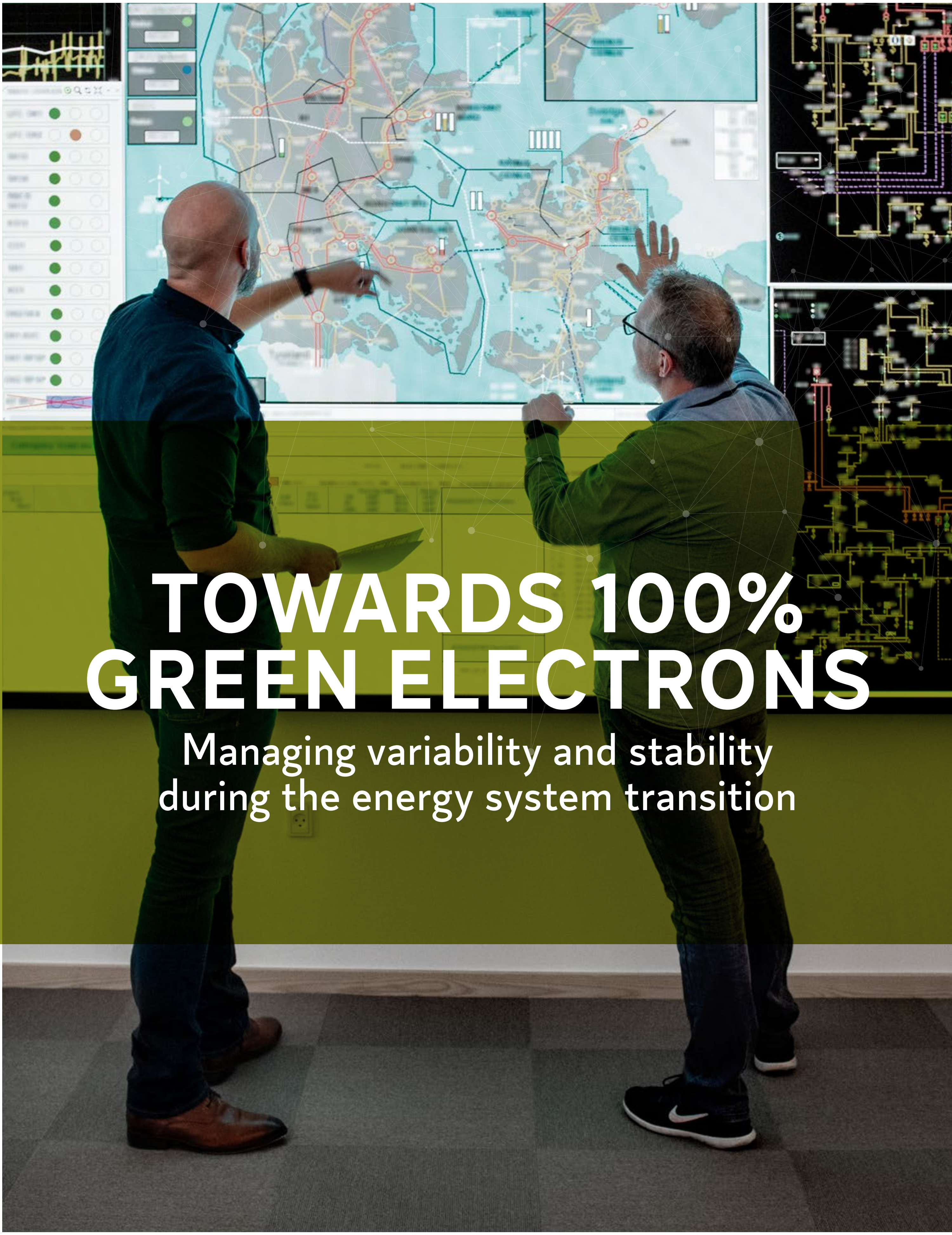

TOWARDS 100% GREEN ELECTRONS

Managing variability and stability during the energy system transition

MEGAVIND

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CONTENT

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Managing variability and stability during the energy system transition

June 2022
Publisher: Megavind

Authors:
Jens Gegenbach (Ørsted)
Mattias Andersson (DTU)
Frank Martin (Siemens-Gamesa)
Björn Andresen (AU)
Ole Sønderby (Vestas)
Poul Ejnar Sørensen (DTU)
Martin Hartvig (Energinet)

Photo cover:
Maria Tuxen Hedegaard

Photos from:
Energinet, Siemens Gamesa Renewable Energy, Ørsted and Istockphotos

Graphic design:
Lisbeth Neigaard / vinkdesign.dk

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Denmark and many other countries are currently in the process of transforming our energy systems into a system dominated by wind and solar coupled with additional variable demand from P2X, heat pumps, electrical vehicles and other electricity consumers. This transformation presents numerous challenges to the future operation of the electrical grid, requiring the deployment of new tools, methods and technologies.

Explaining any new technology in detail can be difficult, but the complexity and intangible nature of the electrons transmitted through the electrical grid makes understanding the fundamentals of this challenge especially hard to fathom for non-experts. This Megavind report sets out to achieve two things.

First, to break down the system complexity into two categories: *variability* and *stability*. Hopefully, this will provide non-expert readers with a framework to navigate the complex nature of the topic.

Second, to outline the potential solution spaces for the development of the electrical grid towards becoming 100% renewables-based and provide specific recommendations for the realisation of that goal.

As an outcome of COP26 in Glasgow in 2021, countries around the globe have pledged to establish net-zero energy systems by 2050. Energy consumption in the transport, housing and industry sectors represent ~70% of global emissions. In 2020, renewable energy supplied ~11% of that energy. By 2050, that figure must reach 100%. Achieving this goal will require the development of an integrated energy system allowing for the optimal use and conversion of electricity, heat and sustainable gasses.

Since renewable energy is predominantly generated as electricity, direct electrification should be the first choice where feasible. According to the National Academy of Engineering electrification was the greatest engineering achievement of the 20th century. The energy transition to a 100% renewables-based integrated energy system is poised to claim that title for the 21st.

An electricity-centred energy system requires a well-functioning electrical grid. Electrical grids are the largest systems operating in the world. They have been designed, built and expanded over a period of more than 100 years and must now face total transformation within the next two decades. Our current electrical power systems have been developed around conventional power plants and although it requires significant expertise to operate these giant systems, the inherent system challenges are well understood and solutions tried and tested.

Future electrical power systems, powered entirely by wind, solar and other renewables, are a very different proposition and understanding the design and operation of such systems will be fundamental to the green transition.

The simplest way to describe the associated challenges is to divide them into issues related to system *variability* and system *stability.*

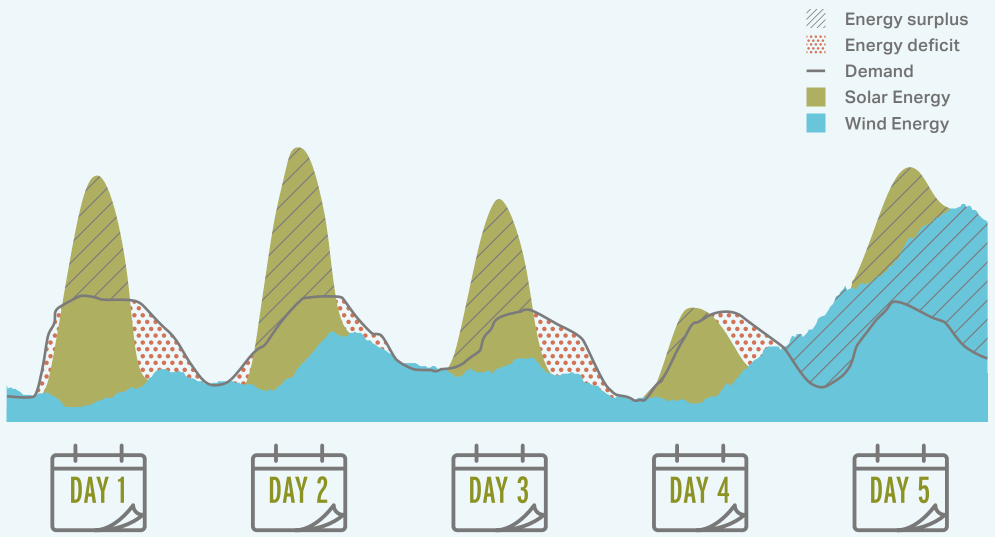
Variability

Variability centres on having the necessary amount of energy at any given time to balance supply and demand. Variability reflects changing patterns of e.g. weather conditions and demand. The challenge represented by variability becomes critical at higher shares of renewable generation in an energy system.

Any public debate about the shift towards renewable power generation will at some point lead to the question: what do we do when the sun isn't shining or the wind isn't blowing?

These questions raise the issue of variability and how we match supply and demand through renewable energy.

System operators need to consider variability at different time scales when planning how to balance supply and demand. There is variability at an hourly scale, such as the consequence of daytime – night-time periods in systems based on a high share of solar power. There is variability over days or weeks associated with changing weather patterns that result in fluctuating wind and solar resources. And there are seasonal variations of available resources from wind and solar combined with shifting demands for energy.



The sun doesn't always shine and the wind doesn't always blow.
The variable patterns of generation and consumption need to be matched.

Variability becomes critical for the energy system with high shares of renewable generation when there are no longer sufficient fossil power plants available as backup energy generators. Apart from the challenge of energy supply deficit periods, periods with substantial energy surplus from renewable generation need to be addressed to maintain the economic viability of the renewable generation assets. That is why significant efforts are invested in developing technology solutions to mitigate the variability challenge by moving from a singular control of production to a combined control of supply and demand. This technology development must be accompanied by changes to the market regulatory framework, long term policy planning for the deployment of renewables, storage technologies as well as fossil power plant decommissioning. Orchestrating a cost-efficient and secure energy system transformation process will necessarily involve all of these elements.

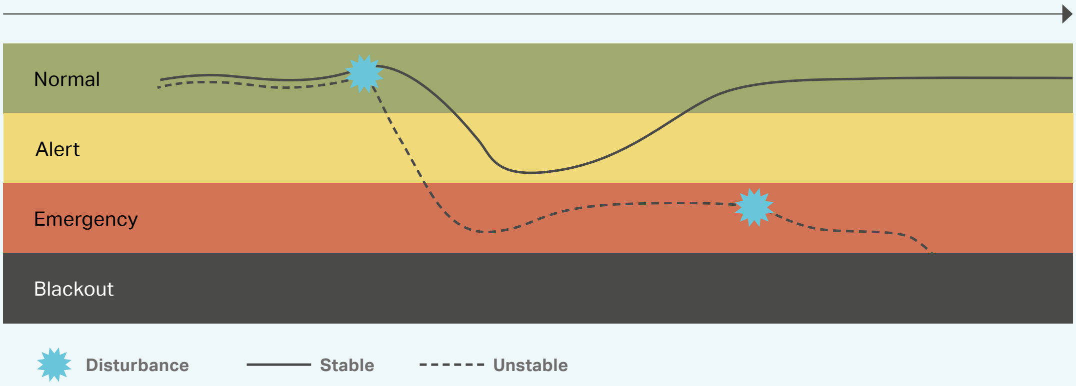
Although solutions to the variability challenge are an imperative, they are not alone enough. Both today and at all future stages of the transformation, the electrical grid also needs operational stability and balance to enable reliable delivery of power to end-users.

Stability

Stability concerns the quality levels and control of the electricity transmitted through the electrical grid. Voltage and frequency must remain within narrow limits to maintain grid stability. Specific events can quickly give rise to instability. Stability challenges increase steadily as more and more converter-based units are connected to the grid.

Grid stability receives less attention compared to variability when discussing the transition to a zero-emission energy system. One obvious reason is that it is simply more difficult to understand: As electricity consumers, we do not experience instability in the same way that we notice a lack of wind or sunshine; we only experience the consequences of instability (a periodic lack of electricity) and in well-operated grids with limited alert events this rarely occurs. Yet stability represents a critical challenge to the energy transition. The Danish and European electrical grid operates at a frequency of 50 Hz and must at all times function within very slim margins of that frequency to remain stable. An unstable grid system can easily transition from normal to emergency state and further to black outs, with serious ramifications. A system crash on a 10GW offshore energy island in the North Sea could blackout the entire European electrical grid, but also smaller local or regional blackouts due to complications in the distribution grid are problematic. Adequate system measures need to be in place to maintain normal operation and handle alerts correctly. The instruments and methods involved are different from those addressing variability, because unlike variability (measured in hours, weeks or months), stability is measured in milliseconds to minutes. Production and consumption must balance on this short time scale to maintain frequency and voltage stability.

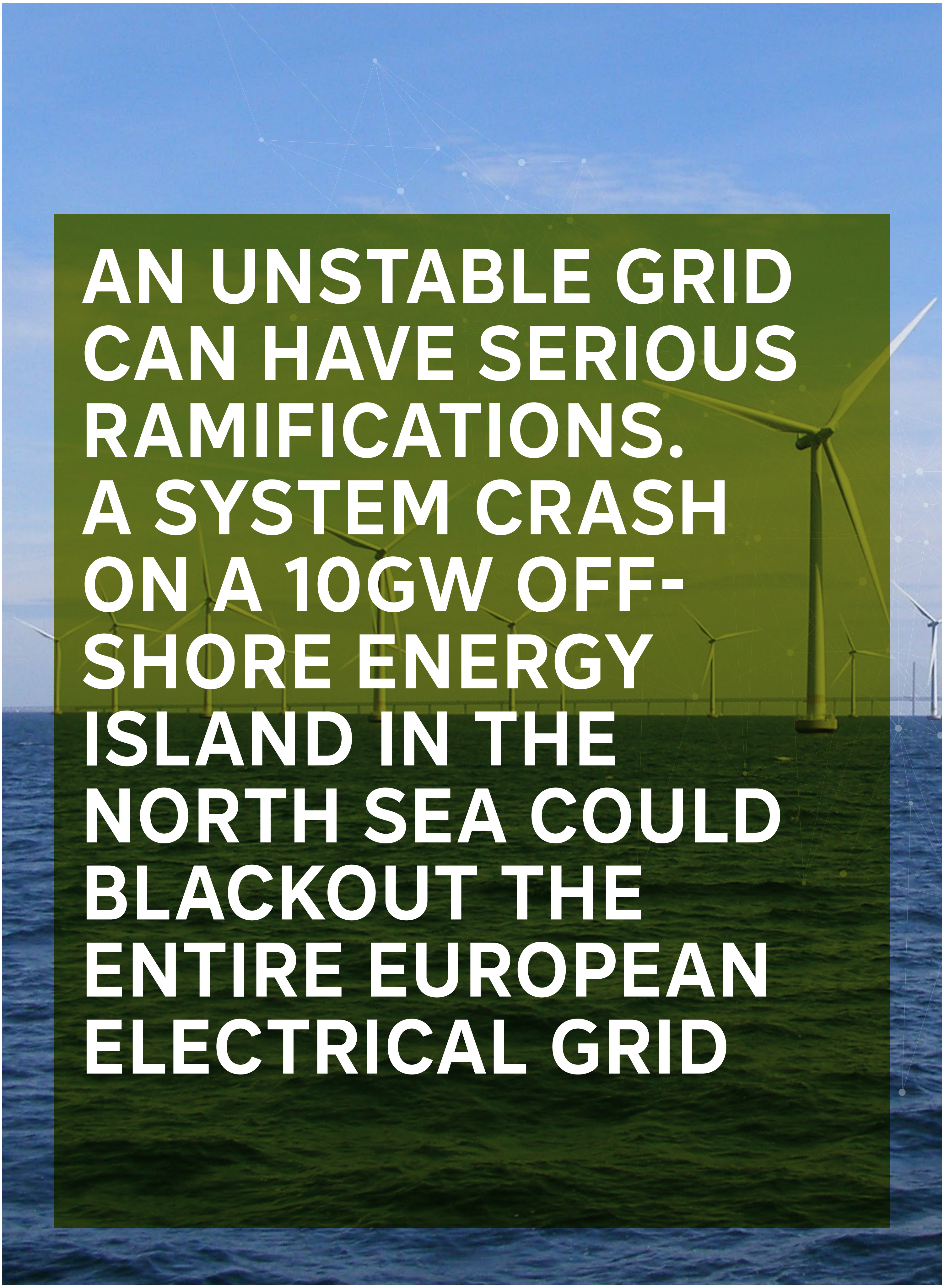
The time scale for power system stability is between milliseconds and several minutes, depending on the type (e.g. voltage and frequency) and duration (short-term or long-term) of stability.



Power system stability is ensured keeping the system in a normal state most of the time, allowing transition to an alert state if a disturbance happens, and take actions to return to normal state as fast as possible. If the disturbance brings the system further down to the emergency state then there is an increased risk that an additional disturbance will cause a blackout.

The electrical power system is a highly dynamic and complex system. In this system, instabilities occur on a much faster timescale than variability in supply and demand (milliseconds to minutes compared to hours or weeks). Since stability needs to be maintained at all times, stability challenges grow continuously as an increasing number of renewable generation assets are connected to the electrical grid and the number of actively operated fossil power plants is reduced. This is because stability support is provided by the power generation units, or dedicated ancillary service units, connected to the grid at any given time. Today conventional power plants provide stability support to the electrical grid. Currently, renewable generation assets such as wind and solar only provide limited grid stability support. Any change to the profile of the generating units therefore affects the system's stability. Furthermore, renewables also result in a shift from proven centralised to novel decentralised solutions, incorporating further changes within the system.

As the share of renewables in the grid increases, wind or solar power plants consequently must provide progressively expanding grid support capabilities during the transition period until the point where they are fully capable of supporting a stable and resilient electrical grid is reached. Several elements of grid equipment, including their protection systems, will need to be adapted, updated or renewed. Achieving this requires a more comprehensive understanding of the role played by the interaction of grid supporting and protecting equipment with smart converter-dominated systems and these need to be de-risked and utilised.



AN UNSTABLE GRID CAN HAVE SERIOUS RAMIFICATIONS. A SYSTEM CRASH ON A 10GW OFF-SHORE ENERGY ISLAND IN THE NORTH SEA COULD BLACKOUT THE ENTIRE EUROPEAN ELECTRICAL GRID

Enabling variability and stability solutions

The energy transition requires the integration of new and existing energy sources across sectors and technologies. Extending, advancing and coupling existing models will enable a simulation test bed to explore the generation and consumption assets behaviour across all time scales thus optimising the future energy system. Models to consider for parallelisation, coupling and further advancement include:

- Parallelise and couple different models together
- Energy price and weather forecasting models
- Asset performance models together with energy price and electrical network models to identify optimal size and location of assets
- Large multi-level control models and electrical network models to test grid designs
- Individual asset stability models and large grid stability models to identify grid stability issues
- Electricity and ancillary service price models coupled with hybrid power plant control models to evaluate market frameworks

This list is not exhaustive and further reasonable couplings may be identified. The ability to test the system impact and its behaviour coupled with the possibility of creating different scenarios will enable us to develop optimal solutions for the net-zero energy system that account for the variability and stability issues. Although many solutions will often support both variability and stability to some degree, it is still useful to maintain the distinction when examining potential component and system solutions for the future electrical power system. In the following, we will categorise the different options as belonging to either variability or stability.

Variability solution options

With growing shares of renewables, there is an increased need to apply some or all of the following energy system improvements at local, regional or international scale to handle variability in supply and demand.

1. Flexible demand

Increasing flexible demand can mitigated power production variability. Options available include on the one hand large scale off-takers for sector coupling, such as power to heat or hydrogen production, and on the other hand demand control for distributed loads on the electrical grid, such as smart charging of electrical vehicles or smart dispatching of electric heat pumps.

2. Energy storage and energy conversion

Energy storage technologies will be critical in balancing production and consumption at all times and will support a stable electrical grid operation. The storage solutions will need to support a wide range of applications and technologies to reinforce the different aspects of the future energy system. It will require rapid high-power solutions (batteries, flywheel etc.) for short term grid services as well as high energy solutions to store large amounts of energy that can cover energy demands for days, weeks and seasons (e.g. pumped hydro, flow batteries, compressed air, thermal storage, etc.)

These storage models will be placed on different voltage levels, locations and markets and their overall management and control system need to include the necessary flexibility to support these decentralised solutions.

Energy conversion solutions (e.g. PtX, heat solution, etc.) will play a significant part in future energy systems by increasing the demand flexibility as well as enabling decarbonised transport solutions.

Other solutions will close the loop from power to X and back from X to electric power, thus maintaining a resilient electrical grid for extreme intermittency durations, seasonal demand and supply balancing.

3. Smart transmission system upgrades

Enabling and deploying flexible hybrid renewable energy plants with high-capacity factors will help reduce transmission system upgrade costs. These costs can also be limited by replacing deterministic worst-case planning methods with probabilistic planning methods. Other improvements may include dynamic line rating technologies for overhead lines and cables to utilise the correlation between variable renewables generation and dynamic line capacity, resulting in an enhanced utilisation factor.

Strong interconnected electricity grids allow system operators to transmit electricity over great geographical distances, which reduces the overall system variability. This can be stimulated by designing and installing meshed offshore electrical grids through an integrated development of offshore wind and interconnectors.

Local conditions matter

The optimal energy transition for a country does not only depend on the share of variable renewable generation within the electrical power system. It also depends on the existing electrical grid and its interconnections as well as the geographical, political and market characteristics of a given society.

A typical example of dependence on the existing grid is the western Danish power system, which is highly interconnected to neighbouring countries including the Nordic Region's flexible hydro generation. In comparison, the Irish system is a relatively small system with a very weak degree of interconnection. Added to this, the Irish system is an AC island, whereas the western Danish power system is AC connected to the large continental synchronous area reaching down to the Mediterranean. Therefore, Ireland is facing inertia challenges at much lower shares of renewables than the western Danish power system.

Another factor is the more local weakness of the grids, which affects the voltage control and fault ride through capability at much lower shares of converter based renewable generation than in stronger grids. Smarter converter and plant-level control can allow more RES capacity to be connected to locations with the best renewable weather resources, even in very weak grids.

Stability solution options

1. Converter opportunity

Although we have more than a hundred years of experience of operating the current electrical grid, within the next decade we must develop and learn to operate a renewables-based electrical grid. This is a challenge, but also an opportunity, and the key lies in the potential of converters.

In the existing electrical grid, stability is partly provided by the mechanical interaction of the fossil fuel generators and the grid. In a renewables-based electrical grid, the stability will be provided by the software-controlled interaction of the converters used in all kinds of energy assets (e.g. wind power plants, solar plants, battery energy storage systems, HVDC systems, etc.). We therefore need to create algorithms that enable grid-supporting features from the different set of assets. This will include the ability of some assets, enabled by grid forming capabilities, to actively control frequency and voltage levels as well as enabling black-start capabilities. As time is crucial, these software solutions should be also utilised on existing renewable-based generation, to support continued stability already in the short-term.

Such "smart" software-controlled electrical grids offer a much higher degree of controllability and adaptability and improve the efficiency and resilience of the electrical grid. It can be compared to the shift from cell phones to smartphones. A smart electrical grid enables significantly more powerful and sophisticated solutions.

2. Renewable auxiliaries

A wide variety of auxiliary equipment beside the renewable-based generation exist that can enable advanced grid support and better system integration of high shares of renewable energy sources. These auxiliaries can operate on their own or be physically/virtually co-located/co-operated. Typical examples of supporting auxiliary systems are

- Static Synchronous Compensator (STATCOM) – *Voltage stability*
- Synchronous condenser – *Voltage stability/Frequency stability/Inertia*
- Energy storage solutions – *Frequency stability*
- Hydrogen and synthetic fuel plants – *Frequency stability/voltage stability*
- Power-to-heat solutions – *Frequency stability*
- Interoperable HVDC connection systems – *Frequency stability/voltage stability*

These auxiliaries and renewable-based generation will be best scaled and placed in a joined optimisation process. Their joint operation can be optimised based on improved energy demand and supply forecast systems across all sectors.

Act now

If Denmark and other countries are to fully decarbonise energy systems by 2050, we must research and innovate now. The generation, storage and grid assets within our system have a lifespan of more than 25 years: This means that what we plan and install now will still be in operation as we approach the 100% renewable energy target. Consequently, we must swiftly enable energy assets to contribute to system requirements at high levels of renewables. Encouraging early identification of the optimal solutions will also greatly limit the cost of the coming energy system transformation.

There has been much research into technologies that address system variability, but solutions to support the system stability have received less attention. This needs to change.

Research & Development recommendations

To successfully transform our independent energy systems for electricity, heat and mobility into one integrated energy system with electricity as the backbone, the following system integration priorities in research and development need to be addressed; to solve the variability and stability challenges and create a stable, reliable and resilient renewables-based energy system.

1

Stable grid operation and the integration of large number of variable converter-based production systems requires:

a. Development of new advanced models applicable for short term, long-term and other stability analysis.

b. Development of new large systems models applicable for transmission and distribution planning.

c. Development of new control methods to support stability of converter-based electrical power systems.

d. Development of new protection systems and methods, to secure a stable and reliable power system operation at transmission and distribution level of a converter-based power system.

e. Development of combined control systems for hybrid power plants as well as distributed power production and consumptions systems to support a better utilization of the grid and production assets.

2

Integration of flexibility solutions to handle the variability requires:

a. Development of forecast systems across technologies, metrology systems, regulations and markets.

b. Development of flexibility analysis tools, to ensure optimal placement and type for new application purposes

c. Development of market operational strategies and energy management systems for the new flexibility systems.

3

Design of the future energy systems requires:

a. Development of analysis, design and planning tools for optimal grid and cross sector related expansion plans.

b. Development of standardized communication systems across sector and technologies

c. Development of digital solutions to support the monitoring, optimal usage and integration of technologies.

d. Development of standardized model interfaces and validation methods to enable large systems studies

A successful cross-energy sector and cross-country operation of the future energy systems based on these recommended developments is only possible if clear regulatory frameworks are established in a harmonised way across interconnected electrical power systems.

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