for various technologies and capacities of wind turbines which should be matched with the actual Wind power plants in question, but this study only obtained the REE content for a 2 MW turbine. However, the study used the total install base of Wind to minimise the impact of this limitation on the simulation.

2.2. Updating the LCA GHG emission estimates in the grid model

Adjusting studies using new data introduces a risk of either double-counting or omitting the life-cycle GHG emissions. The challenge arises from the fact that UNECE (2021) includes very low impact from mining and processing, while Golroudbary et al. (2022) focus solely on mining, processing and permanent magnet manufacturing. This challenge has been resolved by removing a certain amount of life-cycle GHG emissions from the data used by Emblemsvåg (2021a) and replacing it using data from Golroudbary et al. (2022). However, due to the significant amount of uncertainty of LCA data in general, and the fact that the life-cycle GHG emissions from Wind in Table 1 are very low, the data uncertainty is a far greater source of imprecision than the described replacement. Thus, the life-cycle GHG emissions from the production of REE for the permanent magnets completely dominate.

Table 1 contains the life-cycle GHG emission data from Emblemsvåg (2021a), derived from 828 LCA studies largely provided by Koffi et al. (2017) where the Emission Factor (EF) is the GHG emission per unit energy produced. Both expected values and uncertainty ranges are shown. Note that the other energy sources are kept constant to remove their impact on the results. The life-cycle GHG emissions of the other energy sources were 3.6 million tonnes or 29% of the total in 2019.

The Wind LCA EF estimates in Table 1 are very different from those computed in Section 2.1, which strictly speaking are only partial because only REE is considered. This difference suggests that the LCA EF estimates for Wind given in Table 1 include a very limited part of the total emissions. Alternatively, the authors considered that the processing industry of REE could run on VRE and Hydro. However, all such energy intensive industries require 100% reliability, which means that VRE is too unreliable (Emblemsvåg 2023). For this reason, the energy required in mining and processing of minerals usually comes from fossil fuel sources and not from Wind or Solar PV. Mining and processing are one of the top global climate gas emitting industries (Golroudbary et al. 2022).

It follows that the 354 kg CO_2-eq./MWh identified in Section 2.1 must essentially be added to the fifth column of the Wind line in Table 1. To stay on the conservative side, however, the estimates of Wind in Figure 1 is used (11 kg CO_2-eq./MWh). Adding that estimate with the one in Section 2.1, results in a total life-cycle GHG emission for Wind of 365 kg CO_2-eq./MWh in the updated model. This is over 60% of the life-cycle GHG emissions from Gas.

2.3. Updating the grid model of Ireland

Updating the Irish grid model is straightforward, as it is merely to replace the Wind life-cycle GHG EF data. Since the work of Emblemsvåg (2021a) and Golroudbary et al. (2022) are based on 2019 and 2020 data, the results given in this paper are based on the same years. Note that possible impact of the COVID-19 on data is unknown.

An additional advantage of using the Irish grid is high-quality grid data with 15 min resolution, which allows for accurate modelling. For example, the impact Wind has on Gas for balancing- and backup power can be modelled accurately, as can the effects of ramping up and -down gas turbines in response to changes in Wind output, and the life-cycle GHG emissions of keeping the grid reserve (spinning turbines that can react to load changes in seconds), and so on. In fact, Emblemsvåg (2021a) calculates the standard deviations of the ramping, it is 14.6 GWh with Wind in the grid, but only 6.9 GWh without Wind, and the grid reserve increased from 470 MW to 660 MW. All these effects drive the life-cycle GHG emissions upwards because these system services must be provided by synchronous- and dispatchable power sources such as Gas in the model. In real life, Ireland also uses Peat and Coal which have very high life-cycle GHG EF as shown in Table 1.

To model the uncertainty, a Monte Carlo simulation with Latin hypercube sampling is run 10,000 trials using the Oracle Crystall Ball software. Essentially, 10,000 years of Irish power production is modelled, and the effects on the life-cycle GHG emissions of both the Wind + Gas alternative and the Gas Only alternative are estimated. The grid demand and supply of various power sources are modelled using normal distributions where the mean and the standard deviations are estimated using several years of data. The demand uses a 1% standard deviation of any hourly demand in 2019 whereas Wind has 4% standard deviation. This variation in demand and Wind, will subsequently drive the variation of all other energy sources in the model according to certain dispatch priority rules. Hydro and Bio are always producing whereas Coal and Peat are handling some seasonal variations, and Wind is given priority dispatch over Gas. The other input parameters in the model are modelled using triangular uncertainty distributions to allow flexible modelling. Detailed descriptions of how Monte Carlo simulations work are provided by Emblemsvåg (2003).

3. Results

The key results are shown in Figure 3.

The Wind + Gas alternative outperforms the Gas Only alternative by merely 344 tonnes CO_2 eq. per year, (or 1.5% of total emissions) when indirect effects are ignored, which is essentially well within the margin of error. More alarming is the fact that that the Wind + Gas alternative will never meet the 'low carbon' target even if grid forming inverters can be implemented on large scale to run the entire Irish grid on Wind. Thus, we can preliminarily conclude that Wind with permanent magnets is not sustainable as defined by the life-cycle GWP. The word 'preliminary' is important because in Section 4, countermeasures for this poor performance are discussed.

The results become even more interesting when we also include the indirect effects. The indirect effects refer to the environmental impact of spending more resources on an economically more expensive power system for the Wind + Gas alternative than the Gas Only alternative. These indirect effects essentially tip the balance in favour of the Gas Only alternative by more than 9% of the life-cycle GHG emissions of the power system in Ireland. It should be noted that during the energy crisis of 2021/2022, this line of argument would have tipped the results in favour of the Wind + Gas alternative due to the high cost of Gas.

Wind also increases the life-cycle GHG emissions by 1 million tonnes when increasing the grid reserve and additional ramping of the gas turbines, as shown in Figure 4.

In the Wind + Gas alternative, these effects deterministically constitute 12% of total grid life-cycle GHG emissions. Additionally, 2.3% of Wind production is being curtailed to avoid passing the SNSP limit of the grid. More Wind capacity will raise the curtailment further.

The direct life-cycle GHG emissions of the Irish grid hardly changes as shown in Figure 5. If we ignore the grid technical aspects, Gas contributes the most with 54% of life-cycle GHG emissions, Wind with 23%, and from the model details we find that Peat contributes with 15%, Coal with 4% and 4% for the rest.

This result stands in stark contrast to the assessment that Wind using permanent magnets avoids 42 thousand tonnes of CO_2 eq. over its life time (Nugent and Sovacool 2014). However, that result is true only if we ignore both (1) the production of critical components such as permanent magnets and (2) grid stability aspects related to synchronisation, grid reserve, ramping, balancing- and backup power.

To understand the results better, a sensitivity analysis is also performed, see Figure 6. Clearly, the usage of fossil fuels as balancing- and backup power is detrimental to the Wind + Gas alternative. Note that the revised Wind EF (365 kg CO_2 eq./MWh) does not show up despite being more than 3 times higher than the requirements of a 'low carbon' grid (100 vs 354 kg CO_2 eq./MWh). The

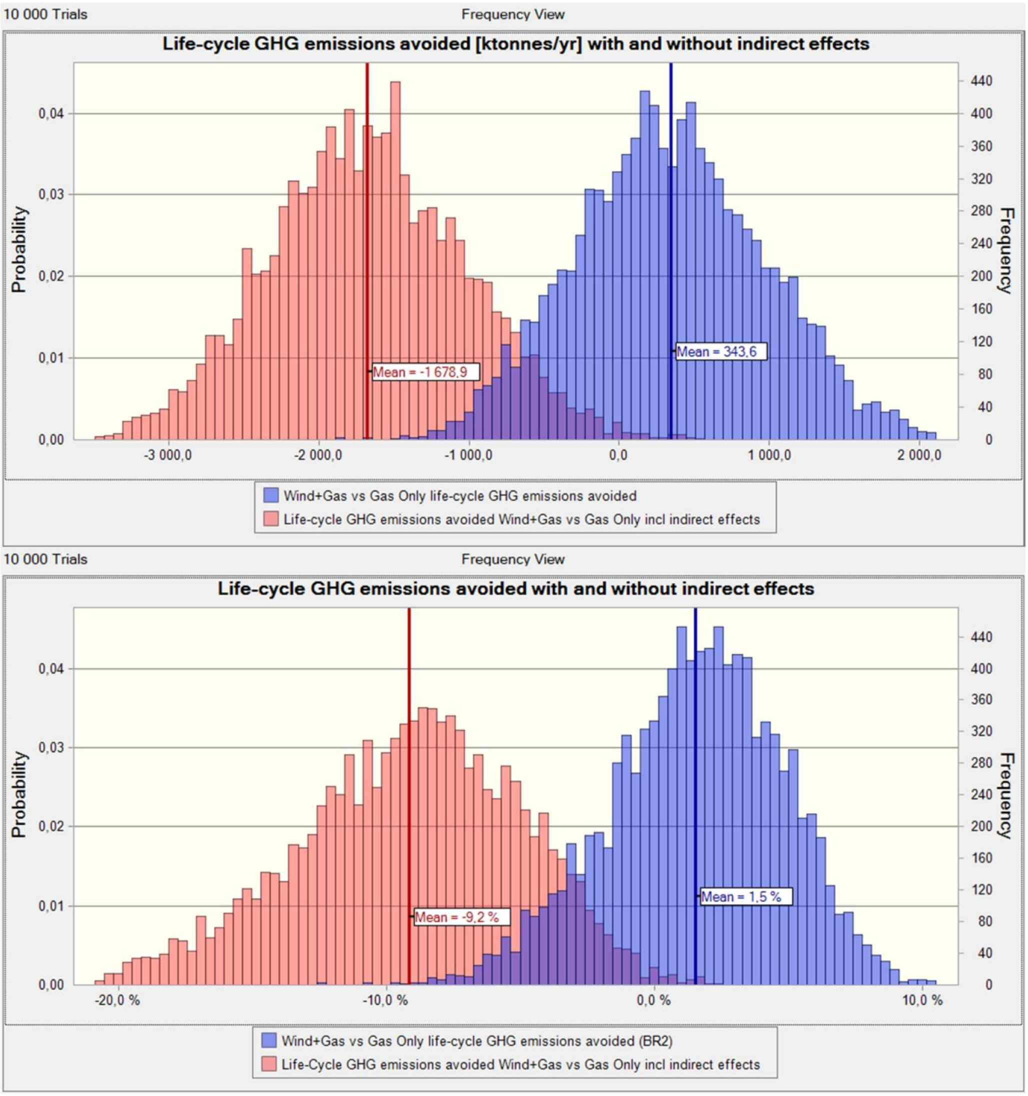

Figure 3. Life-cycle GHG emissions avoided for Wind + Gas compared to Gas Only.

reason is that the model calculates the 354 kg CO_2 eq./MWh from the data provided. It is, in other words, not an input variable but an intermediate result that is subsequently used in the model.

> 'IE Wind variation 3602' indicates that this effect took place in the 3602nd consecutive hour of the year, assuming that the first hour is 01:00 on January 1st while on December 31st at 23:00 we have hour number 8760. When there is a negative rank correlation with the variable for which the sensitivity analysis is performed, then an increase in Wind leads to a reduction in the direct life-cycle GHG emissions of the Wind + Gas alternative. Similar interpretations should be done for all other variables.

Then, there is a list of factors related directly to the early phases of manufacturing the permanent magnets. Interestingly, both Hydro and Coal are identified. Both of them are important for Ireland in providing a load in the bottom and if their EF increases, it will increase the life-cycle GHG emissions for the Wind + Gas alternative. Therefore, running Peat efficiently is particularly important due to its high EF and overall significant contribution (15%) because fossil energy sources running

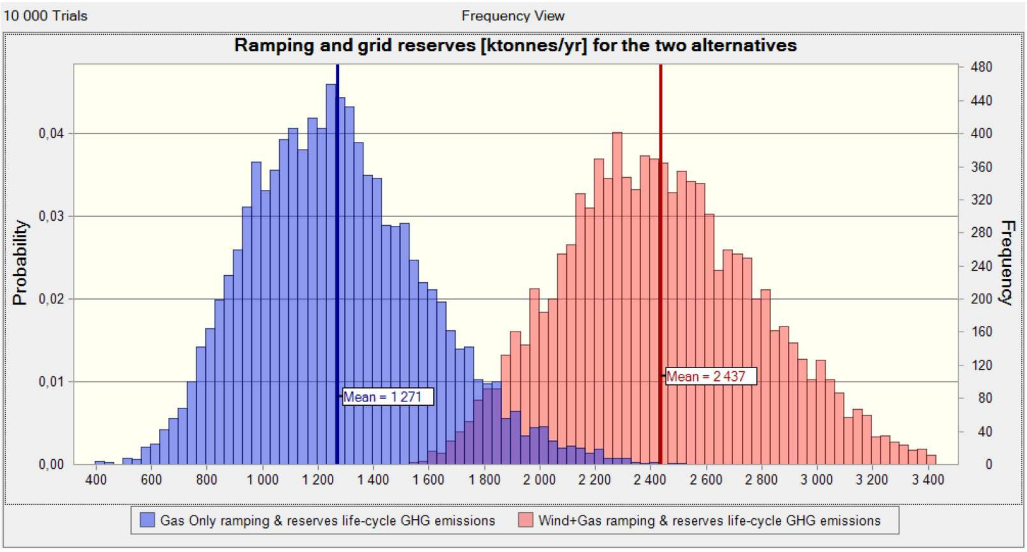

Figure 4. Changes in life-cycle GHG emissions [ktonnes] related to grid reserve and gas turbine ramping for the two alternatives.

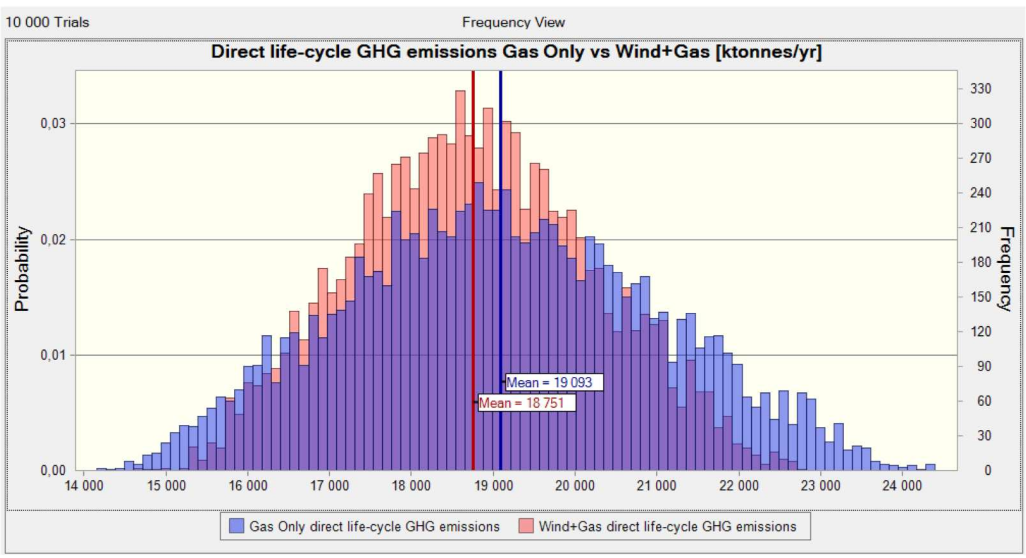

Figure 5. Direct life-cycle GHG emissions [ktonnes/year] of the Irish grid for both alternatives.

on low load in between cause extra life-cycle GHG emissions. This effect is included in the model, and it will exacerbate the problems of balancing and providing backup power very rapidly to follow the variations of Wind.

To summarise, it has previously been shown that Wind using fossil fuel balancing- and backup power is not sustainable (Emblemsvåg 2021a), and that '… an increase by 1% of green energy production … … increases GHG emissions in the exploitation phase by 0.90%' (Golroudbary et al. 2022). When these two analyses are merged, the inescapable conclusion is that Wind based on permanent magnets is not sustainable because the grid will not meet the 'low carbon' targets set forth.

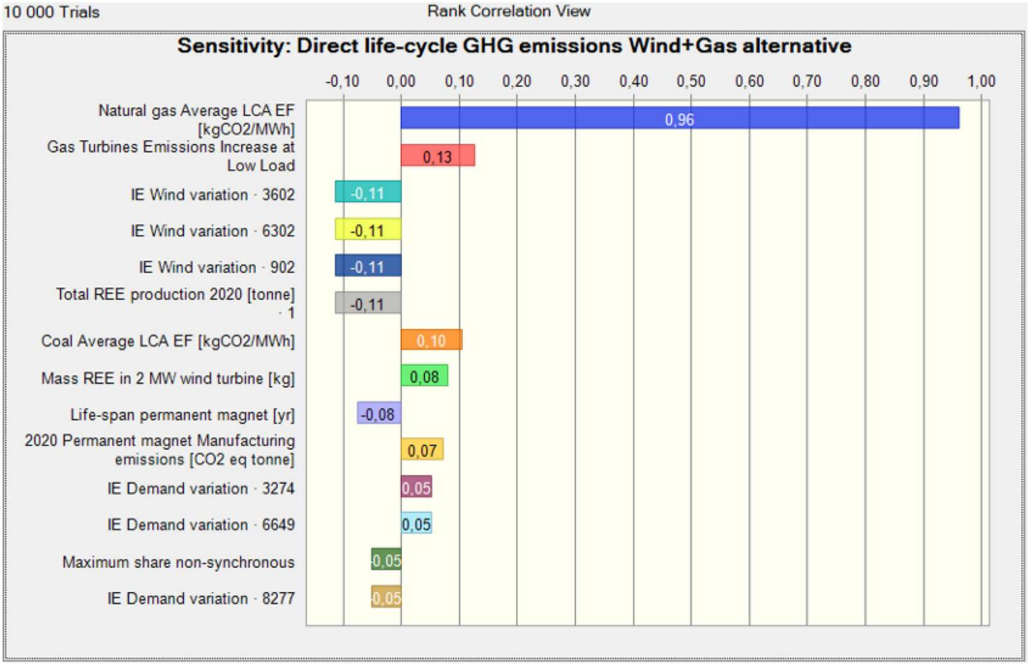

Figure 6. Sensitivity analysis that measures the combination of uncertainty and impact of the Wind + Gas alternative.

That is true under the current *modus operandi* of Wind in Ireland and in most countries. Next, countermeasures are discussed.

4. Discussion

The indirect effects discussed in Section 3, can also be witnessed in the real world because using two power systems is far more resource intensive than having one power system that fulfills all requirements. As Smil (2020) notes in the context of Germany's Energiewende (the German terms for the German energy transition policy); 'In 2000, Germany had an installed capacity of 121 gigawatts and it generated 577 terawatt-hours, which is 54% as much as it theoretically could have done (that is, 54% was its capacity factor). In 2019, the country produced just 5% more (607 TWh), but its installed capacity was 80% higher (218.1 GW) because it now had two generating systems'.

Indeed, the German Federal Accounting Office (Bundesrechnungshof) writes that 'The Bundesrechnungshof warns that the energy transition in its current form [based on the Energiewende] poses a threat to the German economy and overburdens the financial capacity of electricity-consuming companies and households' (Bundesrechnungshof 2021). The actual costs are difficult to identify, but Emblemsvåg (2024) estimates that it approaches 700 bn euros nominally for Germany alone excluding a number of alternative costs such as the extension of the German grid and the cost of insufficient energy security as exemplified by the energy crisis costing 1500 bn euros (Woodard et al. 2023).

Such economic realities also have an environmental burden, or indirect effects as it is dubbed here. However, the analysis points to the fact that the production of permanent magnets emits a large amount of GHG even without including any other effects – i.e. Wind emits more than 60% of Gas. This is difficult to change in the foreseeable future because it would require an entirely different power supply in China that is both low carbon, synchronous and dispatchable, which includes only Nuclear power (dubbed Nuclear in the remainder of this paper) and Hydro due to the reliability requirements, as mentioned earlier. However, there are three possible countermeasures that will improve the situation for Ireland, as discussed here.

4.1. Reusing the permanent magnets

Permanent magnets have a long lifespan and reusing them is beneficial as can be seen from Figure 6. Thus, it is important to design and implement various measures intended to increase REE reuse, and recycling (the current rate is less than 1%), encourage dematerialisation, and substitution, and develop new elimination technologies (e.g. an engine without permanent magnets) (Golroudbary et al. 2022).

According to NeoMagnets,[1] a permanent magnet supplier, the lifespan of a neodymium magnet will vary depending on many factors, including temperature, humidity, magnetic fields, and physical damage, but up to 100 years is realistic. Given the 20–25 years planned lifespan of Wind, it is conceivable that the permanent magnets can be reused 4 times. This lowers the life-cycle GHG emissions for the wind turbines from 354 to 88 kg CO_2-eq./MWh. However, the overall improvement for the Irish grid is to shift the EF from 644 to 555 kg CO_2-eq./MWh, deterministically. The reason is that Wind reaches the SNSP limit with increasing frequency.

Such reuse requirements should be achieved through standardisation of turbine sizes. Hence, the really important step going forward for the wind turbine industry is to actually stop making turbines bigger and rather address the fact that permanent magnets are used. In other words, the wind turbine industry must, to a much greater extent than today, focus on the life-cycle GHG emissions and not just the emissions in the use phase of the wind turbines.

4.2. Lower the planned capacity for wind to require less gas for balancing and backup

The planned capacity of Wind can be lowered so that the life-cycle GHG emissions from the balancing and backup from Gas equal those from Wind, see Figure 7 where the production is presented in descending order from left to right over a year. This change is based on the fact that the current strategy works so that Wind + Gas is essentially more Gas than Wind with 65% of the production being Gas. In the alternative strategy, the capacity of Wind is adjusted through curtailment so that the life-cycle GHG emissions of Wind is the same as Gas. Then, Wind becomes 54%, 7% is curtailed and the rest is Gas. The alternative strategy will result in a significant loss of production – i.e. 12.8 TWh/year.

If the lost production is replaced by Nuclear, then significant improvements in the life-cycle GHG emissions of the Irish grid can be expected. A simple analysis without grid technical issues and uncertainty included, indicates that the Irish grid would reach 257 kg CO_2-eq./MWh under the assumption that the rest of the fossil power sources are replaced with Hydro and Nuclear to maintain synchronicity and dispatchability, and that the data in Figure 1 are used for Hydro and Nuclear.

4.3. Combining the countermeasures and addressing remaining challenges

The two aforementioned countermeasures can also be combined. Then, the Irish grid would reach 164 kg CO_2-eq./MWh, which is still above the low carbon threshold of 100 kg CO_2-eq./MWh. Thus, both the production of permanent magnets itself and the overall life-cycle GHG emissions of the dispatchable energy sources in the grid should be addressed.

The final challenge, ignored by the model, is that there is also redispatch (replanning) due to incorrect weather forecasts in the day-ahead market. In Figure 8, the redispatch in Germany is shown, and despite having significant import/export possibilities with nearby countries, there is clearly a large increase in the number redispatches over the last 10 years. According to Herbert

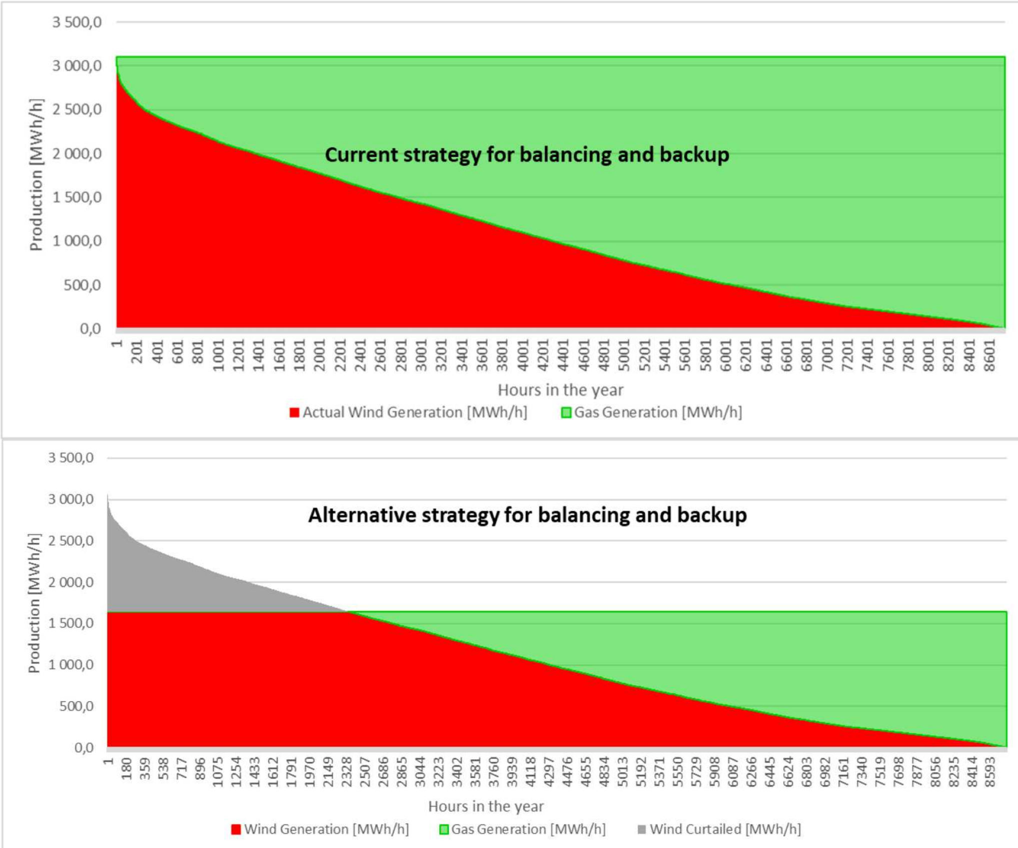

Figure 7. Changing the strategy of Wind to match the life-cycle GHG emissions from Gas that are used for balancing and backup.

Saurugg[2], the number of incidents 20 years ago were in the single digit range – now it is on average 40 per day. The sheer volume is also very large – 25 thousand TWh of redispatch in 2023.

If the model included the redispatch, the results would be worse for the Wind + Gas alternative. Hence, it is very difficult for Wind to become a sustainable energy source, but not impossible.

4.4. The critical insights

The volatility of Wind is a fundamental challenge to sustainability even though the life-cycle GHG emissions in the production of the permanent magnets are cut directly through (1) using Hydro and Nuclear or (2) indirectly through reusing the permanent magnets and (3) by lowering the capacity of Wind for planning purposes to minimise balancing and backup needs. In fact, permanent magnets must be reused *and* manufactured using Hydro and/or Nuclear to achieve the low carbon grid target.

The fundamental problem caused by the fact that Wind requires balancing- and backup power is still unresolved, not to mention redispatch. The large volume of redispatch or planned ramping simply cannot be tolerated because most countries do not have enough flexible clean energy sources to handle it. Gas basically brings too much life-cycle GHG emissions into the grid. Traditional Nuclear can offload Hydro from being a baseload energy, and Nuclear can be load-following to some extent (World Nuclear Association 2023).

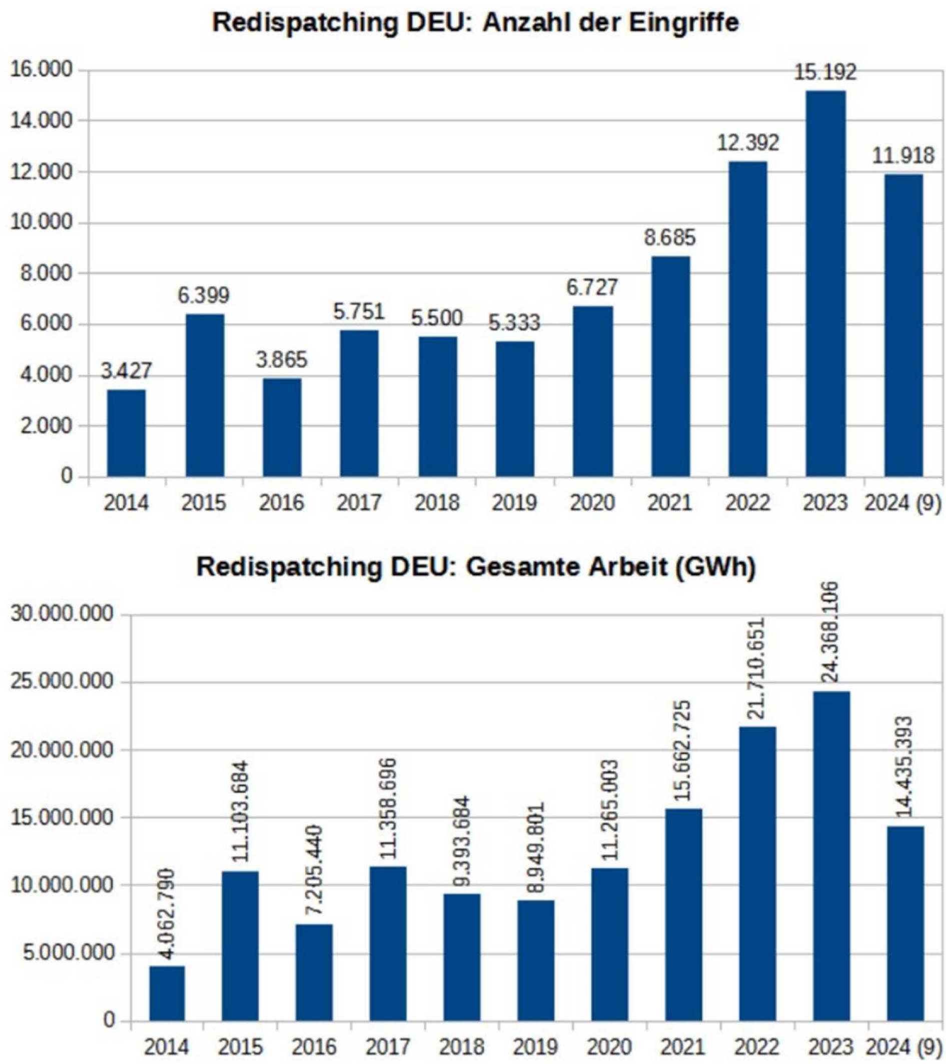

Figure 8. The consequences of redispatch in Germany. Used with the kind permission of Herbert Saurugg. He has obtained that data from www.netztransparenz.de/de-de/Systemdienstleistungen/Betriebsfuehrung/Redispatch.

Hence, a situation where Wind in combination with Hydro and Nuclear can be sustainable if (1) Nuclear serves as the baseload energy source and there is enough Hydro to provide balancing- and backup services for variability either at the supply side or the demand side, (2) permanent magnets are reused at least 4 times, (3) Wind capacity is lowered for planning purposes to reduce the need for balancing- and backup power, and (4) the energy sources used in manufacturing of the permanent magnets must be Hydro and/or Nuclear. In this case, Wind must be curtailed significantly to fit into the production profile of Hydro and Nuclear and not the other way around, as is found today. The reason is that only Gas ramps quickly enough to follow Wind, and with too much Gas (more than approximately 15% of the grid mix) the entire LEDS rationale for Wind is missing. These findings suggest that the Wind power strategies of most countries today actually lead to higher life-cycle GHG emissions because they have not changed the current *modus operandi* and failed to address the four items listed above.

Note that due to the life-cycle GHG emissions of batteries, batteries with the current technologies cannot serve as a major load carrier in the grid. For example, Hottenroth et al. (2018) estimate that electric batteries have life-cycle GHG emissions of 175 kg CO_2-eq./MWh and pumped Hydro has 145 kg CO_2-eq./MWh plus the life-cycle GHG emissions from the power itself. This discussion shows how difficult it is to attain the low carbon target.

Interestingly, Solar PV, despite having higher life-cycle GHG emissions than Wind according to Figure 1, can more easily be integrated because of slower changes in production and therefore easier ramping of both Hydro and Nuclear. That analysis is future work, but it should be similar to the analysis of levelised cost of energy of Solar PV as exemplified by Emblemsvåg (2021b) where all grid technical aspects are included. However, Solar PV without substantial Hydro and Nuclear also is unlikely to meet the low carbon targets for similar reasons as discussed for Wind in this article. Essentially, if there is more Gas (or any other fossil fuels) than about 15% in a grid, the low carbon target will not be attained.

5. Limitations and future work

The presented work builds on the findings of Golroudbary et al. (2022), who take a top-down approach. Such a top-down approach makes it relatively easy to assess the reality of the situation on the macro-level, and this author finds no reason to question the results as good approximations. However, more studies should be carried out to verify the results, and reduce the uncertainties.

A possible limitation of the presented study is that the conversion of the macro-level estimates is based on a small turbine (2 MW) that no longer represents the future nor the median in the recent past of wind turbines. According to IRENA (2019), wind turbine capacity has increased over time, and the ongoing increase in wind turbine capacity for onshore applications is set to continue, from an average of 2.6 MW in 2018 to 4 to 5 MW for turbines commissioned by 2025. The presented study should therefore ideally be updated to more representative turbine sizes and capacities. However, with the overwhelmingly negative result for Wind in this analysis, it will not significantly change the conclusion.

The single, most significant shortcoming of the presented study is probably the fact that redispatch is not modelled. The model currently identifies the life-cycle GHG emissions of the Irish grid through a set of dispatch rules that are based on emission targets and ramping capabilities. Since Wind constitutes a major element of the Irish grid, redispatch on the intraday market can become quite challenging where fossil turbines must run on lower loads than estimated by the model to stand by for redispatch. This shortcoming essentially introduces some conservatism in the model by underestimating the life-cycle GHG emissions of the Wind + Gas alternative.

Finally, nobody has to the knowledge of this author, conducted a similarly detailed study on Solar PV. All the studies known to this author, suffer from poor data availability from the Chinese part of the supply chain, and some use unrealistic assumption regarding the energy sources powering mining, material processing and manufacturing of Solar PV. Grid technical aspects are normally always excluded. As an extension, hybrid grids of Wind and Solar PV should also be studied. Conducting such studies is part of future work.

6. Concluding remarks

Assessing the life-cycle GHG emissions in the early stages of the supply chain of permanent magnets for wind turbines has been difficult for years due to poor data availability, but new research shed light onto the production of permanent magnets showing that the life-cycle GHG emissions are much higher than previously claimed. Based on the data from that research, this study offers revised Wind life-cycle GHG emission estimates at 365 kg CO_2-eq./MWh, which is about 60% of the life-cycle GHG emissions of Gas, which is around 573 kg CO_2-eq./MWh.

However, this paper offers more novelty and goes a step further by including the grid technical issues of balancing- and backup power, most commonly supplied by Gas. The conclusion is inescapable – Wind in its current *modus operandi* is not sustainable as long as permanent magnets are used. Including the indirect effects related to higher costs through subsidies, the net life-cycle GHG emissions actually increase when Wind is replacing Gas.

However, there are countermeasures to change this conclusion. Wind in combination with Hydro and Nuclear can be sustainable with today's commercially available technologies if (1) Nuclear serves as the baseload and there is enough Hydro to provide balancing- and backup services for variability occurring at the supply side and/or the demand side, (2) permanent magnets are reused at least 4 times, (3) Wind capacity is lowered for planning purposes to reduce the need for balancing- and backup power, and (4) the power used in manufacturing of the permanent magnets must be either Hydro and/or Nuclear. Arguably, these countermeasures are difficult to implement but not impossible.

Notes

1. Accessed 2024-10-25 from https://neomagnets.net/how-long-do-neodymium-magnets-last/.
2. Personal communication 2024-10-14.

Acknowledgements

The author would like to express his gratitude towards the reviewers for pointing out how to improve the manuscript from its first version to the final, published version, which made a significant difference. Also, the proof-reading provided by Cecilia Haskins has been invaluable.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data are provided both within the manuscript and in a supplementary information file.

References

Bobba, S., S. Carrara, J. Huisman, F. Mathieux, and C. Pavel. 2020. *Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study*. Brussels: European Commission, Joint Research Centre.

Bundesrechnungshof. 2021. *Bericht nach § 99 BHO zur Umsetzung der Energiewende im Hinblick auf die Versorgungssicherheit und Bezahlbarkeit bei Elektrizität* [*Report According to § 99 BHO on the Implementation of the Energy Transition with Regard to Security of Supply and Affordability of Electricity*]. Bonn: Bundesrechnungshof.

Clappi, C., G. Brineri, and K. Karousakis. 2010. "Low Emission Development Strategies (LEDS): Technical, Institutional and Policy Lessons." OECD/IEA Climate Change Expert Group Papers, No. 2010/02. Paris: OECD Publishing.

Dodd, J. 2018. "Rethinking the Use of Rare-Earth Elements." *Windpower Monthly*. London, Haymarket Media Group Ltd. https://www.windpowermonthly.com/article/1519221/rethinking-use-rare-earth-elements.

Emblemsvåg, J. 2003. *Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks*. Hoboken, NJ: John Wiley & Sons.

Emblemsvåg, J. 2021a. "Wind is Not Sustainable When Balanced by Fossil Energy." *Applied Energy* 305. https://doi.org/10.1016/j.apenergy.2021.117748.

Emblemsvåg, J. 2021b. "On the Levelized Cost of Energy of Solar Photovoltaics." *International Journal of Sustainable Energy* 40: 1–26. https://doi.org/10.1080/14786451.14782020.11867139.

Emblemsvåg, J. 2022. "How to Sustainably Integrate Wind." Proceedings of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), 16–18 November 2022, Maldives, IEEE.

Emblemsvåg, J. 2023. "Powering Large Industrial Facilities – Using Wind- or Nuclear Power?" *International Journal of Sustainable Energy* 42: 1241–1263. https://doi.org/10.1080/14786451.14782023.12260008.
Emblemsvåg, J. 2024. "What if Germany had Invested in Nuclear Power? A Comparison Between the German Energy Policy the Last Twenty Years and an Alternative Policy of Investing in Nuclear Power." *International Journal of Sustainable Energy* 43 (1). https://doi.org/10.1080/14786451.14782024.12355642.
European Commission. 2018. *A Clean Planet for all - A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*. Brussels: The European Commission, The European Council, the European Economic and Social Committee of the Regions and European Investment Bank.
Finkbeiner, M., R. Ackermann, V. Bach, M. Berger, G. Brankatschk, Y.-J. Chang, M. Grinberg, et al. 2014. "Challenges in Life Cycle Assessment: An Overview of Current Gaps and Research Needs." In *Background and Future Prospects in Life Cycle Assessment*, edited by W. Klöpffer, 207–258. Dordrecht: Springer Science + Business Media.
Fishman, T., and T. E. Graedel. 2019. "Impact of the Establishment of US Offshore Wind Power on Neodymium Flows." *Nature Sustainability* 2: 332–338. https://doi.org/10.1038/s41893-41019-40252-z.
Gaffney, F., J. P. Deane, and B. P. O. Gallachoir. 2019. "Reconciling High Renewable Electricity Ambitions with Market Economics and System Operation: Lessons from Ireland's Power System." *Energy Strategy Reviews* 26. https://doi.org/10.1016/j.esr.2019.100381.
Golroudbary, S. R., I. Makarava, A. Kraslawski, and E. Repo. 2022. "Global Environmental Cost of Using Rare Earth Elements in Green Energy Technologies." *Science of the Total Environment* 832. https://doi.org/10.1016/j.scitotenv.2022.155022.
Hottenroth, H., J. Peters, M. Baumann, T. Viere, and I. Tietze. 2018. "Life-cycle Analysis for Assessing Environmental Impact." In *Energy Storage Options and Their Environmental Impact*, edited by R. E. Hester, and R. M. Harrison, 261–295. London: Royal Society of Chemistry. https://doi.org/10.1039/9781788015530-9781788000261.
IPCC. 2013. *Climate Change 2013 the Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.
IRENA. 2019. *Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects. Global Energy Transformation Paper*. Abu Dhabi: United Arab Emirates, International Renewable Energy Agency (IRENA), IRENA Innovation and Technology Centre.
Jin, H., P. Afiuny, S. Dove, G. Furlan, M. Zakotnik, Y. Yih, and J. W. Sutherland. 2018. "Life Cycle Assessment of Neodymium-Iron-Boron Magnet-to-Magnet Recycling for Electric Vehicle Motors." *Environmental Science & Technology* 52 (6): 3796–3802. doi/org:10.1021acs.est.1027b05442.
Koffi, B., A. K. Cerutti, M. Duerr, A. Iancu, A. Kona, and G. Janssens-Maenhout. 2017. *Covenant of Mayors for Climate and Energy: Default Emission Factors for Local Emission Inventories*. Luxembourg: Publications Office of the European Union.
Marx, J., A. Schreiber, P. Zapp, and F. Walachowicz. 2018. "Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits." *ACS Sustainable Chemistry & Engineering* 6 (5): 5858–5867.
Nugent, D., and B. K. Sovacool. 2014. "Assessing the Lifecycle Greenhouse gas Emissions from Solar PV and Wind Energy: A Critical Meta-Survey." *Energy Policy* 65:229–244.
Pearce, F. 2009. "How a Wind Farm Could Emit More Carbon Than a Coal Power Station." *The Guardian*, London: https://www.theguardian.com/environment/2009/aug/2013/wind-farm-peat-bog.
Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. 2018. *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above pre-Industrial Levels and Related Global Greenhouse gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (Edited by V. Masson-Delmotte, P. Zhai, et al.), 93–174. Geneva: IPCC/WMO.
SEAI. 2020. *Energy Security in Ireland; 2020 Report*. Dublin: Sustainable Energy Authority of Ireland (SEAI).
SEM Committee. 2017. *DS3 System Services Tariffs and Scalars SEM Committee Decision*. Dublin: Single Electricity Market (SEM) Committee.
Smil, V. 2020. "Energiewende, 20 Years Later." *IEEE Spectrum* 57 (12): 22–23.
Smith, J., D. R. Nayak, and P. Smith. 2014. "Wind Farms on Undegraded Peatlands are Unlikely to Reduce Future Carbon Emissions." *Energy Policy* 66:585–591.
Stanek, W., B. Mendecka, L. Lombardi, and T. Simla. 2018. "Environmental Assessment of Wind Turbine Systems Based on Thermo-Ecological Cost." *Energy* 160:341–348.
UNECE. 2021. *Life Cycle Assessment of Electricity Generation Options*. Geneva: United Nations Economic Commission for Europe (UNECE).
Verdolini, E., F. Vona, and D. Popp. 2018. "Bridging the gap: Do Fast-Reacting Fossil Technologies Facilitate Renewable Energy Diffusion?" *Energy Policy* 116:242–256.

Wang, M., A. Elgowainy, U. Lee, A. Bafana, S. Banerjee, P. T. Benavides, P. Bobba, et al. 2021. "Summary of Expansions and Updates in GREET® 2021." Argonne, IL, Department of Energy. Argonne National Laboratory. https://doi.org/10.2172/1824336.

Woodard, J., J. Glascock, P. Block, D. Harris, and C. Flanagan. 2023. *The RIC Report: The Nuclear Necessity*. New York: Bank of America Securities, Research Investment Committee.

World Nuclear Association. 2023. *World Nuclear Performance Report 2023*. London: World Nuclear Association.