Same Goal, Different Pathways for Energy Transition

LOW- AND ZERO-CARBON POWER SYSTEMS ARE central to global decarbonization efforts. Costs for renewable energy (RE) and storage have fallen significantly, and advances in technologies and practices have improved the grid flexibility and stability needed to maintain the reliability of high-RE systems. Zero-carbon power systems, in turn, enable deep decarbonization through the electrification of other sectors, including transportation, buildings, and industry.

These changes have underpinned a policy push toward power sector decarbonization. In this context, system planners are conducting detailed analyses of how to achieve reliable zero- or low-carbon power systems. Until recently, studies of how to achieve 100% RE power systems addressed the notional generation mix and approximate transmission investments. In contrast, more recent planning reflects the practical considerations of system operator-led 100% RE studies. These plans address a new set of challenges: the detailed engineering and balancing requirements needed to maintain reliability; market and regulatory contexts needed for operations and investment; coordination across jurisdictions needed to meet the scale of this challenge; and—critically—motivations, concerns, and participation of the people in their jurisdictions.

For example, 100% RE planning incorporates distinct new analyses, including system stability with high levels of nonsynchronous generation [i.e., inverter-based resources (IBRs)] as well as resource adequacy as each system approaches 100% RE. Many factors complicate this planning, such as the impacts of a changing climate and greater uncertainty. Planning also addresses the transformative roles of the customer through the rise of distributed generation, demand response, and autonomous operations of end users in response to price signals. Other complicating factors include cybersecurity, economy-wide interactions, and the centrality of goals beyond least-cost reliable planning (e.g., energy justice).

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A More Holistic, Multisector, Community-Driven Approach

This article reviews highlights from several of these system operator-directed plans, including the following:

- ✔ Los Angeles Department of Water and Power (LADWP), with a focus on hydrogen to provide firm capacity and energy justice as part of the 100% RE transition
- ✔ EirGrid Group, with a focus on stakeholder engagement to create a roadmap to 2030
- ✔ National Grid Electricity System Operator (NGESO), with a focus on its Pathfinder projects to competitively procure grid services
- ✔ Red Eléctrica de España (REE), with a focus on maximizing the value of existing network assets
- ✔ Hawaiian Electric (HECO), with a focus on managing 100% IBRs through advanced modeling and control techniques
- ✔ SEV of Faroe Islands, with a focus on the potential for tidal energy to produce continuous power
- ✔ European Network of Transmission System Operators for Electricity (ENTSO-E), with a focus on end-to-end interconnections (software and hardware).

These diverse global examples of preparations to reach high RE deployment illuminate that, while the solutions are technically similar (e.g., grid-forming inverters and more transmission), the processes used to map the transitions reflect the unique stakeholders and regulatory environment of each region.

LADWP: City of Los Angeles

In 2021, Los Angeles committed to a 100% RE power system by 2035. LADWP, which is the largest municipal power utility in the United States, serves the city's 4 million-plus residents. LADWP has extensive transmission (ac and high-voltage dc), which is essential for accessing a diversity of low-cost renewable resources, including solar in the Southwest and wind in the Pacific Northwest and Rocky Mountains. Nevertheless, a reliance on transmission is not without its vulnerabilities. Another feature is that, while

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LADWP is electrically connected to the rest of the western United States, it is a balancing authority and conducts planning and day-ahead operations to ensure self-sufficiency in supply. To meet its 100% RE target, LADWP plans to own or contract for an RE supply that is available at all time scales and under all contingencies without relying on a broader electricity market.

To evaluate pathways to achieve this target—within the context of other city objectives, such as the decarbonization of buildings and transportation sectors, clean energy jobs, and improved outcomes for energy justice—LADWP partnered with the National Renewable Energy Laboratory (NREL) on the "Los Angeles 100% Renewable Energy Study (LA100)" study. LA100 evaluated investments and operations for the bulk generation, transmission, and distribution needed to maintain reliability. The reliability considered not just a typical year but the impacts of extreme events, such as the load growth from a hotter climate and transmission outages due to wildfires.

Analytical advancements used to assess the reliability included hundreds of millions of simulations of how the future grid—and its customers' needs—might evolve. For example, the distribution grid alone required more than 25 million simulations to analyze more than 1,500 feeders at multiple timepoints in each study year for each scenario. For each of these feeders and timepoints, the distribution models simulated randomized patterns of solar deployment to capture uncertainty about how the location of customer solar could affect the reliability on each feeder.

The distribution grid is not isolated. The impacts of changes to customer demand and the distribution grid affect—and are affected by—changes to the bulk grid investments. LA100 modeled these interrelationships across a suite of models. For example, as LADWP adds more solar or as customers adopt more energy-efficient appliances, how might these changes affect the value of customer-sited solar? LA100 extended the analysis beyond the grid to include impacts to workforce needs, economic impacts, air quality, public health, and environmental justice.

Key findings and next steps include the following:

- ✔ Wind and solar—coupled with diurnal storage—could serve 70–90% of the annual generation; i.e., LA100 showed that all technical pathways to approximately 90% RE are very similar.
- ✔ The pathways to 100% RE diverge in how the city meets the electricity demand in that last 10%, which occurs during periods of very low wind and solar, extremely high demand, and unplanned events like transmission outages.
- ✔ To partially meet this last 10%, LADWP plans to fuel local power plants with green hydrogen (Figure 1). LADWP is currently analyzing the potential for market fuel purchases, supply chain considerations for self-supply, and fuel storage options.
- ✔ Local hydrogen plants help address the challenge of serving a large urban population in a constrained area. A resource mix that, instead, builds more wind, solar, and batteries would more likely suffer a loss of load in the event of major multiday transmission outages.

- *Who*: LADWP
- *Where*: Los Angeles, California
- *Responsible for*: all power system planning and operations (a vertically integrated municipal utility with its own balancing area)
- *Peak demand today*: 6,500 MW
- *Planning for*: 100% RE by 2035

Energy Justice

A 100% RE supply is just a starting point for LADWP's integrated resource plan. LADWP is working with diverse community members to envision an energy future more holistically. Topics include reduced energy bills, increased access to energy services (energy efficiency, demand response, mobility, and distributed solar) for renters and owners, and access to training and employment in the clean energy industry. For example, a demand response that encourages daytime electric vehicle charging when solar availability is high reduces the cost of a clean energy transition. However, LADWP wants to incentivize the demand response in a way that does not penalize customers who lack flexibility in mobility and charging options. To better understand the implications for energy justice, LADWP has expanded LA100 to address the following:

- ✔ procedural justice, by enabling community members to prioritize the outcomes that LADWP should meet to improve energy justice as part of the 100% RE goal
- ✔ recognition justice, through community engagement surveys and an analysis of the factors contributing to energy inequities
- ✔ distributional justice, by evaluating implementation strategies that achieve community-prioritized equity outcomes.

How Will LADWP Measure Distributional Justice?

LADWP is updating its data collection and modeling to

- ✔ better capture the characteristics significant to environmental justice (e.g., household size and access to smart devices) in its efficiency, electrification, demand response, and solar programs
- ✔ more comprehensively represent benefits in its program design (e.g., energy upgrades to provide resilience to heat waves)
- ✔ analyze neighborhood-level impacts (positive and negative) to establish expectations and revise protocols as needed
- ✔ track progress against plans through improved metric-tracking tools.

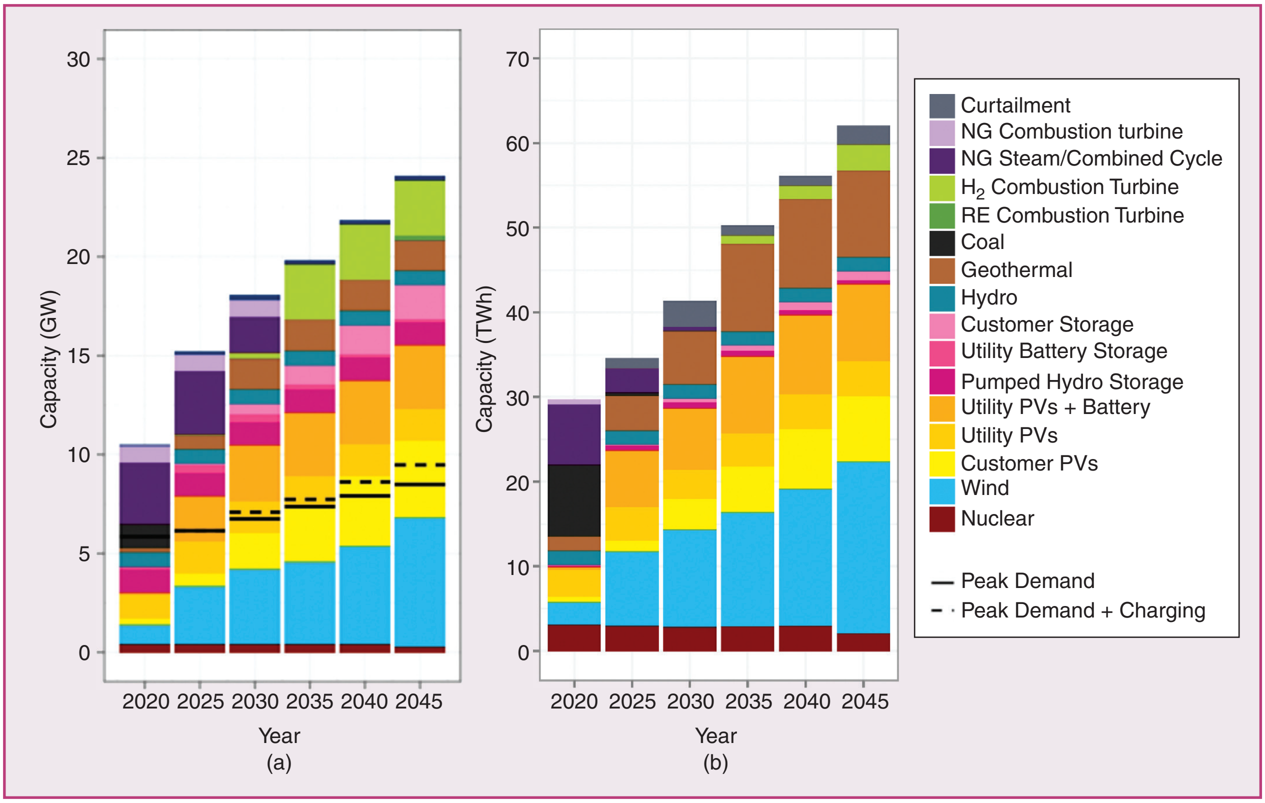

figure 1. The (a) capacity mix and (b) annual generation, 2020–2045, for an LA100 scenario that achieves 100% zero-carbon operations by 2035, with high energy efficiency, electrification, and demand response. NG: natural gas; PVs: photovoltaics.

Thus, LADWP is fundamentally rethinking not just 100% RE power system operations but the preeminent significance of energy justice in this clean energy transition.

EirGrid Group: Ireland and Northern Ireland

In November 2021, EirGrid and the System Operator for Northern Ireland (SONI), in consultation with stakeholders across society, government, and industry; market participants; and electricity consumers, prepared and published the *Shaping Our Electricity Future* roadmap. The roadmap provides an outline of the key developments from network, engagement, operations, and market perspectives to support Ireland and Northern Ireland's secure transition to 2030 renewable ambitions. Figure 2 shows the locations of generation by 2030. The assumed locations for future connections are informed by consultation, grid connection applications, the outcomes of auctions, and projections of the available grid capacity.

EirGrid Group's initial consultation focused on three perspectives: networks, operations, and markets. However, the public consultation process identified public engagement as equally—if not more—important in delivering structured changes on the pathway to 100% renewable electricity. The final roadmap elevated public engagement as an integral workstream on par with the initial three.

Public Engagement

The 14-week public consultation identified some key insights. There was huge interest in the future of the electricity system. People care about and want an active role in the transition—whether that is acquiring knowledge, installing distributed energy resources (DERs), or implementing large-scale community projects. Providing an open forum allowed people to be comfortable, enabling them to actively participate in the discussion; they learned by asking relevant questions and exchanging views. In the deliberative dialogue, people clearly indicated that they do not want to privatize the grid but, rather, to see a proper transition that uses future investments for the greater good.

- *Who:* EirGrid Group (EirGrid and SONI)
- *Where:* Ireland and Northern Ireland
- *Responsible for:* system operations and the wholesale electricity market of the entire island
- *Peak demand today:* 7,100 MW
- *Planning for:* 70% RE by 2030, including operations with 95% IBRs

Transmission Network

An outcome from the consultative process was the need to ensure coordination among transmission system operators (TSOs), industry, interested parties, and communities. The coordination can enable a new approach that will help minimize new grid infrastructure needs and enable more efficient and timely delivery, which are critical in achieving such goals as delivering 5 GW of offshore wind by 2030. Technologies such as active power flow controllers can help manage network congestion and maximize existing network capacities. The focus on DERs in the public consultation was higher than originally anticipated. DERs have been part of the scenarios, but public feedback underscored their importance now and for the future.

System Operations

The island of Ireland is geographically small and isolated from central Europe. High RE goals will require the power system to operate at levels of instantaneous IBRs up to 95% (currently 75%) with fewer conventional units online. Operating at these levels is unprecedented and poses several technical challenges, many of which are yet to be experienced by other larger power systems.

A program of work has been developed to enable enhanced power system operational capability by 2030, including the following:

- ✔ setting and clarifying operational standards, including grid codes and system services, and monitoring the performance against these standards
- ✔ enhancing system service arrangements and facilitating service provision by new and innovative low-carbon technologies
- ✔ removing barriers to entry and enabling the integration of new technologies
- ✔ continuing the evolution of operational policies, e.g., the minimum number of dispatched large synchronous units
- ✔ developing new and enhanced control center tools and systems
- ✔ collaborating with other TSOs to share lessons learned and potential solutions
- ✔ partnering with the distribution system operators (DSOs) to coordinate and deliver value for consumers who can then benefit from participation in system service and energy markets.

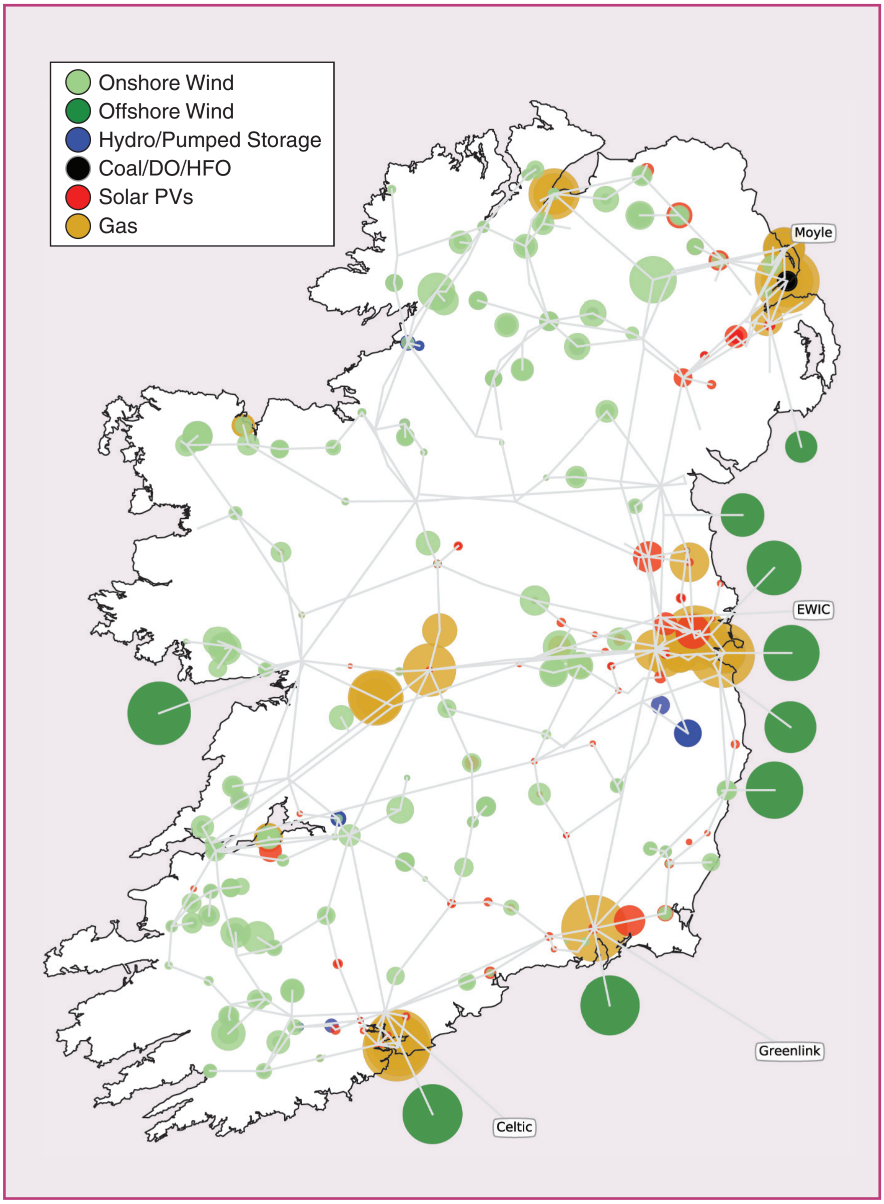

figure 2. The spatial distribution of generation, 2030. DO: distillate oil; EWIC: East West Interconnector; HFO: heavy fuel oil.

Future Markets

EirGrid Group listened to stakeholders about what was required in relation to transmission tariffs and transmission loss adjustment factors, and these findings are incorporated into the roadmap. A focus on the security of the supply was identified, highlighting the need for urgent capacity market design changes to ensure long-term resource adequacy provision.

> Providing an open forum allowed people to be comfortable, enabling them to actively participate in the discussion; they learned by asking relevant questions and exchanging views.

To ensure that the market delivers the operational capability for renewable ambitions, markets and operations need to be aligned. Much of the electricity market design is set by European Union regulations. Until recently, this design has been focused on an energy-only market. This assumes that necessary services (e.g., frequency support through inertia) are inherently available from the plants. With the rise of IBRs, the roadmap identifies the need for other markets and investment signals to ensure that TSOs have access to the operational services required to run a resilient and secure power system. Additionally, in a system with high levels of weather-dependent generation, there is a need to recognize the resource adequacy risk during weather conditions such as dark calm spells. Finally, the market design will consider sector integration and efficient interaction with emerging technologies, such as power to gas, and new infrastructures, such as hydrogen.

NGESO: Great Britain

NGESO is operating a rapidly decarbonizing power grid—a 66% reduction in emissions since 2013. Through the extensive customer and stakeholder engagement undertaken when developing its Future Energy Scenarios (Figure 3) and through NGESO's own detailed analysis, a significant increase in renewable generation is seen across all scenarios. Figure 4 outlines the generation capacity mix into the future across the scenarios compared to today. In all of the pathways, offshore wind makes up more than half of the electricity supply by the late 2030s, and wind and solar provide at least 78% of the electricity generation by 2050. Connecting these high volumes of new zero-carbon generation, particularly offshore wind, to the electricity system will be challenging in the short term due to the need for network reinforcement.

In addition, NGESO has an ambition to operate the Great Britain electricity system carbon free by 2025. This goal will require a transformation of the operation of the electricity system and innovative systems, products, and services to ensure that the network is ready to handle 100% zero-carbon energy. For example, the reduction of conventional technologies with inherent sources of system inertia increases the requirement for the procured frequency response. In October 2020, NGESO launched a new frequency response service known as *Dynamic Containment*, which is contracted the day ahead for 24 h. Providers respond within 1 s of a significant frequency deviation with power proportional to the frequency deviation. Additionally, NGESO is exploring a new suite of faster-acting frequency response services to support operations as well as exploring ways of increasing the system inertia.

The Pathfinder Approach

The projects through which NGESO wants to resolve the challenges of enabling the net-zero transition are known as *Pathfinder projects*. The projects involve learning-by-doing and engaging solution providers in an ongoing conversation about how tender processes can be improved for long-term contract opportunities. This will help attract competitive and innovative service proposals, leading to contracts for the services that are needed. The Stability Pathfinder looks for the most cost-effective way to address stability issues in the electricity system created by the decline in transmission-connected synchronous generation. This involves the creation of a first-of-its-kind market for stability services and a huge step forward in operating the Great Britain electricity system carbon free by 2025.

To manage zero-carbon operation, NGESO will need a minimum of around 100 GVAs of inertia to ensure that system stability can be maintained in the event of a significant loss and that the frequency does not fall too low. The Dynamic Containment product currently helps to stabilize frequency variations, and the implementation of

- *Who*: NGESO
- *Where*: Great Britain
- *Responsible for*: transmission system operations
- *Peak demand today*: 58,000 MW
- *Planning for*: by 2025, an electricity system that can operate carbon free and, by 2050, net-zero emissions

- *Who*: REE
- *Where*: Spain
- *Responsible for*: transmission system operations
- *Peak demand today*: 40,000 MW (Spanish mainland)
- *Planning for*: economy-wide net-zero carbon in 2050, including 100% renewable electricity by 2050

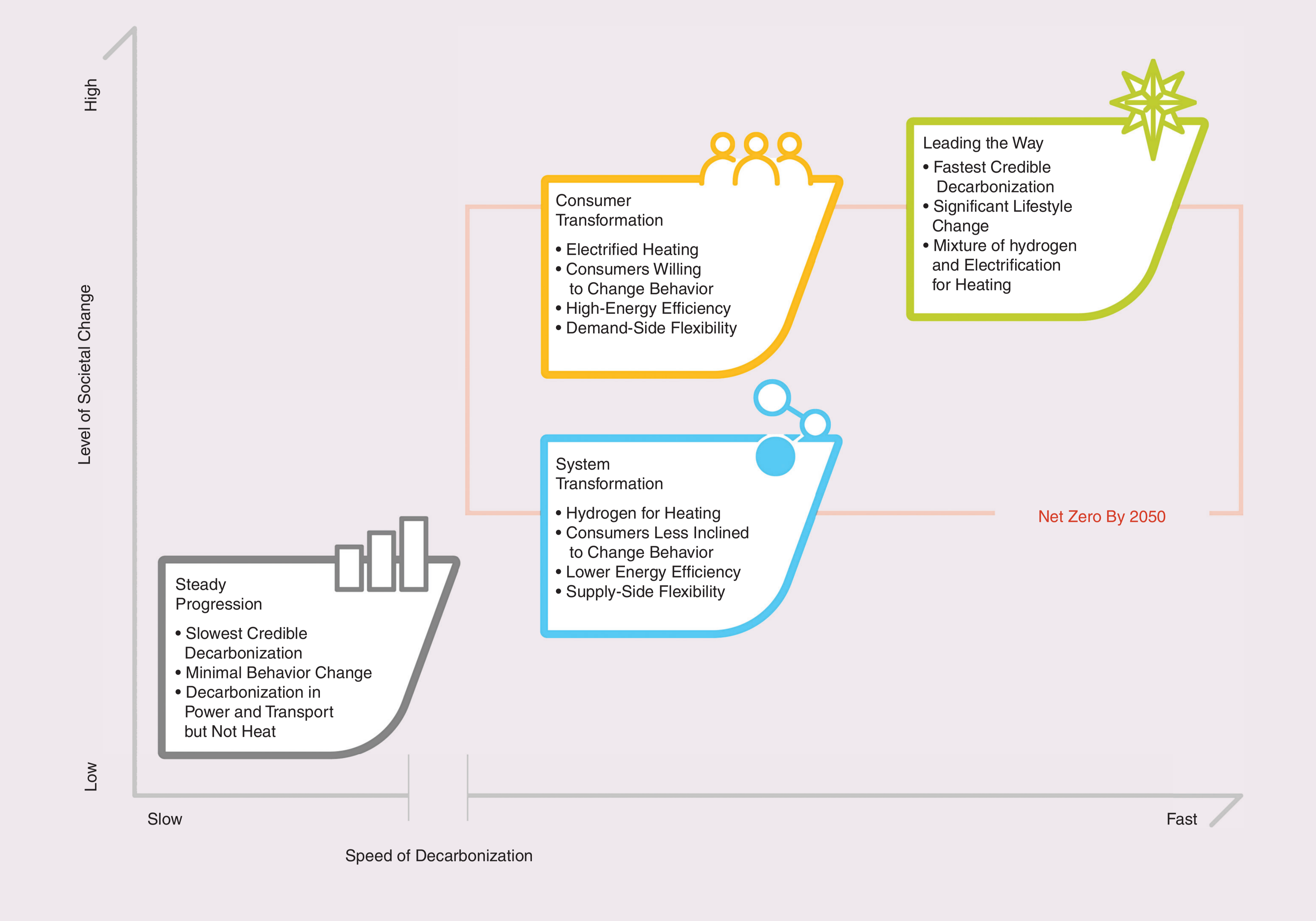

figure 3. The Future Energy Scenarios framework: four different credible pathways for the future of energy in Great Britain through 2050. (Source: Future Energy Scenarios 2021, https://www.nationalgrideso.com/document/199871/download.)

faster-frequency services in the future could reduce the inertia requirement further. Across all future energy scenarios, there is a notable and continuous decline in the inertia provision to the market. NGESO is currently procuring inertia to meet this forecasted shortfall through phases 1–3 of the Stability Pathfinders. The combination of the volumes procured through these Pathfinders means that the inertia requirement of around 100 GVAs can be met until 2027. NGESO continues to forecast future requirements beyond 2027 to ensure there is sufficient capability on the system to meet needs.

REE: Spain

Spain's "Net Zero by 2050" target assumes an increasing share of electricity from renewables, from 46% in 2020 to 74% in 2030 and 100% in 2050. During this time, the annual electricity demand is expected to grow by 60% due to the electrification of new sectors and new types of demand, such as data centers.

Meeting this target will necessitate new distributed and utility-scale zero-carbon generation. The location of this new generation is of the utmost concern due to its impact on network flows. Spain's National Development Plan uses an approach to estimate the location of future renewable generation based on a success probability. The approach considers geographic information system resource data; the ease of installation in terms of environmental restrictions and administrative procedures; and the market interest, which reflects other relevant factors that are hard to quantify.

To accommodate the demand growth, future generation, need for system flexibility, and other complementary elements, Spain is assessing long-term system needs and network investments. These network investments begin with an extensive focus on maximizing the use of the existing infrastructure according to the European energy-efficiency-first principle.

The first step of network planning includes evaluating the likely future conditions of current infrastructure, including the impacts of climate change. Decisions will be made on whether and how to invest in extending the life of assets and whether to do so in one or multiple steps and through a partial or total renovation. REE uses an advanced asset management solution, the SAGA tool. The tool implements a condition-based maintenance, replacing the previous frequency-based maintenance. Multiple artificial intelligence models are integrated to calculate various indices that provide the effective age, degradation, failure probability, and risks, among other things. Artificial intelligence enhances the prioritization of the maintenance actions to be performed on assets from a holistic point of view in which other variables, such as business rules, value, and network availability, are considered, as depicted in Figure 5. Therefore, this tool makes maintenance and replacement planning easier due to the multiple intelligent components that facilitate decision making.

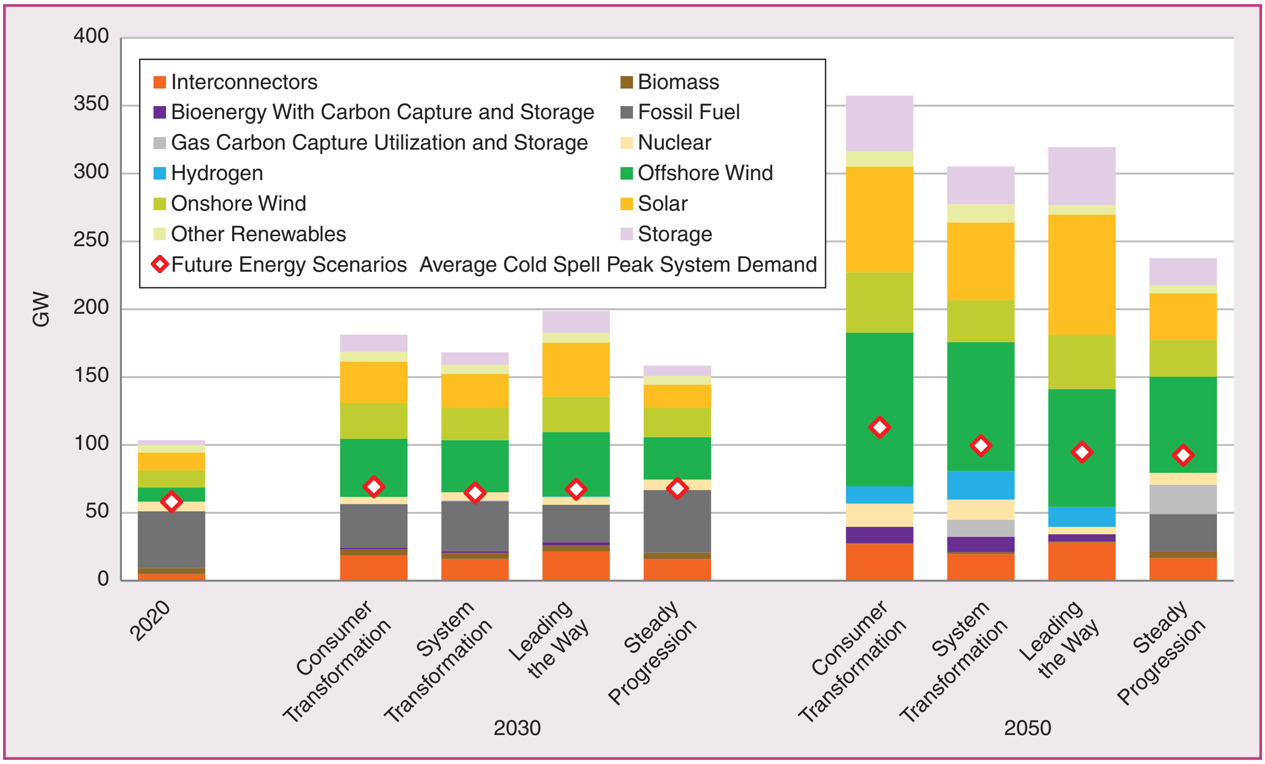

figure 4. The installed electricity generation capacity, storage, and interconnection through 2050. (Source: Future Energy Scenarios 2021, https://www.nationalgrideso.com/document/199871/download.)

Hawaii, which relied on oil for more than 60% of its electricity as recently as 2019, passed legislation in 2015 mandating that electric utilities achieve 100% RE by 2045.

To plan for future—and likely new—flow patterns, Spain applies a decision tree for network planning that starts with the least-impact measures, such as operational changes. For example, REE is implementing a mechanism to automatically reduce generation within 5 s after the failure of any network element, replacing the need for larger preventative generation curtailments. The key for system operation will be the capability of the Spanish National Renewable Energy Control Center to see and communicate with nearly every renewable generation unit.

Planning new low-footprint devices includes dynamic line ratings (DLRs) to allow more efficient use of the network in moments when environmental conditions are favorable. Nevertheless, climate change will impact their value. DLRs might not be efficient in hot areas where the maximum temperatures approach the maximum design temperature of the lines. Additional devices that can optimize the use of existing networks include phase shifters and flexible ac transmission systems.

Finally, when there is no other option, new rights-of-way for transmission lines will be considered to the extent compatible with environmental constraints, including interconnections between countries and systems. REE is expanding its cost–benefit analysis to better capture all possible benefits (e.g., system flexibility). Communication with stakeholders on the value of new network infrastructure for net-zero electricity is an essential step to improving acceptance.

Identifying the right investments for 2050 exceeds national, sectoral, or corporate approaches and involves TSO–DSO cooperation and multisectoral planning. Moreover, it implies new approaches in many fields. Being able to enrich the energy models with all aspects related to the energy transition increases the complexity of the models, computation, and data analysis and is one of the challenges to designing the optimal future network.

HECO: Maui Island

Hawaii, which relied on oil for more than 60% of its electricity as recently as 2019, passed legislation in 2015 mandating that electric utilities achieve 100% RE by 2045. This legislation is an effort to improve the state's energy security, reduce electricity costs, and support sustainability. The state has now surpassed 35% RE generation, and the county of Maui, which includes Maui Island, exceeded 50% RE generation in 2020.

For Maui Island, with the recent and forthcoming procurement of utility-scale hybrid photovoltaic (PV) battery systems and stand-alone systems, power system modeling of the energy balance shows sufficient capacity from solar, wind, and battery to enable the dispatch of 100% renewable electricity for multiple consecutive hours as early as 2023. Maui Island could be the first interconnected transmission system to operate with 100% IBR generation, although some other islands, for example, Kauai Island, have achieved 100% renewable power for cumulative hours, in part through synchronous generator-based biomass and hydro.

The primary requirement for IBRs is to remain connected during a wide range of disturbances, including under-/overfrequency, under-/overvoltage, and fast changes in the voltage phase angle. Hawaii's rule 14H (DER interconnection) specifies that smart inverter functionalities

- *Who*: HECO
- *Where*: Maui Island
- *Responsible for*: all planning and operations (a vertically integrated utility, with each island its own balancing area)
- *Peak demand today*: 200 MW
- *Planning for*: nearly 100% RE by 2030 on Maui, with many hours of 100% inverter-based generation by 2023

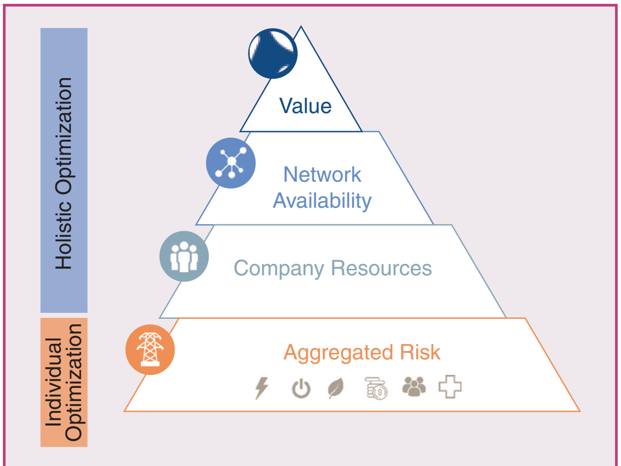

figure 5. The different levels of optimization within SAGA, including the individual optimization for each asset and enhancement of these individual optimizations with a holistic point of view that takes into account the resources, availability of the grid, and top value health index of the whole grid. (Courtesy of Elewit.)

must include voltage and frequency ride-through, transient overvoltage mitigation, volt–var control, frequency–watt control, soft start, ramp rate control, and remote upgrade capability. Some of the requirements require DER inverters to tolerate a much wider range of deviations compared to the requirements for IBRs integrated into large continental grids. This is important for island power systems, where the range of disturbances is generally wider than on large interconnections.

To improve the stability of a low-inertia island grid, IBRs can be required to provide a range of other services to stabilize the grid voltage and frequency. In particular, IBRs can be required to provide the class of grid services known as the *fast frequency response*, which can inject instantaneous power into the grid in response to a frequency deviation.

Grid-forming inverter control is another key component to enabling a 100% IBR future. Grid-forming controls tend to be more stable than grid-following controls in low-inertia or weak grids. To some extent, they can help dampen power oscillations. Large-scale electromagnetic transient simulations model the transmission system at subsecond timescales. Such simulations indicate that deploying grid-forming controls on some IBRs could help stabilize the Maui Island grid in response to large contingencies, such as the tripping of the largest online generator. Another practical way for HECO to maintain stability during 100% RE operations is to coordinate newly installed grid-forming technologies and converted synchronous condensers with both utility-scale and distribution-connected grid-following inverters.

To help plan for operations at 100% IBR levels, HECO has partnered with the NREL to create the multi-timescale integrated dynamic and scheduling (MIDAS) model for the Maui Island grid. MIDAS enables HECO to evaluate the tradeoffs of dispatching renewable (and nonrenewable) assets based on the momentary cost of electricity and grid service needs for stability and reliability. MIDAS supports HECO's planning study with subsecond operations, day-ahead scheduling, and out to years-ahead planning.

SEV: Faroe Islands

In 2014, the power company SEV in the Faroe Islands announced its vision to become 100% renewable by 2030. The Faroe Islands is a group of 18 islands located in the North Atlantic Ocean, electrically isolated from other power systems. The power system consists of seven individual grids, of which five supply small islands with a considerably smaller demand. The total installed generation capacity consists of 100 MW diesel, 40 MW hydro, 24 MW wind, 1.5 MW biogas, 0.25 MW PVs, and a tidal power development project of 0.2 MW. The power system can be seen in Figure 6.

- *Who*: SEV
- *Where*: Faroe Islands
- *Responsible for*: all planning and operations (a vertically integrated utility)
- *Peak demand today*: 65 MW
- *Planning for*: 100% RE by 2030

SEV's "100by2030" roadmap for generation, storage, and transmission translates economic optimization to realistic, hands-on projects. Suitable investment sites with local resource profiles, power plant and cable sizes, the installation year, and industry know-how have been considered in the optimization and roadmap. SEV considered only investment sites where issues such as shadow flicker (the sun shining through rotating blades) and noise do not affect populated areas. SEV also commits to returning sites to their original state after decommissioning.

Although the renewable resource potential in the Faroe Islands is high, balancing it with 100% renewables in the summer is challenging. The winter holds high wind speeds and precipitation for hydro, but, in the summer, these resources are significantly lower. Solar energy would complement the other two resources well, especially in the summer, but the resource is limited due to the northern latitude and cloudy climate. Pumped hydro reservoirs help to make up the balance. Going from 96% renewables in 2028 to 100% renewables in 2030 more than doubles the size of the reservoir needed.

A renewable resource that is currently not being utilized is tidal stream energy. Tidal currents are highly predictable, they do not depend on the weather, and they are as high in the summer as in the winter. The tide has a beneficial phase shift between different fiords and straits. This means that, although the tide turns every sixth hour, at which point the current speeds become negligible, placing generators in different fiords and straits can produce generation at a near-constant output (Figure 6). Although tidal power is not included in the roadmap due to the technology development stage, a study showed that, in a 100% RE system, tidal energy could reduce the total generation capacity in 2030 by 18% and the needed reservoir capacity of the pumped storage system by 75%.

ENTSO-E: The Importance of Interconnections

Early in their decarbonization efforts, Europeans recognized that it is more cost-effective to decarbonize through cooperation with neighboring systems rather than individually. ENTSO-E (a mandatory association of national TSOs) leverages its highly interconnected network to jointly plan across 35 countries to facilitate ambitious net-zero emission targets. Transmission interconnections across the network improve operational security and resilience as well as increase access

- *Who*: ENTSO-E
- *Where*: Europe
- *Responsible for*: network of TSOs to ensure the security of the power system and optimal functioning of interconnected electricity markets
- *Peak demand today*: 540,000 MW
- *Planning for*: interconnections that facilitate Europe-wide net-zero emission targets

to flexibility across countries and sectors. Every two years, ENTSO-E conducts a 10-year network development plan that addresses interconnections between countries as well as national-level projects that impact the cross-border capacity over a 20- to 30-year period.

In addition to these horizontal transmission interconnections among TSOs, there are vertical linkages between TSOs and system operators across all voltages down to the distribution level, the DSOs. DERs are blurring the boundary of functions between transmission and distribution: the proliferation of the number and types of DERs is leading to TSO requirements for visibility, observability, and some degree of control (at least coordinated transmission and distribution control) for aggregated DERs. Even with today's moderate levels of DERs, TSOs and DSOs must exchange detailed data and criteria for defining scenarios, coordinating the provision of flexibility, agreeing on common metrics and planning, and coordinating operations and market-based dispatch.

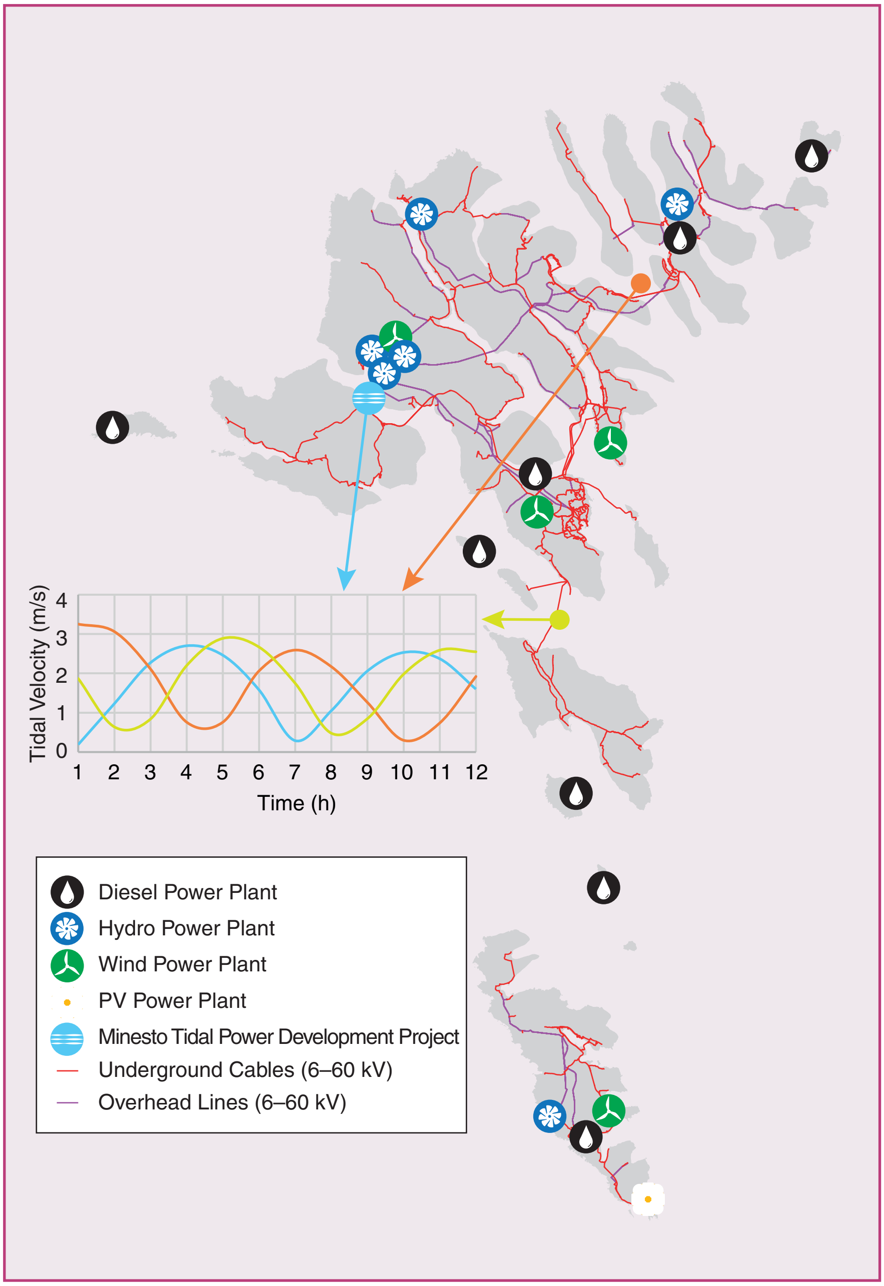

figure 6. An overview of the Faroese power system with an example of the tidal streams in different locations.

A third dimension is linkages to adjacent energy demand sectors (transport, buildings, gas, and industries). This system of systems includes large-scale loads (e.g., large electrolyzers, electric vehicle charging hubs, and electrified district heating) and small-scale loads (e.g., diffused smart charging infrastructure, dispersed storage, and load management). Europe is providing guidance in energy sector integration—the European Commission has published a smart sector integration strategy, and industry is investing significant funds in power-to-gas initiatives.

Other European Studies

Building on Europe's interconnected network, several recent studies have modeled macroregional or even global power grids. Transmission investments are about an order of magnitude cheaper than generation or storage and can, therefore, reduce the costs of decarbonization. For example, CIGRE has conducted a prefeasibility study on a global electricity network, simulating investment decisions and the optimal dispatch of resources. The results show that, even with high utilization of demand response and storage, transmission interconnection is an important component of the least-cost option for decarbonization.

The implementation of such a global network would require an unprecedented effort of collaboration among countries and regions. This study has analyzed existing trading rules and governance as well as possible solutions in the form of long-term contracts, commercial agreements, and operational agreements between different regulatory jurisdictions. The study finds that a fully harmonized regulatory framework is not necessary to realize benefits from transmission interconnections even between systems with very different market frameworks (e.g., a vertically integrated market and a competitive wholesale market).

The Way Forward

System operators representing a variety of power systems have charted new planning methodologies, models, market designs, operational practices, and community involvement to enable low-carbon power systems. Each operator has selected and prioritized its unique solutions that reflect differences in geography, resource availability, network size, system risks, and local policies, among other influences.

Many of the forerunners to decarbonized grids represented island systems, which, due to their smaller size and isolated grids, must more quickly implement technical solutions to maintain reliability and secure operation. Nevertheless, the examples featured in this article reflect more than just technical solutions. Due to the value derived from many elements—interconnections, diverse sources of flexibility, and optimized cross-sectoral decarbonization—operators of the systems in this article are planning at scales that transcend both their jurisdictions and sectors. Also, they are doing so in ways that more meaningfully engage stakeholders in envisioning and implementing the many different pathways toward a low-carbon future. The article's title, "Same Goal, Different Pathways," embodies the speed and strength that can come with encouraging a broad rather than standardized set of solutions to the energy transition.

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For Further Reading

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