Optimisation Strategies To Reduce Renewables Curtailment Using Transportable Energy Storage Systems

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Abstract

Increasing shares of renewable energy sources in power systems worldwide have led to increased renewable curtailment due to network and/or stability limitations. Energy storage systems, both stationary and mobile, are widely proposed as a promising solution for reducing such curtailment. The paper presents a detailed analysis of renewable energy curtailment, taking the case study of a future Irish grid scenario, to identify the prospects of transportable energy storage systems (TESS). A combined unit commitment optimal power flow formulation has been developed to evaluate the locational curtailment from all renewable sources. The study establishes a baseline understanding of the locations and durations of renewable curtailment, providing insights on short-term/long-term TESS relocation, along with short/long distance movement possibilities, paving the way for optimal sizing and management of TESS units.

1 Introduction

Renewable energy sources (RES), such as wind and solar PV, are highly variable and uncertain compared to more traditional generation sources. High levels of renewables are presenting challenges for their incorporation within power systems, which leads to network or operational constraints, forcing the system operator to reduce the output of renewable generators, or ‘curtail’ (or ‘dispatch down’ in Ireland TSO context), at certain times [1]. System balancing issues, stability constraints and transmission congestion are the main reasons for RES curtailment, but short-term and long-term solutions, based on identifying additional sources of flexibility, can be applied. Potential solutions include physical additions (e.g. distributed storage), grid capacity expansion, institutional changes (e.g. access to new system services markets), and operational changes (e.g. improved forecasting and dispatch, including curtailment of lower priority generation) [2, 3].

Employing grid scale energy storage systems has been considered as an effective long-term solution to alleviate wind energy curtailment problems [4]. Battery energy storage systems (BESS), with high efficiency and fast response capability, can be a suitable candidate to improve power grid flexibility, increase management of network loading, and hence reduce RES curtailment. They may be centrally scheduled to provide (contingency reserve, regulating reserve, voltage support, etc.) grid services, or combined with distributed generators, as hybrid power plants, to mitigate the uncertain nature of RES. However, since battery locations are fixed and planned according to historical data, they are not always best placed to address evolving local system congestion (including voltage support requirements) and operational constraints, particularly noting that network topologies vary with time due to network outages, maintenance schedules, new wind and PV generation installations, short circuit fault current considerations, etc.

In contrast, mobile or transportable energy storage systems (TESS) have been proposed for scheduling and operation within active distribution systems [5–9]. TESS systems aim to provide a sustainable and cost-effective solution for grid congestion mitigation and demand-side management, by offering a mobile platform to alleviate curtailment associated with renewable energy sources (RES). The deployment of TESS units across the power system is expected to increase the volume of renewable energy delivered to consumers. Wind (and potentially solar PV) farm owners will benefit from reduced curtailment volumes and reduced financial risk, while electricity consumers will benefit from reduced costs for renewable electricity. The avoided wind (solar PV) curtailment associated with TESS deployment could also lower annual production costs and reduce carbon dioxide emissions significantly.

A number of research studies have been completed in recent years to identify the feasibility and the scheduling/management of TESS [6–9]. For example, a graph theoretic-based network expansion and transportable energy storage planning strategy has been proposed to enhance grid under extreme events [6]. Using the IEEE-30 and IEEE-118 bus systems, savings in the total cost and reduced load shedding were achieved. In [7], the authors proposed a long-term transmission-planning model coordinated with both stationary and mobile storage units as a potential alternative to managing transmission congestions. Similarly, a two-stage stochastic management scheme has been proposed in [8] to minimise the total system cost by coordinating the operation of TESS, hybrid AC/DC microgrids with high RES share while considering transportation and distribution network uncertainties. The proposed method achieved improved TESS scheduling accuracy under traffic uncertainties while maintaining cost-effectiveness. Furthermore, potential applications for utility-scale portable energy storage have been studied in [9], including an economic justification for California using a spatiotemporal decision model that determines the optimal operation and transportation schedule. It is shown that mobilizing energy storage can increase its life-cycle revenues by 70% in some areas and improve renewable energy integration by relieving local network congestion.

Despite the number of mobile storage studies completed, the conclusions reached tend to be system specific. The Irish power system, with its renewable ambitions, presents a very specific challenge in reducing renewable curtailment. Hence, the current study considers a future Irish power system, with the objective of better understanding TESS requirements, in terms of optimal sizing and fleet management, and the contrasts with stationary BESS systems.

Section 2 describes the optimisation methodology and the developed Irish grid network model used for the study. Section 3 details the curtailmet results and analysis for a 2028 Irish grid scenario, investigating the benefits of longer-term vs short-term TESS relocation, including inter-area vs intra-area transitions. Finally, Section 4 presents the overall discussions and conclusions of the study.

2 Optimisation study and Irish grid model

A combined unit commitment optimal power flow formulation has been developed, with the specific case of the Irish power system considered to determine the locational renewable curtailment daily and seasonal patterns.

2.1 Optimisation study for analysis of RES curtailment

The optimisation methodology for analysing RES curtailment for the Irish grid is shown in Fig 1. Historical solar irradiation and wind speed data, along with forecasted demand time, are used to prepare the study scenarios. Regional time series are extracted based on the clustering of the island of Ireland into several sub-regions. Regional time series are extracted based on clustering the input data, with 6 and 14 sub-regions identified for solar and wind power, respectively. A rolling unit commitment scheduling framework is adopted based on executing sequential optimisation runs across a scheduling period (e.g. one year) [10]. A parallel framework is also utilised to mitigate the computational burden of including network constraints by splitting the scheduling period into a number of distinct intervals, e.g., weeks or months, which are solved separately.

After each optimisation run, contingency screening is performed, where critical line contingencies are detected, and the required network constraints are added to the problem. The optimisation is then re-run, and the process is repeated until no further violations are observed for the line emergency short-term loadings. The optimisation process provides several detailed outcomes, such as line flows, nodal curtailment levels, carbon emissions and market surplus (based on nodal prices), as part of highlighting the impact of increased RES shares and assessing different technology options (stationary BESS or TESS). The overall optimisation methodology, in future studies, will also take inputs of transit time between network nodes and TESS data for optimal sizing and management of a fleet of TESS units.

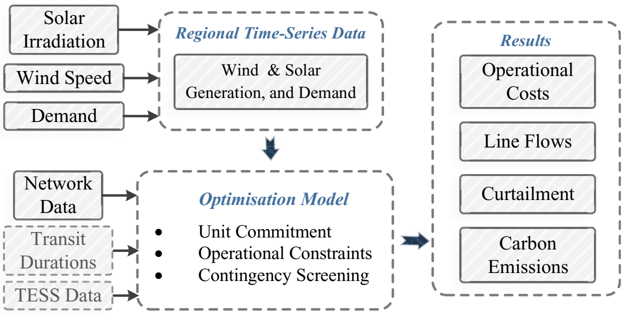

Fig. 1 Optimisation methodology for analysing RES curtailment.

The objective function is formulated to minimise operational (fuel) costs, including penalties for load shedding, while also considering the (depreciated) capital cost of new assets (e.g. TESS, stationary BESS, power flow controllers).

$$\begin{aligned} Minimise: C_{Total} = C_{Fuel} + C_{CO_2} + \\ C_{Interconnector} + C_{Load-shed} + \\ C_{TESS(capital\ \&\ operational)} + C_{BESS(capital)}, \end{aligned} \tag{1}$$

where, C_{Fuel} is the fuel cost, C_{CO_2} is the associated carbon emission cost, and $C_{Interconnector}$ is the cost associated with interconnector import/export flows. A power balance constraint is applied at each bus, which imposes a balance on the local injected power, and inflows and outflows for lines connecting to the bus. Power flows are formulated using an angle-based approach, with the angular difference across a line limited for stability and operational reasons. Such a constraint can be specified as follows:

$$|f_l| \leq f_{max} \tag{2}$$

where f_{max} represents the maximum flow limit of line l.

The unit commitment enables reduced renewable curtailment by de-committing conventional units when renewable output is high. Primary reserve and line security constraints are considered, together with stability-oriented constraints required for low inertia systems. Finally, after each optimisation run, contingency screening is performed for existing lines, which is followed by the detection of critical lines for associated outages and adding required line security constraints to the model. Through iterative optimisation runs, the model is gradually bound until any additional critical contingencies are not found.

2.2 Irish Grid model

With the new renewable energy targets laid out in the Climate Action Plan [11], Ireland has committed to deliver an 80% renewable electricity target by 2030, with renewable capacity approaching 22 GW. The new target comes with a considerable increase in solar PV capacity of 5 GW by the year 2025 and 8

GW by the end of 2030, which is a significant jump from 1.5 GW defined previously for 2030. Accommodating such a large amount of renewables in such a small island power system will have an unprecedented impact on the overall planning and operation of the system. It follows that without mitigation measures, the frequency and duration of curtailment periods will be significantly increased during periods of excess wind and/or solar PV generation. Hence, understanding of the prospects of storage and mobile storage, in particular to support the rapid adoption of RES in the Irish network, is a must.

The Irish grid model used here is developed from publicly available data published by the Irish TSO, EirGrid, for 2028, in PSS/E format [12]. The model consists of relatively conservative assumptions for the Irish grid in 2028, e.g. inclusion of only the two existing 500 MW interconnectors without any new interconnectors, and a negligible amount of offshore wind farms. The peak all-island demand is 8.35 GW. Installed onshore wind and PV capacities are considered as 7.02 and 0.70 GW. These figures align with the *'delayed transition'* and *'least effort'* scenarios defined by EirGrid and SONI (TSO for Ireland and Nothern Ireland). Wind and solar power portfolios are adapted and assigned to different equipment according to classified sub-regions. Aggregation is applied to distribution nodes to create an overall transmission network model considering up to 110 kV lines (i.e. 110 kV, 220 kV, 275 kV and 400 kV), resulting in a grid with 559 nodes and 674 branches. Conventional generators are transferred to the nearest transmission substation. Distributed generation and demand are also aggregated for different types up to the transmission level. Furthermore, as shown in Fig. 2, for ease of analysis and understanding of curtailment locations, the Irish grid has been divided into 14 study areas [13] (also interchangeably used as *regions*), with the corresponding wind and PV capacities indicated.

3 Analysis of RES curtailment

Regional curtailment analysis for the Irish grid model is split here into longer duration analysis, involving seasonal and monthly variations, and shorter duration analysis, involving weekly, daily and hourly analysis. The sub-division aims to help understand the relative benefits of mobile storage being mainly employed for inter-area (longer duration) or intra-area (shorter duration) relocation applications.

3.1 Seasonal and monthly variations

Seasonal and monthly variations in the curtailment of RES suggest the possibility of longer-term deployment/relocation of TESS. Fig 3 shows the monthly curtailment of PV and wind for the future year, with comparison made against 2021 figures [14]. As expected, curtailment is much higher for the later year (13.3% relative to 6.4%), given that the renewable capacity has increased from 5.68 GW to 7.7 GW. Furthermore, curtailment tends to be higher during the winter months and less so during summer and autumn, which aligns with seasonal wind speed variations. The installed PV capacity considered here is low (0.7 GW), so even during the summer curtailment levels are low, but it is noteworthy that Ireland's PV target for 2030 is 8 GW, which suggests that PV-related curtailment will likely be higher in the future unless mitigation measures are introduced.

Fig. 2 Ireland transmission network with study areas [13], along with installed wind and PV capacities for 2028 scenario.

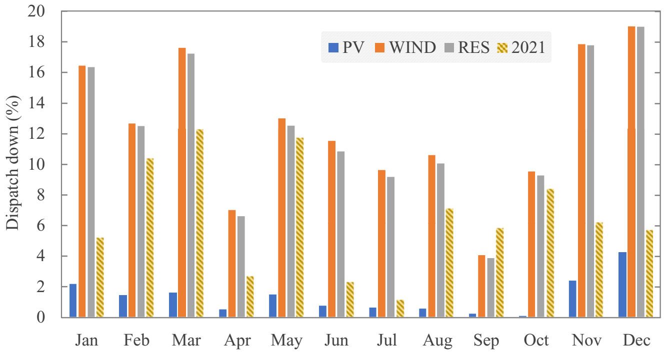

Fig. 3 Monthly curtailment for PV, wind and combined RES, and 2021 figures.

The seasonal variation in renewable curtailment for the 14 study areas is shown in Fig 4. Curtailment is highest during the winter (16.42%), followed by the spring (12.95%), autumn (12%) and summer (10%) months . It can be observed that the highest curtailment are found in areas A, B and E; with the highest in area E (42%), followed by B (30%), A (16%), NW & H1 (each 3%). Higher shares of curtailment in areas E, B, and A are in line with the higher installed capacities of wind generations in these areas. Furthermore, more variations throughout the seasons in terms of curtailment can be observed in these areas.

Looking further forward than the presented analysis, large volumes of offshore wind capacity are expected off the east coast of Ireland (with some off the west and south west coasts), while residential and utility scale PV projects are also anticipated, mainly towards the eastern and south eastern areas (aligning with major urban areas). It follows that curtailment areas will likely evolve in the coming years, and opportunities for monthly seasonal relocation of TESS units will be increasingly economically justified, with wind-rich regions being preferred during the winter months and relocated to PV-rich regions during the summer time.

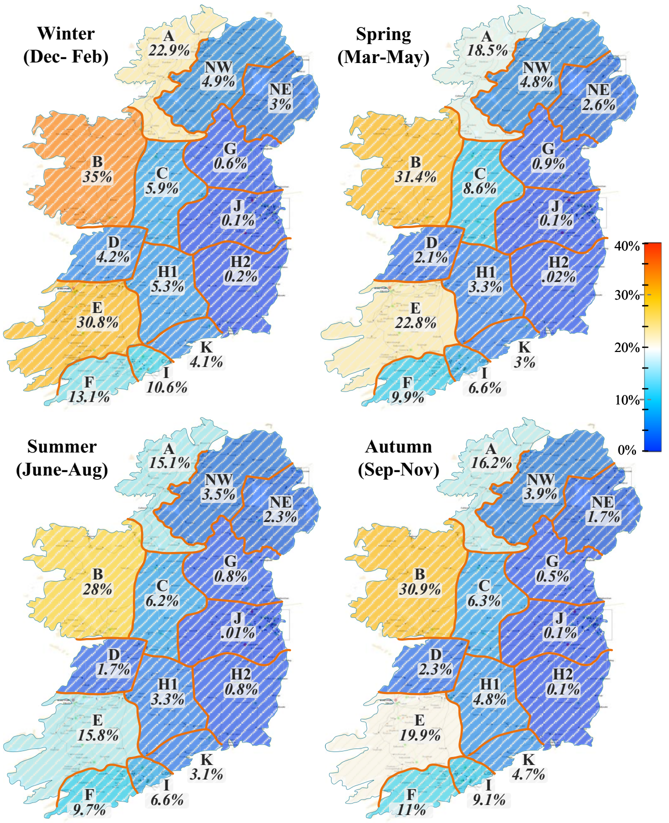

Fig. 4. Seasonal RES curtailment for Ireland sub-regions.

3.2 *Weekly, daily, and hourly variations*

Weekly curtailment for areas A, B and E is shown in Fig 5, representing 87.4% of the annual total, and indicates a very similar trend to the monthly curtailment, but with additional granularity. It might be expected that future PV growth would indicate greater weekly variations, with more curtailment seen during the summer weeks. Further investigation within areas (RES-connected buses), and analysis of shorter timeframes (including within a day) will further reveal inter-area and intra-area TESS deployment opportunities.

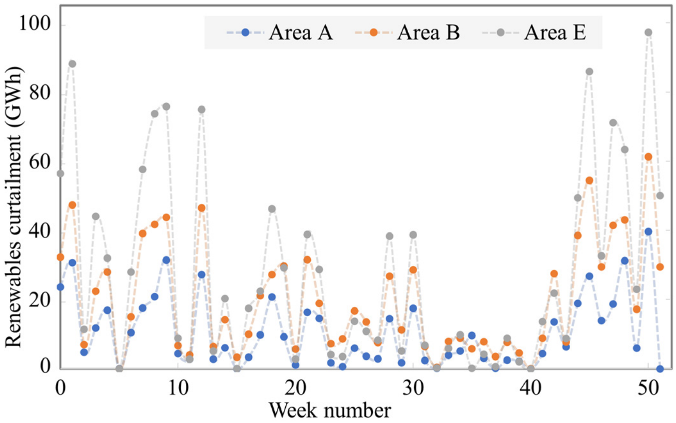

Fig. 5 Weekly curtailment for selected sub-regions (A, B and E).

Fig 6 shows the daily curtailment for 2 representative buses in areas B and E (214 km apart), showing possible opportunities for inter-area TESS relocation. Both buses have relatively high renewable capacity, namely 174 MW at bus B-1 and 167 MW at bus E-1. The E bus only experiences a few periods of high curtailment (days 132, 157, 196 and 215), while the B bus experiences multiple periods of high curtailment, which potentially creates opportunities for inter-day TESS relocation to reduce overall curtailment. Relocating TESS units on a daily basis is investigated to better understand the opportunities for intra-area and inter-area transitions, recognising the distances (and travel times) involved. However, the examples considered here have not been optimised, and are instead intended to be representative of future TESS opportunities.

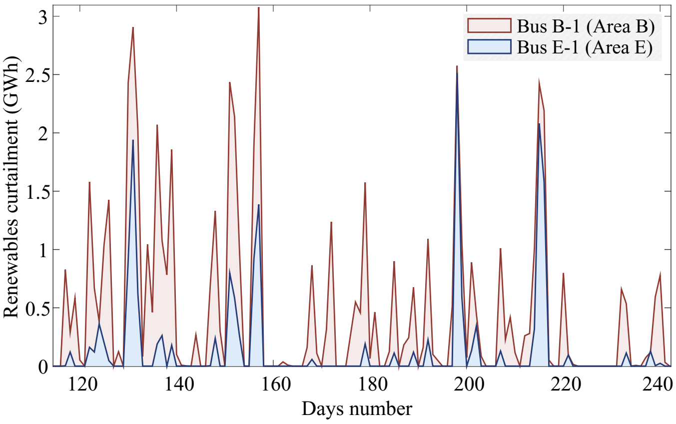

Fig. 6 Daily curtailment for individual buses in sub-regions B and E.

Given that sub-region E experiences the highest curtailment, it suggests that there may be opportunities for intra-area relocation. Consequently, Fig. 7 shows the 3-hourly curtailment for two selected buses E-2 and E-3 , which consist of 179 MW and 100 MW of wind generation, respectively. The two buses are 108 km apart from each other. The highest curtailment occurs at bus E-2 on day 66, while more frequent curtailment (but lower) peaks are seen at the other bus, E-3, which suggests that a TESS could be usefully relocated to bus E-3 even when (lower) curtailment is being experienced at bus E-2.

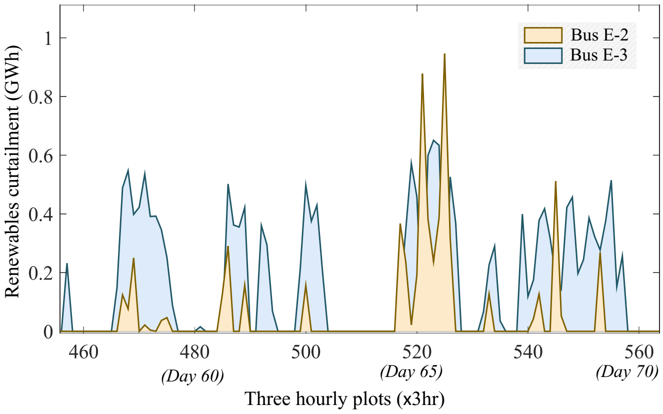

Fig. 7. 3-hourly curtailment for two buses in sub-region E.

Finally, Fig 8 8 shows the annual average hourly curtailment for each sub-region, and emphasizing again the dominance of A, B and E to the total curtailment, although certain sub-regions (such as F and H2) tend to experience curtailment during the early morning hours but not for the reminder of the day, which might again indicate TESS relocation opportunities.

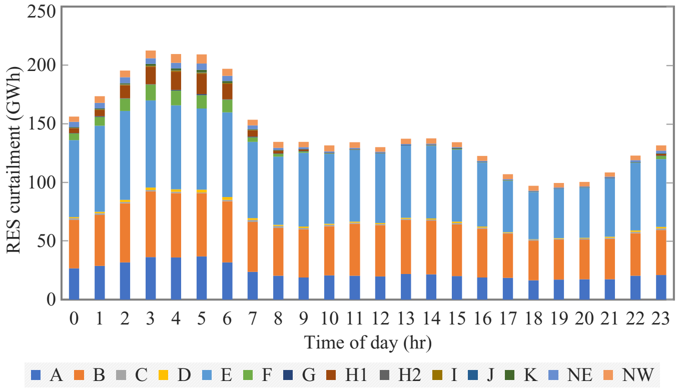

Fig. 8. Average hourly renewables curtailment by sub-region.

4 Discussion and Conclusion

Against a background of increasing renewable targets in many countries it can be expected that increasing curtailment due to network and/or operational (stability) constraints will occur. The particular case of a future Irish power system was considered, with a combined unit commitment and optimal power flow optimisation process implemented to predict locational renewable curtailment. By understanding where, how often and how long curtailment tends to occur it then becomes possible to understand potential locations for mobile storage to be suitably employed. Seasonal relocation of TESS units is suggested between the east coast of Ireland, where PV farms are likely to be built, and near urban areas, and moved to the west coast during the winter where wind farms are more likely to be located. Short-term relocations, on the timescales of hours and days, may be suggested between wind- or PV-rich buses and load buses, involving short-to-medium travel distances.

The analysis presented here has focused on mobile storage supporting renewables curtailment, but other stacked applications can be considered to improve the economic justification for a fleet of TESS units. For example, TESS could be applied in locations with ageing infrastructure [15], notably in the distribution network, such that they can enable transmission and distribution system upgrades to be conveniently delayed. TESS units can also provide local and system-wide services, such as voltage support, contingency reserve and regulating service, leading to additional revenue streams, as well as supporting the displacement of conventional generation providing the same capabilities. Future work will consider rolling (unit commitment) scheduling to better recognise uncertainties associated with renewable forecasting, and more detailed (medium voltage) distribution network representations will be implemented to better capture the TESS fleet intra-area utilisation and relocation opportunities.

5 Acknowledgements

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