

Addressing Dunkelflaute Events in Energy Systems With High Renewable Shares

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Abstract— Optimising energy systems requires consideration of fuel costs, operational efficiency, resilience, emissions, and meteorological variability. A key challenge for high-renewable systems is managing prolonged low-generation periods, such as dunkelflaute events, which pose resilience risks. Long-duration energy storage offers a promising solution by storing surplus renewable energy for deployment during such periods, reducing reliance on fossil fuels. This study evaluates the potential of grid interconnection and future storage solutions to enhance system resilience and decarbonisation objectives. A scenario-based approach is adopted, using baseline meteorological and demand data to establish reference costs and portfolio sizing. Metrics include system renewable share, operational costs and emissions reductions. Focusing on Ireland’s 2030 renewable electricity targets, the study provides insights into the potential value of long-duration storage, guiding policymakers and investors on building resilient, low-carbon energy systems.

Keywords – Energy system optimisation, long duration storage, renewable integration, dunkelflaute events.

I. INTRODUCING DUNKELFLAUTE PROBLEM

In 2024, the Earth exceeded the 1.5-degree warming threshold, a key target outlined in the Paris Agreement. While this milestone has been breached, it remains possible to limit global warming to below 2 degrees above pre-industrial levels and mitigate the impacts of climate change on biodiversity. Achieving this goal requires countries to establish clear pathways toward carbon neutrality as swiftly as possible. For most nations, the target for carbon neutrality is set for 2050, with 2030 serving as a critical milestone towards assessing the effectiveness of measures so far implemented. Many countries are currently developing strategies to balance costs, integrate renewable energy, reduce carbon emissions, improve energy efficiency, and increase resilience to unforeseen events. This transition is primarily driven by the large-scale integration of renewable energy sources, such as wind and solar photovoltaic power. However, in most countries, the wind and solar share within the overall energy mix remains relatively low due to dependence on meteorological conditions, which necessitates additional adaptations for broader deployment [1]. Extended periods (i.e. days) of low wind and solar generation, often referred to as dunkelflaute (dark doldrums or energy

droughts), can pose significant operational challenges, and, in the worst cases, lead to wide-scale load shedding [2]. A sustainable future energy system must, therefore, be capable of managing these dunkelflaute events with minimal reliance on fossil fuel-based solutions.

Characterisation of dunkelflaute events has been explored through various criteria that define energy droughts as periods when energy production continuously falls below a specific threshold [2]. This threshold is typically determined by factors such as time of year, energy demand, or production capacity [3]. Such studies aim to identify dunkelflaute events and assess their impact on energy systems by analysing their duration, intensity, frequency of occurrence, and the state of the power and energy system during such occurrences. Furthermore, some studies suggest that the likelihood of energy droughts is expected to increase in northern countries in the future due to climate change [4].

To mitigate the impact of dunkelflaute events, an optimal balance must be found between potential solutions, such as demand-side management, increased grid interconnection, and (long-term) energy storage. Demand-side management focuses on aligning energy demand with production at various scales, ranging from residential to industrial sectors. In the residential sector, this can involve incentives to modify consumer behaviour [5] and technologies that enable demand deferral [6], while in the industrial sector, demand can be shifted to periods of higher renewable energy availability.

Interconnection with other grids, supplied by different energy sources, or located in regions with distinct (or time shifted) climatic conditions, can facilitate electricity imports during periods of grid stress, and exports during surplus production. Grids with a high share of renewable energy that export excess electricity contribute towards reducing global greenhouse gas emissions. However, relying too much on imports/exports may lead to energy security concerns.

Finally, energy storage is a well-established solution to address the variability of renewable energy production, as it allows excess energy to be stored and released during periods of insufficient production. A wide range of storage options exists, including both short- and long-term solutions, with four primary technologies: electrochemical, electromagnetic, mechanical, and thermodynamic storage [7]. For power

systems, short-term solutions such as lithium-ion batteries are widely deployed, often for the supply of system services, reducing network constraints, and energy arbitrage, but their comparatively high cost limits their use on larger scales, or for longer durations. For long-term storage needs, pumped hydro storage is well established as the most cost-effective option, although its development is constrained by geographical limitations, and future installations are often limited by environmental, economic, etc. considerations. Hydrogen, while often proposed for long-term storage applications, remains expensive and requires significant adaptation across various sectors. Recently developed and mature alternative options, such as iron-air batteries, can store electricity over multiple days at a lower cost compared to other technologies with a lower round trip efficiency [8].

The benefits of integrating long-term storage, and the impact of interconnection with neighbouring countries, have been analysed, typically focussing on determining renewable generation capacity factors, and optimising the size of the energy storage and interconnection under a greenfield model, assuming no pre-existing capacity. For example, a case study concerning the probability of dunkelflaute events in Hungary concluded that nuclear energy was the most effective solution for achieving carbon neutrality by 2030, with wind and solar energy contributing a maximum of 60% of total demand [9].

This paper aims to analyse the benefits of two alternative options for addressing dunkelflaute situations: increasing interconnection and installing long-term energy storage. The 2030 Ireland power system will be examined across different weather years, considering various dunkelflaute events that may differ in duration, or occur during different load periods, and thereby implying varying consequences. The study will characterise the system during periods of stress caused by dunkelflaute events. Subsequently, the benefits of additional interconnection and energy storage will be evaluated to determine how such measures influence electricity prices and CO₂ emissions.

Section II introduces the approach to characterise dunkelflaute events, and the context in which the analysis is applied to Ireland. Section III presents results and evaluates how integrating additional storage and interconnection impact costs and emissions, including reflections on electricity market operation. Finally, Section IV summarises the work outcomes.

II. CASE STUDY OF IRISH SYSTEM IN 2030

Before considering the application case of Ireland it is necessary to define a dunkelflaute event, and to present the overall analysis framework. Consequently, a rolling average method is applied here, with the dunkelflaute criteria given as a Boolean value, Dk_d . The Boolean is set to one when the sum of available wind power, P_{wind} , and solar power, P_{sun} , over a specified time period fall below a generation threshold value, $P_{gen,thresh}$ [2], relative to the total capacity, as defined in equation (1). A capacity-based approach aligns well with renewable drought periods associated with low solar PV generation during winter months and low wind generation during summer months.

$$Dk_d = 1 \text{ if } \sum_{t=1}^{24} P_{sun} + P_{wind} < P_{gen,thresh} \quad (1)$$

However, it is also important to evaluate the criticality of a dunkelflaute event based on the system demand level for that period. In northern Europe, the same dunkelflaute event, as defined by the criteria above, will tend to have a greater impact during winter when the demand is typically higher, as compared to the summer. Therefore, an additional threshold value, $P_{load,thresh}$, is required to determine if the drought period occurs during a high-demand period. The cumulative demand for each day of the year is determined. As defined in equation (2), $P_{load,thresh}$ is selected as the first quartile of the cumulative daily demand across the studied year.

$$\text{if } \sum_{t=1}^{24} P_{load} > P_{load,thresh} \text{ then } Dk_d = Dk_{d,highload} \quad (2)$$

The combined Republic of Ireland (ROI) and Northern Ireland (NI) power system is selected as the area of study, recognising that it is a synchronously isolated system with high voltage direct current (HVDC) links to Great Britain. The Irish power system already has one of the highest share of energy produced by wind generation, but there remains significant expansion potential through increased renewable capacity, additional storage, and possible further HVDC interconnection with the grids in Great Britain and France. By 2030, ROI policy objectives aim to reduce emissions in the electricity sector by 75% compared to 2018 levels [10]. This target is set to be achieved by generating 80% of annual electricity from renewable sources by 2030, facilitated by a substantial increase in wind and solar capacity from 5 GW in 2023 to over 22 GW in 2030, and by raising the non-synchronous penetration limit to up to 95% (maximum instantaneous share of non-synchronous generation, notably wind and solar generation, and including HVDC imports, relative to the electrical demand).

These ambitious energy targets may result in extended periods of low renewable energy supply, as well as excess renewable supply. Based on (1), and assuming the forecast installed capacity for 2030, the renewable generation hourly profile for multiple weather years (2010 to 2020) has been estimated using the CorRES tool [11]. Figure 1 shows that for the different weather years Ireland experienced only one event when the capacity factor of the combined wind and solar generation across a rolling five-day period was less than 10%. It can also be seen that dunkelflaute events lasting more than three days are likely to happen at least once every year. For more critical events, when the 5-day capacity factor is less than 5%, no event lasted more than 60 hours, although two events extended beyond 48 hours, while periods exceeding 24 hours under 5% capacity occur at least once every year. The scheduling of all generating units on the island (ROI and NI), along with their reserve and ramping capabilities, and locational, operational and stability constraints, can be optimised using a unit commitment and economic dispatch model at an hourly time resolution to ensure cost-effective system balancing, while respecting frequency and voltage

stability considerations. Unlike other optimisation studies, unit commitment focuses on the operation of units rather than their sizing or installation, as these are not relevant variables in this context. Generation must meet the electrical demand at each time step across the study period.

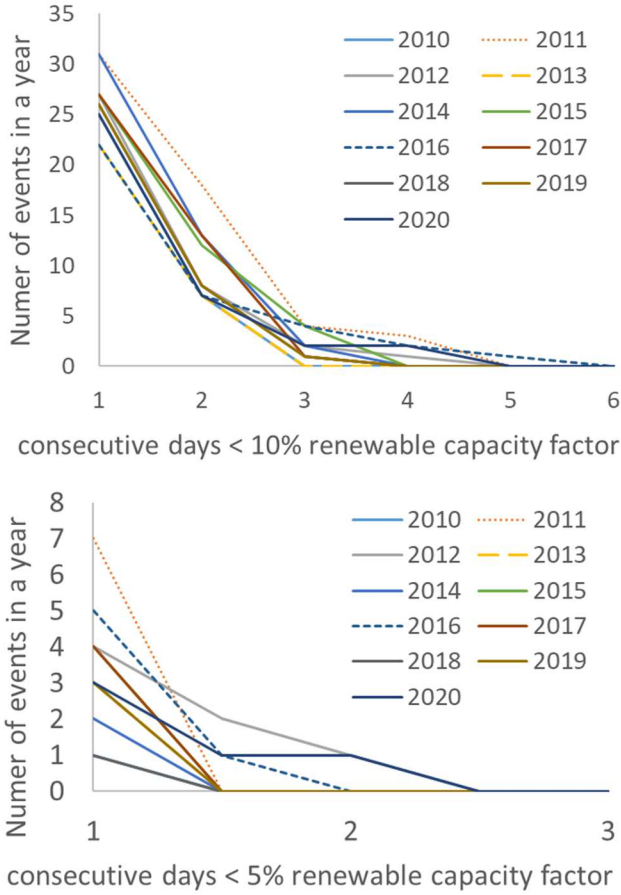


Figure 1. Number of consecutive days of dunkelflaute events with less than 5% and 10% renewable capacity factor per year.

The unit commitment aims to minimise total costs v^{obj} , defined as an objective function that considers start-up costs u_t^{s-u} , fuel costs u_t^{fuel} , and carbon tax costs u_t^{ghg} over all time steps, as shown in equation (3). Two penalty functions u_t^{voll} and u_t^{voir} , are introduced to account for small energy imbalances or violations of reserve requirements at a high cost, reflecting real-world electricity market condition.

$$v^{obj} = \sum_T \left(u_t^{s-u} + u_t^{fuel} + u_t^{ghg} + u_t^{voll} + u_t^{voir} \right) \quad (3)$$

The generation portfolio for the 2030 power system is based on scenarios proposed by the transmission system operators in both Ireland and Northern Ireland, EirGrid and SONI [12]. Two optimistic scenarios based on installing additional renewable capacity propose a portfolio of 55 gas-, oil-, hydro-, or biomass-fired units, incorporating existing and new open-cycle gas turbines (OGCT) and larger combined-

cycle gas turbines (CCGT). Gas prices are assumed to rise in line with the high scenario from the EU's Reference Scenario, with seasonal price variations also acknowledged. The EU carbon price is projected to be €100 per tonne in 2030. At present (2025), of the nineteen large conventional plants in ROI and NI, at least seven must always be operational (three in NI and four in ROI) to ensure network support across both regions. By 2030, the aim is to reduce the must-run constraint to a minimum of three regionally distributed large gas-fired units: one in NI, one in ROI near the capital city, and one elsewhere in ROI. However, rate of change of frequency (RoCoF) and synchronous inertial energy (GWs) related constraints ensure that system stability is retained despite the expected reduction in the number of online thermal units.

The generation portfolio for 2030 is assumed to include an onshore wind capacity of 11.43 GW, offshore wind capacity of 5.25 GW, a combined (utility and rooftop) solar PV capacity of 8.4 GW and a total of 8.85 GW of storage with various durations between 2 and 8 hours. The estimated national peak demand is 9 GW, and the annual demand is 46 TWh, indicating that the system will be heavily reliant on renewable energy sources [13]. Historical hourly load data has been sourced from EirGrid and SONI, and adapted for 2030 based on projected load growth, particularly relating to data centres, electric vehicles and heat pumps [14]. Given the forecast renewable capacity, extended periods of oversupply may be experienced across the year, $\approx 50\%$ of the time, if interconnectors are available to export the excess energy. The share of oversupply may be reduced to $\approx 15\%$ through HVDC interconnection (2.2 GW), depending on weather and market conditions [15]. The significant curtailment levels highlight the potential value in additional long duration storage, interconnection and demand side management to further reduce renewables curtailment.

By 2030, a total of four HVDC interconnectors to Ireland are expected to be operational: Celtic interconnector with France (700 MW), and three interconnectors with Great Britain (500 MW each). Two additional projects aim to further increase the interconnection capacity between Ireland and Great Britain: LirIC interconnector between Northern Ireland and Scotland (700 MW), and the Mares interconnector between ROI and Wales (750 MW). The potential benefits associated with the two additional interconnectors will be considered here. The interconnection supply cost, including transport losses, is assumed to be 65 €/MWh, which represents a high estimate for systems driven by renewables creating additional energy market variability [16], [17]. Additional storage capacity could be considered, particularly long-duration storage, capable of energy charge/discharge across several days. A pilot project for a 10 MW, 100-hour iron-air battery is currently being developed in County Donegal (northwest Ireland). Iron-air technology is seen as a promising long-term battery solution. Here, however, an aggregated generic, long-term battery energy storage of 500 MW, 50 TWh is assumed [18], [19].

The analysis approach involves modelling the year 2030 under different weather years, with the aim of meeting Irish

policy objectives [10]. Various dunkelflaute events, based on the observed weather years between 2010 and 2020, have been selected as reference cases, based on the assumption that climatic conditions, and the occurrence of dunkelflaute events, are reasonably well demonstrated from observations between 2010 and 2020 [4]. Sensitivity analysis is conducted on the integration of two additional options: interconnectors with GB (LiriC and Mares projects are currently under evaluation) and long-duration iron-air battery storage. The unit commitment model is solved using these additional options, with the impact on costs and CO₂ emissions quantified.

III. IMPACT OF DUNKELFLAUTE ON COSTS AND EMISSIONS

The renewable energy share across a rolling window period for the different weather years (2010 to 2020) was reviewed from the annual unit commitment profiles. The dunkelflaute event for the January 2020 weather year is first examined, which represents the most critical event observed over the decade. Figure 2 shows that the renewable capacity factor is less than 5% for more than two days, and the system demand lies in the first quartile of the total daily demand for that year, as defined in (2), such that $Dk_d = Dk_{d,highload}$.

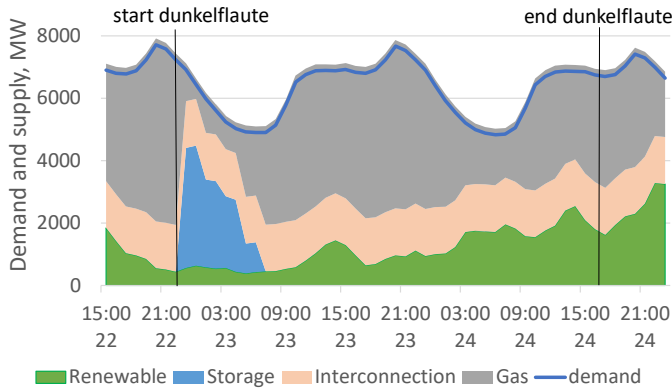


Figure 2. Supply share during dunkelflaute event of January 2020 weather year to match load and reserve in the reference case

The reference case is based on the predicted demand, weather pattern and capacity in 2030, as presented in Section II. During dunkelflaute events, it is reasonable to assume that Great Britain may not be disposed to sell electricity to Ireland, since its grid will also become increasingly reliant on renewable energy sources. Consequently, it is assumed that only half of the 1.5 GW HVDC interconnection capacity to Great Britain is available to supply Ireland. In contrast, France relies on nuclear and gas-fired generation, and it is assumed that the HVDC capacity (750 MW) can be fully exploited, assuming a higher electricity price in Ireland than in France during the dunkelflaute period.

Figure 2 shows how the system demand in Ireland is supplied during the dunkelflaute event, incorporating renewable (wind and solar) sources, energy storage, gas-fired generation and interconnector imports in the reference case. Table 1 indicates that 52% of the electrical supply during this period is obtained from gas-fired (CCGT and OCGT)

generation. It can also be observed that complete discharge of the energy storage facilities is insufficient to significantly affect the CO₂ emissions during the period, since it only covers 5% of the energy demand during the total period. It can also be seen in Table 1 that additional interconnection helps to reduce CO₂ emissions (by 26%) and moderately reduces the operational costs. The reduction in CO₂ emissions is linked to the imported electricity, whose emission factor has not been estimated since it requires determination of the incremental effect on emissions due to increased power export to Ireland. It should be noted, however, that reductions in emissions and operational costs across a few days for a rarely event do not justify by themselves investment in additional HVDC interconnection. Instead, optimisation tools, such as Spineopt [14], must be used to assess the multi-year benefits of additional interconnection options, and the energy trading impacts.

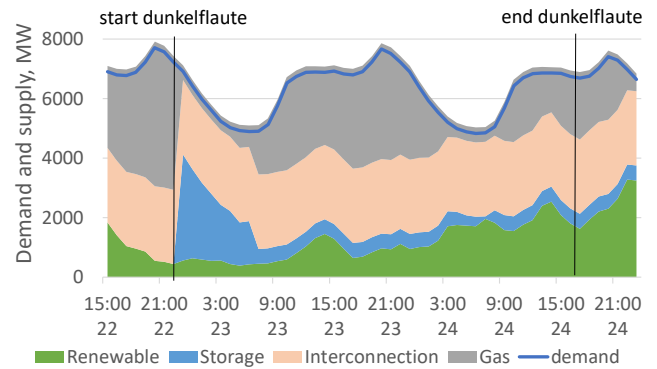


Figure 3. Supply share during dunkelflaute event of January 2020 weather year to match load and reserve, incorporating additional long duration energy storage and HVDC interconnection

If instead of additional interconnection, 500 MW (50 TWh) of long duration energy storage is introduced then 12% of the energy demand across the dunkelflaute period can now be covered, reducing CO₂ emissions and fuel costs by 14% and 11% respectively. Again, however, the capital costs associated with long duration energy storage have not been directly considered here, along with market incentives which might encourage investment in technologies which are primarily intended for utilisation during infrequent events.

Table 1. Summary of renewable share, CO₂ emissions and fuel costs for increased interconnection, storage and combined options

Case	Gas share (%)	Interconnection share (%)	Emission (tCO ₂ eq)	Fuel cost (M€)
Reference 2030	52	23	40.3	19.4
With additional interconnections	38 (-14)	38 (+15)	29.9 (-26%)	19.3 (-0.5%)
With long duration storage	46 (-6)	23 (=)	34.6 (-14%)	17.3 (-11%)
Combined	33 (-19)	38 (+15)	25.1 (-38%)	17.9 (-8%)

Finally, the combined case, incorporating both long duration storage and additional HVDC interconnection, leads to a low gas-fired generation supply of 33% (versus 52% in the reference case) and an increased reduction of 38% in CO₂ emissions across the dunkelflaute period. Fuel costs are lower than the reference case, but higher than the storage only case. Enhancements to the optimisation study, aiming to minimise total costs, may instead choose to not import electricity due to the direct cost benefits rather than emissions. Figure 3, in comparison to Figure 2, shows how combining energy storage with interconnection enables a higher share of the demand to be covered, which reduces indigenous fuel costs and emissions. Integration of additional solutions, such as hydrogen and demand-side management, and their potential benefits, can be studied as part of future work. Moreover, the operation of energy storage capacity must be linked to market structure, to optimise its integration into capacity (or related) markets, and to better understand the utilisation patterns, and charge/discharge cycles, for (comparatively) low efficiency long duration storage.

IV. CONCLUSION

The study underscores the critical challenges posed by dunkelflaute events periods of low wind and solar generation in achieving carbon neutrality by 2050, particularly for energy systems which target being heavily reliant upon renewable energy sources, such as Ireland and Northern Ireland. By analysing the 2030 Irish power system under various scenarios, this research highlights the importance of integrating long-term energy storage and expanding grid interconnection to mitigate the impacts of such events. The findings demonstrate that while both solutions offer significant benefits, their combined implementation, not surprisingly, yields more substantial reductions in CO₂ emission (38%) and a reduction in operational costs of 8%.

However, investment decisions cannot be made based on analysing a few days in a year, particularly when the events under consideration are relatively infrequent. Utilisation of energy storage and HVDC interconnection, along with their optimised energy market integration, should be studied across multiple weather years to better estimate their benefits. Future work will involve modelling the energy market in ROI, NI, and connected countries (France and GB) to study least cost unit commitment decision-making. A similar approach will be adopted to consider how demand-side management and hydrogen storage could further help address dunkelflaute events, as well as their competitiveness against existing technologies.

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