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Impact of Wide-Scale Data Centre Growth on Power System Operation with Large Share of Renewables

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***Abstract*—Driven by the large-scale adoption of cloud-based technologies, the past decade has experienced tremendous data centre growth around the globe. In addition to ongoing increases in energy consumption from the sector, the proliferation of data centres also induces a number of electrical network challenges. In this study, their potential to contribute to demand flexibility is analysed, exploring the trade-off between available flexibility and system energy costs, in a day-ahead electricity market. Data centre operation is modelled within a least cost energy mixed integer formulation for the 2030 Irish electricity sector, sourcing 70% of electrical demand from variable renewables. Subsequent impacts on generation and demand schedules, energy costs, renewable energy curtailment, emission levels, plant operational hours, etc. are evaluated, in order to demonstrate how large-scale data centre growth can affect a system's ability to meet its renewable obligations.**

I. INTRODUCTION

Concerns about climate change manifest themselves as a call for alternative technologies to deliver reliable, secure and affordable energy. Future energy systems must also be capable of accommodating strong demand growth, and, in particular, electrification of the heat and transport sectors, in the form of electric vehicles and heat pumps. Increased digitalisation is also causing rapid growth in the volume of data centres being installed within many power systems, leading to increased cooling load requirements. Globally, data centres accounted for ≈1% of electricity use in 2018, a figure which may reach 8% by 2030, although, in some countries, such as Ireland, this figure could be much higher (≈40%) [1].

Inevitably, this surge in data centre capacity will require significant new energy infrastructure, while increasing the associated electrical demand and emissions. With the goal of reducing their energy costs, extensive research has generally focused on either achieving more efficient hardware designs or dynamically adjusting the number of active servers in data centres [2, 3]. In [3, 4], uninterruptible power supply units are also considered as a means to reduce electricity costs, but, the associated batteries can be costly, with their lifetime sensitive to frequent cycling. The ensuing ability of power systems to respond to future decarbonisation targets may be affected, particularly if the new loads are insufficiently flexible in daily operation. However, at present, it is unusual for data centres to participate in demand shaping or reserve provision, as they can be heavily penalised for downtime periods. The generally flat demand profile could, therefore, stress the grid during peak periods, particularly if clustered near major load centres.

According to published surveys, however, ≈20% of servers within a data centre can be underutilised [5]. Consequently, scheduling of delay tolerant workloads has been studied in [6-8], while, in order to assess the impact of such loads within a competitive market, a risk-hedging approach has been applied to ensure a tradeoff between energy cost and operational risk, based on data centre operator preferences [9]. Of late, various audiences have raised concerns about environmental impacts from data centres, such that technology greening is receiving both academic [10-12] and industry [13] attention. Studies have focussed on delay sensitive [10] or delay tolerant [11] workload scheduling, and/or energy storage [12] to facilitate integration of on-site renewable generation. Existing studies, therefore, emphasise that data centres, as large energy users, represent a promising sector for adoption of demand response measures. In addition, a desire to transition away from fossil fuels, due to global emission reduction goals, has led countries to adopt highly ambitious renewable electricity targets. It is, therefore, imperative to assess the technical and economic implications of data centre growth on future power system operation with a high renewables share. However, in general, the joint impact of large-scale data centre growth and large shares of renewables has not been considered for future energy systems, an issue which this paper intends to address.

In this work, data centre operation is modelled within an energy cost minimisation problem for future energy systems with a high share of variable renewables. Such systems imply both variability and uncertainty in the supply of (renewable) energy, and hence flexibility, either from the remaining generation portfolio, and/or the demand side, is required, in order to minimise renewables curtailment. The efficacy of the approach is evaluated on Ireland's electricity sector, noting its uniqueness in being a synchronously isolated system with limited interconnection and energy storage capabilities, while adopting demanding renewable generation targets. The latest Climate Action Plan for Ireland states that 70% of electricity needs should come from renewable sources by 2030 [14]. In addition, due to its strategic location, Ireland is often referred to as the "Digital Gateway to Europe" for US companies and has, therefore, evolved as a Tier-1 hosting location for data centres [14], currently consuming ≈18% of annual demand, but this figure is expected to grow rapidly towards 40% by 2030. Along with increasing electrification of the heat and transport sectors, this paper examines the impact of large data centre growth, and the benefits of various modes of operation, for the 2030 Irish power system. The remainder of this paper is organised as follows: Section II presents the energy system model, with results from year-long simulations presented in Section III, while, Section IV concludes the paper.

II. MODEL DESCRIPTION

A day ahead unit commitment and economic dispatch model is formulated with a rolling horizon, in order to assess the potential for data centres to contribute to power system support services, including operational flexibility, for the target year of 2030. The resulting model is defined as a mixed-integer linear problem, solved using a highly adaptable energy systems modelling framework, 'Backbone' [16], which is an open-source modelling tool implemented in GAMS. With its highly adaptable grid and node structure, Backbone can model a wide variety of energy sectors. It is comprised of a network structure, with individual layers representing different grids, e.g. water reservoirs, electric power grid. Links between grids are achieved using energy conversion units, e.g. hydro power, power-to-heat, located at particular nodes within each grid, while transfer links within a grid can also be created. Several grids can be associated with an individual node, thereby representing different energy sectors. Such a layered structure facilitates new technologies, such as power-to-gas, EVs, HPs, etc. within the model.

A. *Objective*

The objective function (C^{obj}) combines generating unit start-up ($C_{f,t}^{SU}$) and shut-down costs ($C_{f,t}^{SD}$), fuel and emission costs ($C_{f,t}^{fuel\&em}$), variable operation and maintenance costs ($C_{f,t}^{O\&M}$), unit ramping costs ($C_{f,t}^{ramp}$), and penalties ($C_{f,t}^{pen}$) associated with energy and reserve imbalances. If $p_{f,t}$ denotes the probability of forecast f ($f \in F$) for time interval t ($t \in T$), then the objective function can be formulated as follows:

$$C^{obj} = \sum_{\{f,t\} \in FT} p_{f,t} \times \left(C_{f,t}^{SU} + C_{f,t}^{SD} + C_{f,t}^{fuel\&em} + C_{f,t}^{O\&M} + C_{f,t}^{ramp} + C_{f,t}^{pen} \right) \quad (1)$$

A detailed description on calculating the different terms in the objective function (1) is found in [16]. Decision variables of the optimisation problem include unit generation and commitment status, fuel use, interconnector flows, battery charge/discharge power, reserve contribution from generating units, interconnectors and dispatchable demand.

B. *Constraints*

Transition towards a higher share of renewable electricity involves phasing out conventional generators, and thereby inducing several dynamic challenges to the power system. The rotating mass of synchronous units provide rotational inertia, but with fewer such units online, the physical system inertia reduces, which can present major system stability implications [17]. Following a generation-load imbalance, inertia slows down initial frequency disturbances, and so provides increased time for thermal generator governors to respond and arrest the subsequent drop in the system frequency. This initial rate-of-change-of-frequency (RoCoF) becomes larger with declining system inertia, as the share of variable renewables increases. If $freq_0$ denotes the system base frequency (50/60 Hz), $H_{i,t}$ the inertial constant of unit i, $S_{i,t}$ the apparent power of the unit, and $\Delta P_{i,t}$ the potential infeed loss, then the RoCoF, $\Delta freq / \Delta t$, is calculated per (2):

$$2 \times \Delta freq_t / \Delta t \times \sum_{i \in G^{Inertia}} \left(H_{i,t} \times S_{i,t} \right) \geq freq^0 \times \Delta P_{i,t} \quad (2)$$

where, $\sum_{i \in G^{Inertia}} \left(H_{i,t} \times S_{i,t} \right)$ combines the rotational inertia of all online units of the system for which a floor can be set. In addition, a further operational security metric constrains the total production from non-synchronous infeeds, known as the system non-synchronous penetration (SNSP) limit, and is calculated and constrained as (3) [18]:

$$SNSP_t = \frac{\sum_{i \in G^{RE}} P_{i,t} + \sum_{x \in IC} P_{x,t}^{import}}{\sum_{l \in LOAD} P_{l,t}^{load} + \sum_{x \in IC} P_{x,t}^{export}} \quad (3a)$$

$$SNSP_t \leq SNSP^{max}, \qquad \forall t > T \quad (3b)$$

where, the sets G_{RE}, $LOAD$ and IC consist of non-synchronous resources, load units and HVDC interconnectors (which asynchronously connect the test system to neighbouring systems). $P_{IC,t}^{import}$ and $P_{IC,t}^{export}$ denote power imported / exported through HVDC interconnectors at time t, while $P_{i,t}$ and $P_{l,t}^{load}$ denote power output from unit i and price-inelastic demand. Additional constraints relate to the thermal generation fleet (start-up, shut-down, ramping, up-down times, etc.), transfer capabilities and ramp rates on HVDC interconnector flows, reserve categories, etc. [19]. Constraints on primary and tertiary operating reserves (POR and TOR) are also enforced for the Irish power system [19]. In addition, an N-1 reserve constraint is also included, based on a fraction of the largest single infeed (POR - 75% LSI, TOR - 100% LSI). Reserve provision from renewables is also considered.

C. *New load categories*

A growing population and increasing living standards are expected to increase energy demand significantly over the coming decades, driven primarily by large energy users and electrification of heat and transport sectors, in the form of EVs and HPs. The new load categories will likely contribute towards system support roles in order to mitigate the uncertain and variable nature of VRE sources.

1) Data centres: With increasing digitalisation, data centres have become a significant contributor to electrical demand, such that managing energy consumption is highly important for data centre operators. By exploiting spatial and temporal variations in electricity market prices, operators can minimise their energy cost. In light of this, a number of studies have advocated active participation of commercial cloud providers in demand management [6-8]. Data centre workloads depend on incoming requests for cloud computing services, which are then scheduled [20]. Individual jobs can be classified as (a) delay-tolerant (batch) workloads, which can be scheduled for any time before their deadline, and (b) delay-sensitive (real-time) workloads which should be handled immediately upon arrival. Batch workloads can avail of options for completion as continuous or interruptible time blocks. In the former case, task execution continues until the particular job is completed.

Previous studies have assumed diverse flexibility potential from data centre loads [20, 21]. Assuming up to 50% price responsive demand, a least cost energy management strategy for data centre microgrids was proposed in [20] to improve energy efficiency through waste heat recovery. With a similar assumption, a cooling efficiency enabled demand management strategy was studied in [21]. In the present work, up to 30% of data centre demand is considered to participate in demand management. Based on the Climate Action Plan [14], data centre demand comprises up to 40% of annual All Island electricity demand for 2030. All batch workloads are modelled as delay tolerant jobs, with an interruptible execution time block. For scheduling tasks, servers should accommodate unfinished and newly received job requests within their scheduling horizon, to ensure that there are no unserved tasks at the end of each 24 h period.

2) Heat pumps (HPs): In order to meet 2030 decarbonisation objectives, EirGrid [22] and SONI [23] (system operators for Ireland and N. Ireland) will target 445,000 HPs for domestic and commercial buildings. Significant improvements in air quality can be expected from retrofitting buildings with heat pumps. Using EirGrid assumptions [22], only air source HPs are considered, with a temperature dependent coefficient of performance, and air temperatures taken from [24].

3) Electric vehicles (EVs): The Climate Action Plan [14] aims for 936,000 EVs in the form of electric cars, vans, trucks and buses, on the road by 2030. Weekday and weekend charging profiles are included as input time series of currently plugged in capacity. The time series consider the effects of ambient temperature, EV numbers, charging and driving efficiencies, etc. based on EirGrid and SONI scenarios for 2030 [22, 23], in conjunction with laid down Climate Action Plan targets [14].

III. CASE STUDY

A. Test system description

The system operators of Ireland (EirGrid) and N. Ireland (SONI) have proposed various 2030 scenarios for the expected demand and generation mix, in order to assess the impact of the projected energy transition on the electricity grid. The focus here is on the medium and high ambition *Centralised Energy* scenario of EirGrid [22] and *Modest Progress* scenario of SONI [23], as both scenarios satisfy the 70% renewable energy target of the Climate Action Plan [14]. Table I summarises the aggregated generation capacities for the All Island system [22, 23]. It is to be noted that the generation capacities have been aggregated solely for brevity, and are modelled on an individual unit basis in this work.

TABLE I. AGGREGATED INSTALLED CAPACITIES

Technology/Fuel	Installed capacity (MW)
Onshore / offshore wind	7395 / 3500
Solar	988
Biomass* / Waste***	320 / 40
Hydro / Marine**	246 / 80
Combined cycle gas turbine (CCGT)	3790
Open cycle gas turbine (OCGT)	1201
OCGT (distillate oil)	200
Combined heat and power (CHP***)	350
Demand side management (DSM)	750
Battery energy storage	450
Pumped hydro energy storage (PHES)	292

* Including renewable waste, biogas and landfill gas.
** Wave and tidal. *** Fossil fuel or non-renewable component.

In addition to the existing 500 MW EWIC and 450 MW Moyle HVDC interconnectors between Ireland and Great Britain (GB) it is assumed that additional interconnectors, with GB (500 MW), and France (700 MW), are also built, in 2023 and 2026, increasing the total HVDC interconnection capacity to 2150 MW by 2030. Interconnector flows are modelled considering reduced models of GB and France, with aggregated gas generation and base load. Reducing efficiency is considered for thermal units across their operating range, thereby, replicating a real system with a marginal price curve consisting of multiple units. In addition, interconnectors are also considered to provide N-1 reserve.

A 450 MW battery fleet with a 90% round trip efficiency is assumed [22], and when sufficiently charged, batteries can provide upward primary reserve of up to 50% of their rated capacity. In addition, the base case also considers 750 MW of price-sensitive demand response, with the load shedding cost set to 100 €/MW/h. Capacity factors for renewables are based on weather profiles for 2015 [25]. The base demand time series is based on historical data of the same year [26], with the total demand formed as a combination of the base demand, and components from EVs, HPs and data centres. Time series for both renewables and demand are regionally scaled to match annual projections for 2030 [22, 24]. Finally, an inertial floor of 17.5 GWs [22] is considered. SNSP and RoCoF are constrained at 95% [22] and 1 Hz/sec [22], with carbon and fuel prices based on projections for 2030 [27].

Two cases are considered to examine the implications of data centre demand shaping on the Irish system with 70% renewable electricity: (1) base case, as above, where data centre demand is modelled as constant load. (2) including active participation of data centres in demand management.

B. Results and discussion

1) Base case: it is assumed that data centre load is flat and doesn't vary significantly across the day. Two days with differing VRE / load profiles are presented here, with Fig. 1 illustrating the generation schedules and marginal electricity price for a day with high positive net load (high demand and low wind), while Fig. 2 depicts a windy day with high negative net load (medium demand and high wind). In the former, the model uses all available generation from wind and PV, with the remaining demand supplied from thermal generation and HVDC imports.

It can be seen from Fig. 1 that there are price spikes at 7:00 h, 17:00-19:00 h, which can be attributed to OCGT plant dispatches to meet peaks in demand during these hours. In contrast, for the windy day, available renewable generation exceeds indigenous demand for several hours, with any power surplus exported through the HVDC interconnections. Fig. 2 clearly shows the impact of a high share of zero-marginal cost renewables on the marginal electricity price, which is noticeably reduced, compared to the low wind day, with the price approaching zero at 13:00 h. The fall in energy price can be attributed to the available renewable supply exceeding operational limits that the system can instantaneously accept, and thereby, curtailing surplus VRE generation during the respective periods, Fig. 3. It can also be observed from Fig. 3 that VRE curtailment occurs as SNSP exceeds 80% and approaches its 95% limit, and when rotational inertia approaches its minimum limit of 17.5 GWs.

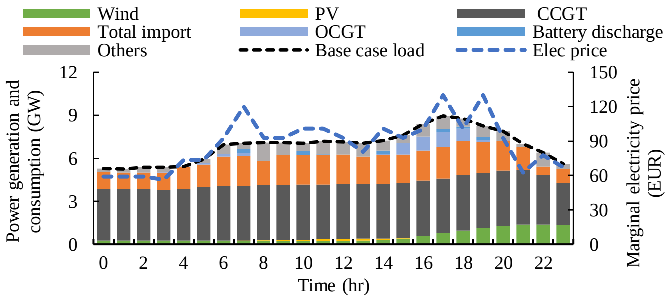

Fig. 1. Optimal operating schedules for low wind day.

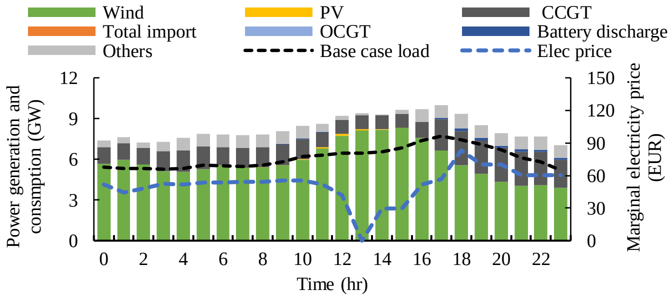

Fig. 2. Optimal operating schedules for high wind day.

While acknowledging the contribution of batteries and price responsive demand to system support, by acting as a source of negative load during peak demand periods and positive load during low demand periods, nonetheless, several higher price periods (Fig. 1) or lower price periods (Fig. 2) can be observed. As the Irish power sector transitions towards 70% renewables, frequent occurrence of such events is highly likely, with technical stability (SNSP, RoCoF, inertia, etc.) constraints promoting the need for additional sources of (ramping, demand shaping, peak avoidance, etc.) flexibility.

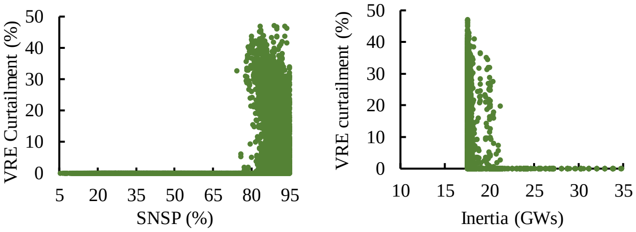

Fig. 3. Impact of SNSP and inertia constraints on annual VRE curtailment.

2) Including data centre load management: now assuming the active participation of cloud providers, as large energy users, with the share of flexible data centre demand studied varied from 10% up to 30%, and with the impact on unit generation and consumption schedules, energy prices and VRE curtailment, analysed. The efficacy of the approach in achieving data centre load shaping, for varying flexibility levels is evident in Fig. 4, indicating the largest deviation in data centre load for each hour of the day, across the one year scheduling horizon. It is noticeable from Fig. 4 that the peak increase/decrease in data centre demand is much smaller than the maximum potential increase/decrease in instantaneous data centre load, thereby, suggesting that energy shaping is more important than power shaping.

Fig. 5 further illustrates the impact of data centre demand shaping on the maximum system marginal electricity price for each hour of the day across the scheduling horizon. It is observed that peak prices noticeably reduce as the flexible demand share increases.

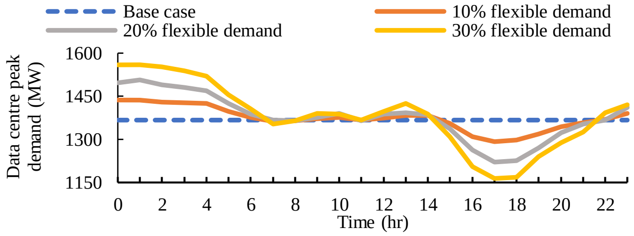

Fig. 4. Maximum (annual) data centre workload allocation decisions.

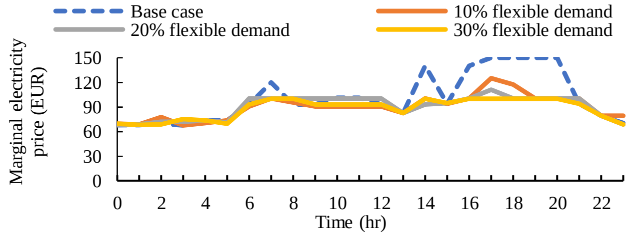

Fig. 5. Impact of data centre demand shaping on (annual) electricity price.

Figs. 6 & 7 illustrate the data centre scheduling results for the same two days as Figs. 1 & 2, with high positive and high negative net load. It is to be noted that results henceforth, correspond to 30% flexible demand from data centres. The impact of data centre peak load shifting and the subsequent reduction in price extremes is evident from Figs. 6 & 7. The resulting VRE curtailment, SNSP and inertia values for the target year are indicated by Fig. 8. Careful comparison of Figs. 3 & 8 shows that the proposed framework reduces VRE curtailment (0.68% reduction), while also pushing the system away from its (SNSP) stability limits.

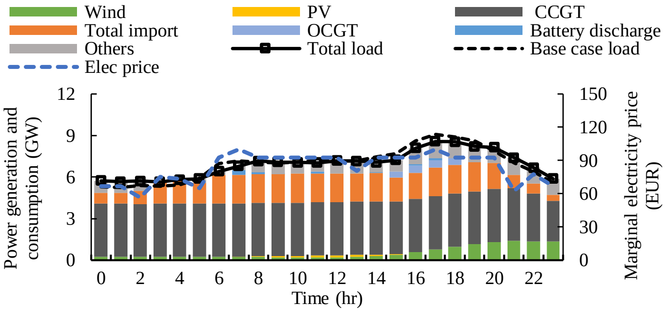

Fig. 6. Optimal operating schedules for low wind day (30% flexibility).

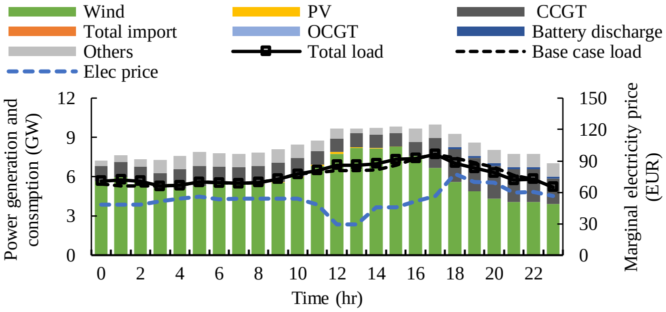

Fig. 7 Optimal operating schedules for high wind day (30% flexibility).

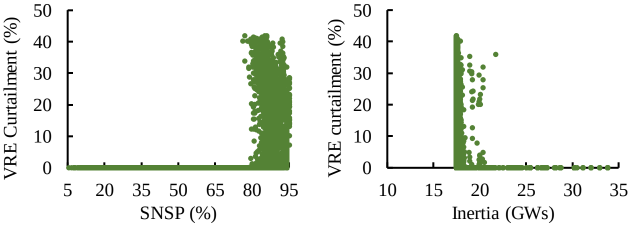

Fig. 8. Impact of SNSP and inertia constraints on annual VRE curtailment (30% flexibility).

Table II assesses the impact of flexibility from cloud providers on OCGT plant starts, operational hours and capacity factors across the year. With data centres actively participating in demand management, plant startups, fleet average capacity factors and operational hours for the OCGT units are now evidently reduced. Table III further summarises annual results on VRE curtailment and emission levels for the two cases considered. It is seen that increasing levels of data centre demand flexibility reduce the VRE curtailment (and emissions) compared to their inelastic counterpart, but also that even with 30% data centre flexibility that the curtailment levels remain relatively high. It follows that while data centre flexibility has a valuable role to play in assisting renewables integration, it does not represent a silver bullet solution, and instead a multi-sectoral approach is required.

TABLE II. ANNUAL (70% RES) OCGT OPERATIONAL SCHEDULES

Parameter	Base Case	10% demand flexibility	20% demand flexibility	30% demand flexibility
No. plant starts	337	284	261	244
Online hours (%)	10.85	10.11	9.06	8.41
Capacity factor (%)	1.14	0.94	0.86	0.75

TABLE III. ANNUAL (70% RES) SYSTEM PERFORMANCE

Parameter	Base Case	10% demand flexibility	20% demand flexibility	30% demand flexibility
Wind curtailment (%)	9.44	9.20	8.98	8.76
PV curtailment (%)	4.38	3.86	3.40	3.39
Total VRE curtailment (%)	9.34	9.09	8.87	8.66
CO2 emissions (Mt)	7.96	7.95	7.95	7.94

IV. CONCLUSION

The potential for large (data centre) loads to provide system support in the presence of a high share of renewables is analysed. The efficacy of the proposed framework was demonstrated for the 2030 Irish electricity sector, sourcing as high as 70% of its annual energy consumption from variable renewables. Results show that data centres can contribute towards system support roles, particularly for systems with limited interconnection and a high share of renewables.

With increasing data centre flexibility, the framework was seen to be effective in reducing electricity price variability, VRE (wind and solar) curtailment, carbon emissions and thermal plant operational hours, while also improving stability margins. With increasing national renewable targets, system operators are keen on leveraging such potential, and the inclusion of flexibility requirements on newer connection offers is imminent.

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