Design and Operation of Energy Systems with Large Amounts of Variable Generation

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***Abstract*— This article highlights key themes from the IEA Wind TCP Task 25 report, which compiles state-of-the-art experiences and study results relating to four challenges for energy systems around the world with growing shares of variable renewable generation. First is the planning challenge, which focuses on how to plan for the long-term adequacy of transmission grids and generation capacity. Second and third are the inter-linked balancing and stability challenges, which focus on how to manage the operations of power systems, including issues like minimizing uneconomic curtailment and providing system support from wind power plants. Fourth is the market challenge, which focuses on how to increase the value of wind energy in future energy systems and improve operational practices and flexibility.**

Keywords—grid integration, wind power, power system, balancing, stability, market design)

I. INTRODUCTION

The design and operation of power and energy systems is an evolving field. As ambitious targets toward net-zero carbon energy systems are announced globally, many scenarios are being made regarding how to reach these future decarbonised energy systems, most of them involving large amounts of variable renewables, mainly wind and solar energy. The secure operation of power systems is increasingly challenging. The impact of both increased amounts of variable renewables as well as new electrification loads together with increased distribution system resources that require more coordination between transmission and distribution systems will lead to somewhat different challenges for different systems.

Tools and methods to study future power and energy systems also need to evolve, and both short-term operational aspects (such as power system stability) and long-term aspects (such as resource adequacy) will probably see new paradigms of operation and design.

Estimating the value of wind energy in future energy systems is replacing older efforts for estimating a system integration cost—a notion that never reached full approval for the methods used and has outlived its usefulness.

The experience of operating and planning systems with large amounts of variable generation is accumulating. Increasing shares of wind also bring about the more challenges events of /instant shares of VRE, as depicted in Fig 1.

This article summarises main findings of a report that brings together experience and study results from 17 countries working in the international collaboration within the International Energy Agency (IEA) Wind Technology Collaboration Programme (TCP) Task 25 [1]. The paper starts by outlining the variability and uncertainty in Section II, and presents the Planning, Balancing, Stability and Market challenges in sections III to VI.

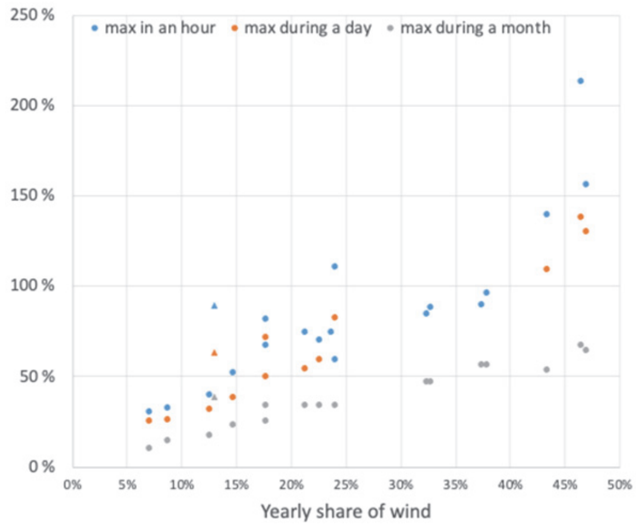


Fig. 1. Wind energy share in 1 hour, 1 day, and 1 month relative to the average share during a year. Recorded values from years 2017, 2019, and 2020 from Denmark, France, Germany, Portugal, Ireland, Texas, and Italy (combined wind and solar data from 2017, marked with triangles).

II. VARIABILITY AND UNCERTAINTY OF POWER SYSTEM-WIDE WIND ENERGY

Data for wind and solar energy is important both to incorporate wind and solar generation and forecasts within system operation and to use in simulations.

More data on large-scale measured wind power production are available, and they show strong smoothing impacts. In Europe, the aggregated wind generation drops to less than 5% of installed capacity only for 1 hour per year, and longer durations of less than 10% of installed capacity are rare (the max in a year is between 30 and 40 consecutive hours). Ramps during storms of 25% of capacity in a hour can hit a single country, but for larger countries even extreme ramping is closer to 10% of installed capacity. The storm events also bring about the largest forecast errors [2].

Simulated time series have previously experienced challenges to capture the smoothing impact, but the latest meteorological data sets, such as ERA5 in Europe, have shown good performance in representing future wind power fleets [3].

There is good complementarity between wind and solar energy, reducing the combined variability.

Short-term forecasts show a pronounced aggregation benefit (Fig 2), and they are still improving. Ways to simulate the forecast errors for power system studies are evolving.

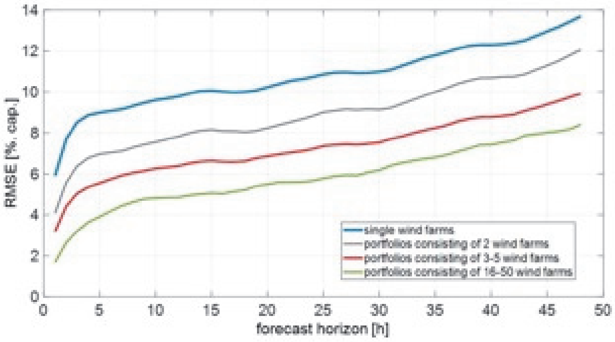


Fig. 2. Aggregation benefits of forecasting from Germany (Source: Fraunhofer IEE).

III. THE PLANNING CHALLENGE

Power system planning aims to determine the least-cost expansion of generation, storage, and transmission resources that meet load within a pre-determined resource adequacy target. The planning process must increasingly consider a wider range of factors, including common-mode outages, fuel supply interruptions, and the role of flexible, price-responsive demand. The planning challenge here focused on trends in transmission planning and resource adequacy. Transmission planning is trending towards regional assessments, covering many balancing areas or countries and including offshore grids. Resource adequacy methods and tools are increasingly incorporating additional data, chronology across all hours of the year, multiple years of timeseries data, correlated outages, and greater levels of operational detail. This is an evolution from traditional approaches that typically focused only on peak load hours with an independent outage assumption.

A. *Transmission planning*

With growing shares of wind generation, transmission is projected to see greater utilization and require additional enhancements. In addition to the large growth of wind and solar generation, demand growth due to electrification and retirements of thermal generation are driving future grid buildout projections. Larger amounts of transmission capacity is a consistent theme in these future scenarios.

Transmission helps reduce the impacts of the variability of wind, increases the reliability of the electric grid, and supports more efficient use of the available generation resources. Although costs for wide-spread expansions of the grid are significant, they make up a relatively small component of the total annualized costs in the scenarios and provide a good benefit-to-cost ratio. Larger amounts of wind and solar give even larger benefits for transmission assets. Investing in interconnectors for regional and continental transmission shows increasing value.

In the United States, a review of a decade's worth of transmission expansion studies by the Energy Systems Integration Group (ESIG) revealed the essential role of transmission expansion in supporting decarbonisation goals at lowest cost. The benefits of transmission over the costs of infrastructure build-out increase at higher wind and solar shares. The report recommends a coordinated, nationwide planning process, introducing designated renewable energy zones that receive priority development, and a macro-grid design plan to unite the country's power systems (Fig 3) [4].

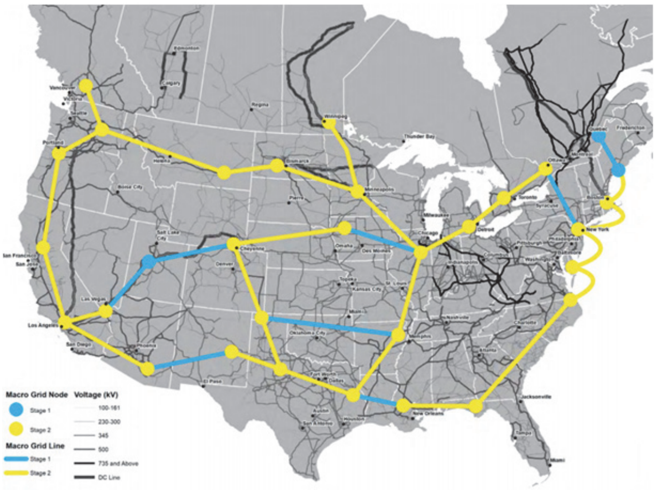


Fig. 3. New interstate transmission lines reduce cost of decarbonization [4].

In the North American Renewable Integration Study (NARIS) report by the National Renewable Energy Laboratory (NREL), an analysis of pathways to modernize the North American power system showed that regional and international cooperation in transmission planning can provide significant net system benefits through 2050. Increasing electricity trade between the U.S., Canada, and Mexico can provide from $10 billion to $30 billion net value to the system, and interregional transmission expansion achieves up to $180 billion in net benefits. Although these values are only less than 4% of the total system costs (which include all capital and operating generation and transmission system costs), transmission plays an important role in minimizing costs, and it is one of the main flexibility providers for the future system operation [5] (Fig 4).

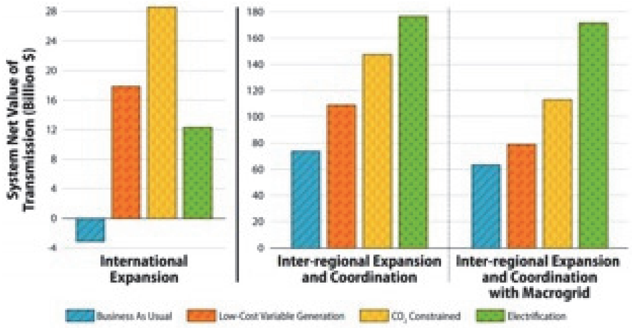


Fig. 4. Continent-wide net value of transmission expansion for the four scenarios in the NARIS study [5]).

Transmission planning in Europe has evolved toward regional, European-wide efforts by ENTSO-E. The ten year network development plan (TYNDP) is published every second year. Transmission system operators conduct a process to identify system needs, which are then translated into infrastructure corridors between the European countries. The identified corridors have the highest value. For the most robust expansion plans, the lines would have benefits exceeding their costs in several future scenarios of demand and generation [6].

Decarbonising other energy sectors and sector coupling are expected to further increase the importance of offshore wind in the green transition. Offshore grids and energy islands are seen as future parts of the interconnected transmission system. A modular and stepwise offshore grid development is assumed by the European transmission system operators, with choices being made on a case-by-case basis between the following options: point-to-point interconnections, radial offshore wind connections (single or via hubs), hybrid projects (combination of offshore wind connections and interconnections), and multiterminal offshore platforms combining interconnections. Several joint initiatives have been formed to foster the analysis and development of offshore grids in Europe, especially in the North Sea. One of them, the North Sea Wind Power Hub (NSWPH), focuses on the concept of energy islands, providing potential cost-savings related to offshore platforms.

B. *Ensuring long term reliability and security of supply*

The second aspect of the planning challenge is resource adequacy, which aims to ensure sufficient resources are procured to meet the bulk system load within a certain tolerance level. A key trend is the need to improve methods and metrics.

One aspect of resource adequacy as applied to wind is the capacity value (or capacity credit). Ideally, the capacity value is calculated through probabilistic approaches, such as those use in probabilistic resource adequacy tools. It is also often used as an input into planning studies and, where relevant, to determine the eligible portion of capacity than can participate in capacity markets. The capacity value of wind tends to be higher for larger areas of well-dispersed wind resources. Larger areas also help to reduce how much the capacity value decreases with increased wind energy.

In most countries, wind energy has not, as of yet, been considered when assessing long-term (strategic) reserve or capacity payments [7]. Adequacy analyses should adapt to reflect wind power capacity value in both the focus and neighbouring areas, considering feasible import possibilities.

Concerns for resource adequacy in future systems where wind and solar energy become dominant are emerging. Considering power system-wide resource adequacy with multi-area methods is important and represents recent practice in Europe [8]. Analyses need data from more weather years to capture the extreme weather events that might occur more often in the future; this includes timeseries data for wind, load, and solar as well as correlated outage and fuel availability data for thermal generators.

For future wind- and solar power-dominated systems, new metrics and tools are needed to capture the storage and demand-side flexibility in adequacy analyses. This includes methods that capture chronology across all hours of the year and metrics that capture the magnitude, duration, frequency, and timing of potential loss of load events. This will make sure that ensuring reliability in traditional ways, through increasing peaking capacity, will not become unnecessarily costly. A set of new resource adequacy planning principles have been developed by the ESIG project Redefining Resource Adequacy [9]:

- Load participation fundamentally changes the resource adequacy construct.
- Modelling chronological operations is essential for modern power systems.
- Quantifying the size, frequency, and duration of outages is critical to finding the right resource solutions.
- There is no such thing as perfect capacity.
- Reliability criterion should not be arbitrary but transparent and economic.
- Neighboring grids and transmission are a key part of the resource adequacy challenge.

IV. THE BALANCING CHALLENGE

Ensuring short-term system reliability, with operating reserves is a basic grid integration study outcome. Renewable curtailment is often seen as revealing a lack of system flexibility and is also an important metric from system impact studies, but it also is increasingly seen as a tool to help provide system flexibility. Maximising the value of wind, and solar, energy in future systems will also ensure most cost-effective system operation.

Wind integration studies have shown that for 30%–40% shares of wind in electricity demand, the possibility to balance wind and solar across a larger area reduced the balancing challenges, while transmission capacity reduced the curtailment challenges, and additional storage for system-level demand-generation balancing was not necessary.

A. *Ensuring short-term system reliability*

The impacts of wind and solar energy on short-term reliability focus on the short-term balancing of supply and demand, as well as setting an appropriate volume of operational reserves for frequency control. With larger shares of solar and wind power, the non-synchronous nature of inverter-based resources also needs to be considered, in addition to the impacts of variability and uncertainty (see Stability challenge section V).

The impacts of wind and solar generation on operating reserves has been a traditional integration study output, showing an increasing trend of reserve requirements as the share of wind power increases [10]. Estimating the increase in operating reserve due to increased variability and uncertainty has evolved toward dynamic reserve setting.

Experience from Germany, Texas, and the U.S. Western Interconnection show another outcome: changing operational practices provide greater savings in reserve utilisation than wind and solar variability creates. Sharing balancing, moving to faster dynamic reserve setting, and using wind power plants (WPPs) for fast response have proved to be powerful tools for enhanced system operation. So, for example, in Texas, despite an increase in wind capacity from 9.4 to 15.8 GW during the period 2011-2015, the regulation reserve requirements declined, Fig 5. By mid-2017, the up-regulation requirements had declined further to 350-400 MW, with the wind capacity now at 19 GW. The underlying reason was due to ERCOT introducing the requirement that all generators, including wind and solar, provide primary frequency response (governor or governor-like response). Hence, wind power plants should always provide an over-frequency response, but they should only provide an underfrequency response if they have previously been curtailed, due to congestion or oversupply reasons.

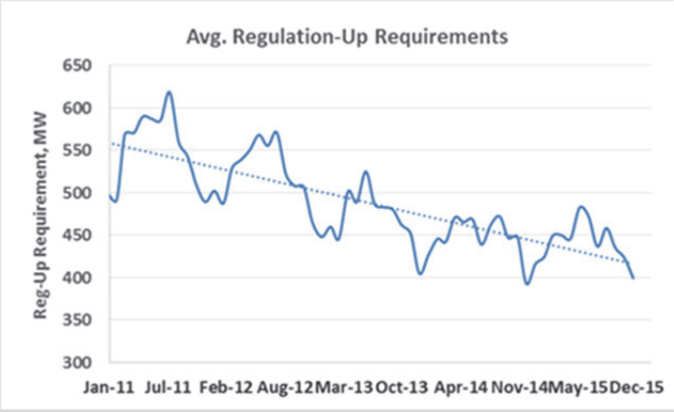


Fig. 5. Average up-regulation requirements during 2011–2015 for ERCOT, Texas (Source: ERCOT).

In France, the system operator, RTE, has implemented an anticipation strategy to assess required reserves and available margins, which is well suited to cope with increasing shares of VRE sources. A new tool MAUI automatically computes the required reserve and the available margin on a rolling horizon, and the available margin assessment considers the minimum advance notice resulting from the dynamic constraints of each generation unit (Fig 6).

More broadly across Europe, a dynamic probabilistic method has been used to estimate the automatic frequency restoration reserve (aFRR) requirement according to shares of renewables. The applied methodology aims to evaluate the power margin needs for a given time horizon (e.g. 15 minutes for aFRR), while considering a predefined risk level, at the scale of a country and for each hour of the year considered. The OPIUM tool includes modelling of the uncertainty sources, (1) forecast-based error (demand, PV, and wind generation) and (2) outage-based uncertainty. For a high share of variable generation (>50%), an estimation of aFRR requirements in Europe is given in Fig 7, revealing that: (1) the risk level chosen by the TSO plays a major role in the aFRR requirement, and (2) large development of renewables leads to a significant increase in aFRR sizing [11].

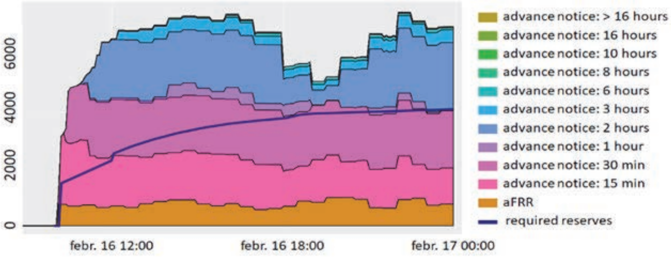


Fig. 6. Automated assessment on a rolling horizon of required and available margins (**Source:** RTE).

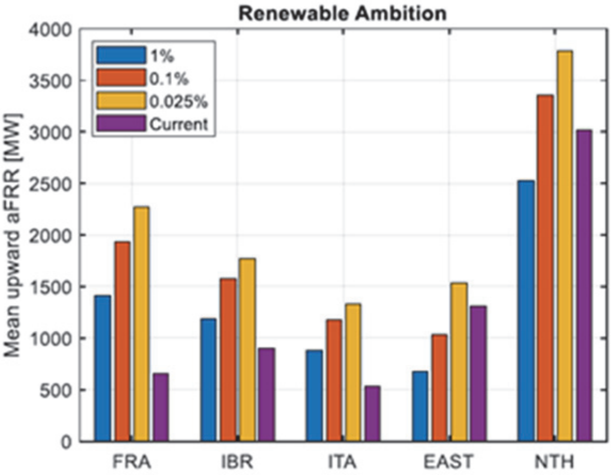


Fig. 7. Evolution of mean upward margins in Europe considering several risk levels. FRA = France; IBR = Iberia (Portugal and Spain); ITA = Italy; EAST = Poland, Czech Republic, Hungary, and Slovakia; NTH = Germany, Belgium, Luxemburg, Netherlands, Denmark, Switzerland, and Austria. The Renewable Ambition scenario has a 66% share of wind and solar in Europe **[11]**.

As part of assessing the flexibility of future systems, a number of tools considering planning and operational timescales have been developed. For example, in the United States, the InFLEXion tool assists planners in determining system flexibility needs [12], based on the ramping of the net load. Metrics calculated include "periods of flexibility deficit" (number of periods when ramping is less than required based on statistical analysis) and "expected unserved ramp" (total amount of ramping (MW) that could not be met). Similarly, in Portugal, the system operator REN, as part of long-term adequacy assessment, uses the PS-MORA model, which is based on sequential Monte Carlo simulation and includes energy and reserve scheduling with limited net transfer capacities. In addition to assessing the adequacy of the generation fleet, whether the technologies available can offer sufficient flexibility to cope with unplanned outages, or short-term fluctuations in renewable power production and demand is addressed. Such an approach is particularly important for systems with a large share of hydropower with storage capabilities, such as Portugal, and up to 40 years of historical hydrological series encompassing a variety of hydrologic conditions are embedded, along with other renewable production, such as wind and solar power. Finally, the International Renewable Energy Agency (IRENA) FlexTool analyses the flexibility of a given power system using an optimisation model to show when there would be insufficient capability to meet the demand [13]. An investment mode enables cost-effective mitigation options to be investigated, recognising transmission limits, other energy sectors, as well as flexibility from demand response and energy storage.

B. Curtailment

Although some renewables curtailment can be efficient for system operation, extensive curtailment of variable power is an indication that the underlying flexibility of the power system is inadequate. The previously high levels of curtailment in China have been mitigated, mainly due to new grid build-out. In Europe, curtailment volumes are gradually increasing with increasing wind and solar shares (Fig 8). Reinforcing the network is seen as a major solution strategy, given that grid bottlenecks are largely the main cause.

However, in some systems, such as Ireland, Texas and Italy, system constraints, due to stability issues, can play a significant role. Surplus generation, leading to curtailment, can often be mitigated by trade with neighbouring areas (such as Denmark to Norway and Sweden), but also some surplus situations in neighbouring areas can aggravate the curtailment seen (such as in Denmark and Germany).

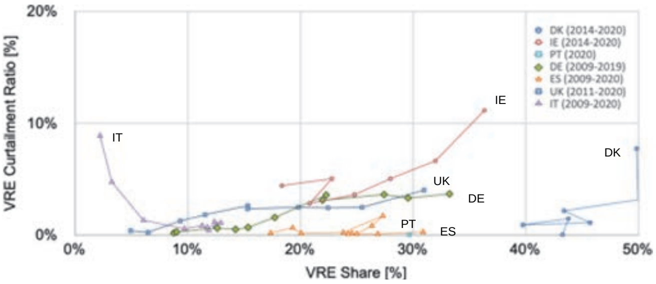


Fig. 8. Wind energy curtailment in Europe—curtailment map [14].

Expected future wind curtailment levels are often calculated from wind integration study simulations for power system dispatch, highlighting some of the challenges of wind integration. For increasing wind and solar shares, curtailment volumes are projected to increase, unless new flexibility measures are introduced, new operational practices adopted, or transmission infrastructure reinforced. The NARIS study estimated that for the low-cost VRE scenario in 2050, 9.3% of the potential wind and solar generation in the United States was curtailed. The bulk of the curtailment occurred in a small percentage of hours, but curtailment occurred somewhere in the United States almost every hour, even if mainly during daytime, in sympathy with solar production patterns [4]. However, a growing number of studies are also highlighting the “new normal” that economic curtailment can play in helping to maintain a demand-supply balance and system frequency [14].

C. Maximising value of wind energy

A more flexible power system can utilise variable energy sources at higher value, and hence a major way forward in maximising the value of wind power lies outside wind power itself. However, wind power can also increase its value by providing system services. Particularly during surplus generation situations, this helps all WPPs to avoid sourcing system services from conventional power generation, and forcing more curtailment of wind power.

The benefits of flexibility from transmission, hydro and thermal power plants, storage, and the demand side have been shown across a range of studies, including, for example, exploiting hydro reservoirs in the Nordic region as “green batteries” [16], utilisation of flexible power-to-heat in district heating networks to reduce renewables curtailment [17], and taking advantage of the ability of electrolysers to vary their power consumption in a few seconds to play a role within balancing and system services markets [18].

The adoption of new operational practices to fully utilise the existing grid are also key: using near-real-time information to determine security margins, as well as active power management (phase-shifting transformers, dynamic line rating, power flow controllers), and reactive power management (reactors/capacitors, synchronous compensators, STATCOMs). Congestion management is evolving, and new ways to capture flexibility from distribution system connected resources are developing. Again, there are many relevant examples, including, introducing a suite of both faster acting and longer duration (ramping) system services in Ireland (EirGrid), a multi-span overhead line model incorporating direct conductor measurements for dynamic line rating (TERNA), and a flexibility hub platform to coordinate the provision of active and reactive power connected on distribution grids [19].

D. Towards 100% renewables and carbon neutrality

Some techno-economic studies have examined how hourly energy balances could be maintained in a 100% renewables power system and a net-zero energy system decarbonising energy sectors beyond electricity (not necessarily considering stability, system adequacy and other challenges).

In Sweden, the system operator SvK studied a future scenario with an increased electrification demand from 140 TWh/year to 179 TWh/year, and where existing nuclear power was assumed to be replaced by renewables. In the “2040-high” case, there is an assumption of 106 TWh of wind energy and 7 TWh of solar energy, with the remainder provided by hydro and biofuels. Significantly more transmission, both within Sweden and to neighbouring countries, was assumed (+16 GW) as well as flexible loads. No specific new power plants were assumed to cover demand peaks, but an adequacy calculation including Monte Carlo simulations of 31 weather years resulted in a need for more capacity during 0.7 hour/year as a mean value [20].

Towards carbon neutral energy systems, energy sector coupling with future power to X options electrifying heat, transport, and industrial processes all offer potential solutions for the short- and long-term flexibility needs of VRE-dominated power system operation. Decarbonisation of the energy system implies modifying all energy sectors. For the power sector, the reduction of direct CO2 emissions by adding only VRE tapers off when the power system is already low carbon; however, decarbonising other energy sectors enables CO2 emissions to be reduced from the heat, transport, and industry sectors.

In Great Britain, the system-level value of deploying flexibility across the heat, transport, industry, and power sectors across different decarbonisation scenarios shows that coordinated operation and planning of hydrogen, gas, transport, heat, and electrify infrastructures will become increasingly important to deliver a secure energy system while meeting the carbon targets at minimum cost. The value of flexibility to the energy system as a whole is many times its value to the electricity sector alone, since it allows for interactions at all levels in an integrated system, between the energy vectors, and on different timescales, from seconds to seasons, that are required to maintain a secure system [21][22].

In the United States, the Net-Zero America report outlined five distinct technological pathways for the United States to decarbonise its entire economy, concluding that through massive, nationwide effort, net-zero emissions of greenhouse gases could be achieved by 2050 using existing technology and at costs aligned with historical energy spending. The study's five scenarios described—in a highly detailed, state-by-state level—the scale and pace of technology and capital mobilisation required, and highlighted the implications for land use, incumbent energy industries, employment, and health [23]. The potential of a power-to-ammonia pathway was studied in [24], noting that ammonia is already used in large quantities in the fertiliser industry, and could be used as an energy vector as well. It is shown that power-to-ammonia can already be competitive with ammonia produced from fossil fuels, under the right circumstances, and that ammonia can be a great source of temporal and spatial flexibility to the power system

V. THE STABILITY CHALLENGE

For higher shares of wind and solar, assessing system dynamics will be important to ensure stability. Wind and solar power plants can help by giving grid support, and their characteristics, like responses to events, need to be known to assess stability. Reaching higher shares of wind and solar will mean close to 100% inverter-based resource (IBR) operation.

A. *Ensuring system stability*

The first experience of stability issues related to wind and solar was highlighting the importance of control and protection settings in wind and solar power plants for responses in fault events.

The system stability analyses largely began with frequency stability, where new tools have been developed for inertia monitoring. Ways to mitigate low inertia are already used in small- and medium-size systems such as Ireland, Texas, Great Britain, and the Nordic power systems, as well as peripherical parts of some synchronous systems such as Italy. Mitigation methods have focussed on ensuring a sufficient number of on-line synchronous power plants, faster responding frequency control, and deployment of synchronous condensers (Fig 9) [25].

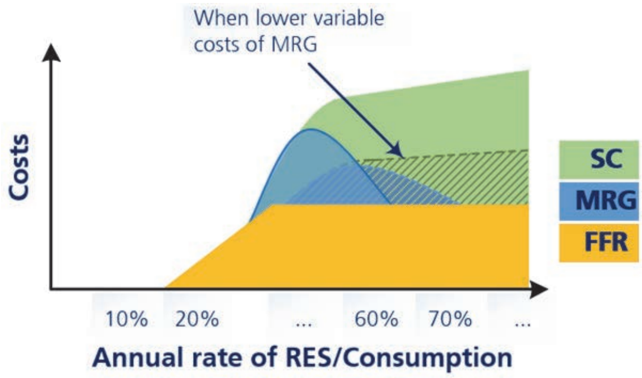
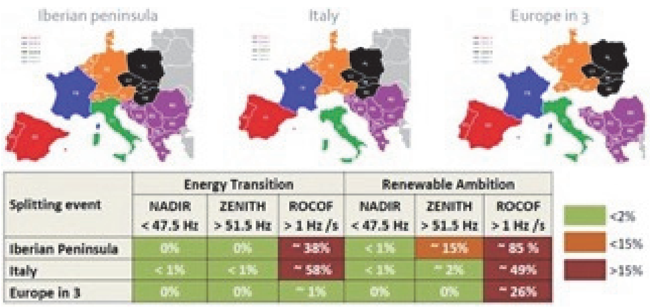


Fig. 9. Mitigating low-inertia situations due to increasing shares of wind and solar. SC: synchronous condenser; MRG: must-run (synchronous) generation; FFR: fast frequency response [25].

In the U.S. MISO area, frequency response was found to stay stable up to 60% instantaneous shares of variable renewables but might require additional planned headroom beyond [26].

A frequency stability study of each region of the Continental Europe system looked at the interconnected incidents in each zone and system splits (Fig 10) [11].



Splitting event	Energy Transition			Renewable Ambition		
	NADIR < 47.5 Hz	ZENITH > 51.5 Hz	ROCOF > 1 Hz /s	NADIR < 47.5 Hz	ZENITH > 51.5 Hz	ROCOF > 1 Hz /s
Iberian Peninsula	0%	0%	~ 38%	< 1%	~ 15%	~ 85 %
Italy	< 1%	< 1%	~ 58%	< 1%	~ 2%	~ 49%
Europe in 3	0%	0%	~ 1%	0%	0%	~ 26%

Fig. 10. System splits assessed in the frequency stability study of the EU-SysFlex project [11].

Also, other dynamic stability issues due to a weak grid are becoming relevant when studying high shares of wind and solar. Reduced short-circuit current levels, and reduced voltage support, due to displacement of synchronous generators, increase the area affected by voltage depression as a consequence of a grid fault. New control techniques (such as deploying grid-forming inverter technology) can reduce the need for additional synchronous condensers and transmission lines.

For the island system of Ireland, it was estimated that voltage and transient stability issues can be mitigated for the anticipated near 40% wind shares, and small-signal stability was not seen as an issue [27]). With new targets for renewables (70% of demand) and wind power dominating the mix, transient stability issues with a reduction in synchronizing torque are also foreseen [11].

For the MISO system in the U.S, the potential for dynamic stability issues due to a weak grid increases sharply beyond shares of 20% renewables. Small-signal stability might become a severe issue beyond the 30% renewable share and can be addressed by specially tuned batteries or must-run units equipped with power system stabilizers. Interconnection-wide small-signal oscillations ranging from 0.1 Hz–0.8 Hz can appear with high shares of renewables. Through detailed analysis, strategic locations can be identified where installing appropriately tuned and designed supplemental power oscillation damping (POD) controllers on renewable resources, batteries, static VAR compensators, STATCOM, or HVDC can help to improve small-signal stability. Overall, critical clearing time improves as large units are displaced, but some locations might observe a decrease and require the installation of new protection techniques or transmission devices [26]. The analysis also indicates that to reduce the cost of grid integration at high penetration levels, it is beneficial to improve the characteristics of IBRs. Better control techniques (such as deploying grid-forming inverter technology) can have the effect of reducing the need for synchronous condensers and transmission lines—both AC and DC.

B. *Wind providing grid support*

Power systems need essential reliability services to operate reliably. During hours of high wind and PV share, and with fewer synchronous generators online, it is important that wind and solar power plants provide grid support services, otherwise they risk being curtailed to commit a synchronous generator to provide services.

Wind power can provide system services—services for balancing and frequency control are already state of the art in some power systems, with voltage control also emerging. In

Spain, the participation of wind power in balancing services started in 2016, and by the by end of March 2021, 17.3 GW of the total of 27 GW of wind power capacity installed in Spain had successfully passed the operational capability tests for imbalance management and tertiary reserves services. Wind power has had an increasing contribution, especially in tertiary reserves, with an hourly participation that reached - 1911 MWh and 350.3 MWh for downward and upward, respectively, in 2018. For downward reserves, wind energy accounted for 14.4% of the total reserves in 2018 and 14.8% in 2019. In terms of upward reserves, wind energy contribution is less than downward reserves, with 4.8% in 2018 and 7.5% in 2019. In Colorado in the United States, Xcel requires all WPPs to provide AGC (Automatic Governor Control) [28]. When WPPs are curtailed due to a surplus energy event they can start providing AGC control (both up- and down-regulation to manage frequency).

New capabilities can be offered for stability support. Among them *grid forming* capabilities stand out as an upcoming service to be required from wind power plants. New capabilities are a subject of research, and how the future system defines the needs for grid-forming capabilities, for example, is yet to be experimented. Basic capabilities from grid-forming inverters in wind turbines have been demonstrated in field trials in UK [29][30][31].

C. Towards 100% inverter based resources

Power system stability has so far been overlooked as part of 100% (energy-balancing) studies, where the main focus is on hourly consumption-generation matching. No study comprehensively addresses both the long-term and short-term challenges so far.

The first studies on stability of 100% IBR-connected systems have been made, showing promising results. IBRs can be highly flexible and controllable, with independent control over real and reactive current, and with an ability to shape the equipment’s response to various grid conditions. Consequently, there could be opportunities to make IBRs behave in a more supportive manner than synchronous machines in some respects. However, the changes are so profound that a fundamental rethinking of power systems is required, including the definition of needed system services.

Study on the effectiveness of emerging control methods, working under grid-following or grid-forming principles, was conducted for the Great Britain test system and for several benchmark systems. The results showed that modified and tuned grid-following control can allow a system to reach an approximate 65% share of inverter-based generation in the studied test systems while maintaining frequency, rotor angle, and voltage stability. Further, it was found that combining grid-following and grid-forming controls allows the system to further push the stability limit—to a theoretical 100% [32].

The Ireland power system test case of the EU MIGRATE assumed that existing fossil-fired generation is replaced by (large) converters of equivalent capacity, such that traditional power system security issues remained largely resolved, even with a 100% inverter-based system [33]. To identify a lower bound on the grid-forming requirements (relative to grid-following converters) for such a system, various disturbances were applied at all network nodes for a range of converter configurations, and the ability of the system to satisfactorily survive such disturbances was observed (Fig 11). It was seen that a minimum grid-forming share of 35%–40% was required, based on the total online converter capacity (MVA). The stability boundary was shown to be ultimately dependent on the phase-locked loop performance of the grid-following converters

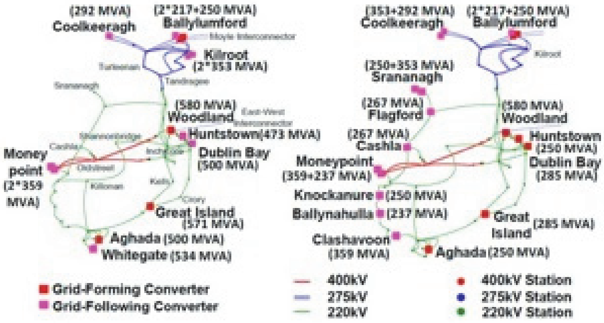


Fig. 11. Ireland power system simulations for MIGRATE project: an "urban" distribution for the grid-forming and grid-following converters on the left and a "remote" distribution on the right [33]..

VI. THE MARKET CHALLENGE

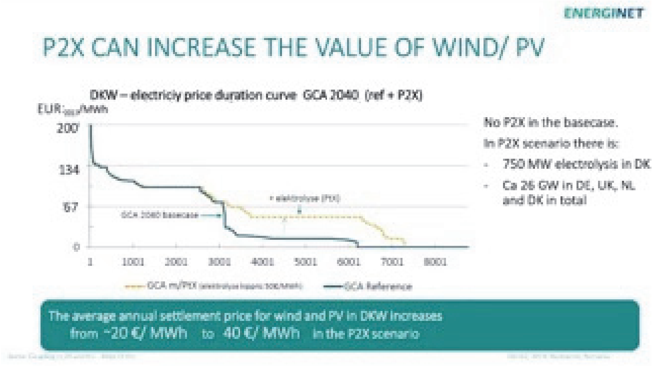
To ensure that all resource types, including renewables, are receiving efficient economic incentives, , it is likely necessary to modify wholesale electricity markets to efficiently signal for the necessary and evolving set of grid services. This requires technology-agnostic support mechanisms that do not bias against variable renewables, which are increasingly contributing the electricity supply in many systems around the world. Market design options to enable both planning (investments) and operations, with cost recovery for the resources needed to ensure grid reliability, are studied.

The market designs should give efficient price-signals for investment and operations of the resources needed to support reliability, include variable renewables and flexibility sources needed for balancing the net loads. Recent research has shown that energy-only markets can give sufficient price-signals in theory [34], but it is not given that this will hold true in real systems. Presently, several markets with energy pricing are supplemented with different forms of capacity mechanisms to incentivize sufficient investment of flexible generation capacity in the system. Market design to allow higher scarcity prices will help cost recovery as well as help incentivize demand response and other flexibilities to cope with both surplus and scarcity situations and wind power cost recovery.

Flexible operational practices can be a powerful enabler of wind and solar in power systems. One way to change operational practices is through wholesale electricity markets. Market design to enable and incentivize flexibility from a range of sources and operation close to delivery will enhance the growth of wind and solar capacity.

Enabling system services from wind and solar power plants provides not only a system-level benefit but adds a potential new revenue stream for wind and solar power in market environments. Wind and solar power plants have already proved their capabilities for providing frequency and voltage support services. Wider use of these services as well as their remuneration, instead of mandating them in grid codes is still evolving. Market design plays a role to enable bidding services in smaller quantities and near real time to avoid or reduce the impact of forecast errors.

For the main income for WPPs for their energy generated in the future, the surplus energy situations where prices plummet are critical for the cost recovery. This could be mitigated by new demand, also through exports and storage, that retains the value of wind during surplus hours (Fig 12).



P2X CAN INCREASE THE VALUE OF WIND/ PV

No P2X in the basecase.

In P2X scenario there is:

- 750 MW electrolysis in DK
- Ca 26 GW in DE, UK, NL and DK in total

The average annual settlement price for wind and PV in DKW increases from ~20 €/ MWh to 40 €/ MWh in the P2X scenario

Fig. 12. Example from the price area of Denmark West (DKW) on how future Power to X electrolyzers can improve the low prices during surplus hours (Source: Energinet).

Example from Denmark shows how much has been saved through transmission and trade with neighbouring areas (Fig 13).

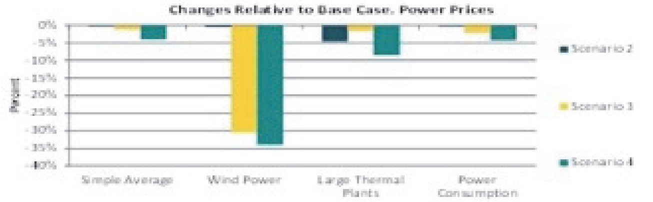


Fig. 13. Changes in market prices in the case of the non-flexible system in Denmark.

VII. CONCLUSIONS

This article draws from the IEA Wind TCP Task 25 report, which compiles state-of-the-art experiences and study results of key challenges and solutions for planning and operating power systems around the world with growing shares of variable renewable energy. These are summarized into four main questions and associated challenges:

- How to plan for the long-term adequacy of transmission grids and generation capacity (the planning challenge)?
- How to manage the operation of power systems (the balancing and stability challenges), including issues like minimizing uneconomic curtailment and providing system support from wind power plants?
- How to eliminate barriers to market participation, and in turn, appropriately value wind energy in future power systems with wholesale electricity markets, as well as how to improve operational practices and flexibility through market structures (the market challenge)?

The planning challenge includes both transmission expansion (or grid adequacy) and resource adequacy. Transmission planning is moving toward coordinated regional planning efforts and the development of enhanced offshore grids. Regional transmission planning efforts have been successful in Europe, and special HVDC overlays augmented by HVAC links for the U.S. grid have shown a desirable benefit-to-cost ratio, which is increasingly favorable at higher wind and solar shares. For offshore wind, larger installations, offshore grid development, and hybrid approachess such as energy islands are growing trends in many countries. For resource adequacy, data and methods are evolving to account for greater operational representation, and there is a growing consensus that the resulting metrics should capture the size, duration, frequency, and timing of potential loss of load events.

For the balancing and stability challenges, short-term balancing is moving from estimating operating reserve requirements to assessing stability. Experience shows that changing operational practices could offset increases in operating reserves due to increasing wind and solar capacity. Maximizing the value of wind power and minimizing uneconomic curtailment—while recognizing the balancing support that curtailment can provide —involves improved operational practices, flexibility, and offering grid support services.

For the market challenge, a key issue is establishing efficient prices that signal for the resources and attributes needed to support reliability, including capacity, energy, flexibility, and potentially other services. Enabling open participation in markets and efficient operational structures have also shown promise of improving overall operations and reliability.

The experience of operating and planning systems with large amounts of variable generation is accumulating. Experience and studies are pushing the limits toward 100% renewable systems, highlighting challenges and evolving methodologies needed for the assessments. Research to tackle the challenges of inverter-based, nonsynchronous generation is growing. Energy transition and digitalization also bring new flexibility opportunities, both short and long term.

Wind and solar energy are expected to make a large contribution to the decarbonization of future power systems and help support ambitious increases in electrification demand—150%–300% of current electricity demand. They also have the potential to form the backbone of future power systems when the full range of inverter capabilities are used. This is still a work in progress, where new paradigms of asynchronous power system operation and long-term resource adequacy are developed, with a suite of new tools and methods being implemented for system operators.

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