

ISSUE BRIEF



BEST PRACTICES FOR VARIABLE RENEWABLE ENERGY (VRE) INTEGRATION

COUNCIL OF ENGINEERS FOR THE ENERGY TRANSITION

An independent advisory council to the United Nations Secretary-General

KEY MESSAGES

There are five key technologies and actions that can provide a practical solution for effectively integrating variable renewable energies into electricity systems. Each of them presents its own challenges, but global experiences show that they can be replicable and successful. Unfortunately, these experiences have not been disseminated on a global scale.

Energy Storage Technology

Battery Energy Storage can provide multiple services to power networks; most importantly is the saving of excess renewable energy during periods of high generation and the releasing of it when needed, providing grid stability and flexibility. High capital costs, lack of enabling regulations, market incentives, and international standards, in addition to technical complexities, all remain challenges to overcome.

Proactive Spatial Planning

Improved spatial planning ensures optimal resource utilization and minimizes environmental impacts. It's important to identify the best locations for renewable energy installations, considering factors like land availability, transmission infrastructure, environmental impact, and community engagement. Some successful strategies in this area include the deployment of special renewable energy zones and the co-location of renewable energy technology with generation and load centers.

Regional Grid Interconnection

Regional grid interconnection brings energy across countries over a large geographical area, allowing for greater optimization of natural energy resources, increased system resilience, and improved energy market dynamics. With investments, regulatory harmonization, strong technical and operational planning, and intergovernmental agreements based on solid and stable policy frameworks, advancements are possible.

Accurate Forecasting

Accurate renewable energy forecasting is one of the most cost-effective ways to integrate VRE into power grids. Rapid fluctuation and unpredictability of weather can make tracking renewables like solar and wind difficult for systems operators trying to match electricity supply and demand. However, advanced digital tools like data analytics, meteorological models, and machine learning algorithms (or AI in general) can overcome challenges and to better predict output.

Streamlined Permitting

Streamlined permitting expedites the approval and construction of renewable energy projects. Bureaucratic barriers and inconsistent standards make permitting one of the most important roadblocks in the way of VRE expansion, but with better governmental coordination, optimization and digitization of processes, and early stakeholder engagement, permitting can be simplified such that projects can begin operation much faster.

EXECUTIVE SUMMARY

Renewable energy (RE) is playing an increasingly pivotal role in the global energy system. As the impacts of global warming intensify, governments across the world are prioritizing the promotion of renewable energy policies as a key component of their energy diversification, decarbonization, and energy security strategies. Furthermore, the integration of digitalization is gaining prominence within the sector, with advanced technologies like big data, Internet of Things, cloud computing, and blockchain being increasingly employed in both renewable and fossil energy systems, as well as in energy consumption practices.

In this context, a dedicated Working Group from the Council of Engineers for the Energy Transition (CEET) has undertaken the task of identifying existing challenges that hinder the widespread adoption of vital decarbonization technologies in the fields of renewable energy and digitalization. Following initial discussions with several experts, the Group has chosen to prioritize topics that currently pose the greatest challenges to achieving the necessary speed and scale of renewable energy deployment required for a successful transition to a net zero future.

While many of these challenges have already been overcome through the implementation of effective practices and innovative technologies in diverse socio-economic contexts, these successful experiences have not been adequately disseminated at a global scale. Thus, this paper also describes key existing solutions that can be implemented to address each of these challenges in order to extend an invitation to policy makers, utility managers, and other stakeholders in the power sector (e.g., grid operators, regulators), urging them to familiarize

themselves with and replicate these exemplary practices within their respective environments.

The majority of the challenges and their potential solutions are associated with addressing barriers in planning, administration, and project development that hinder the widespread implementation of large-scale grid-connected renewable projects¹. These challenges are less focused on pure technological and engineering obstacles, as it is widely acknowledged that existing technologies have the capability to significantly reduce carbon emissions and contribute to a net zero trajectory². However, it is important to note that several technical and engineering challenges still persist, particularly in emerging markets. Therefore, governments should prioritize research and development efforts and promote innovation programs to tackle these specific technical aspects in a more targeted manner.

Despite the multitude of challenges posed by the massive deployment of renewable energies, the expert group decided to focus first and foremost on best practices for the effective integration of variable renewable energies into power systems. Variable renewable energies, often abbreviated as VRE, are sources of energy that generate electricity according to external factors such as weather conditions. They are considered “variable” because their power output can fluctuate, making them less predictable and reliable compared to conventional sources of energy like fossil fuels. Examples of VRE are wind and solar power. Due to the low amount of carbon emitted during the lifecycle of these technologies, VRE are a crucial part of efforts to transition to a more sustainable and environmentally friendly energy system. However, their variability presents challenges for grid operators and energy planners.

1. The Working Group recognizes that there are remaining structural obstacles that continue to impede the widespread implementation of renewable energies. These obstacles include persistent subsidies for fossil fuels, which introduce distortions to the energy market and create an uneven playing field for renewables. According to the International Monetary Fund (IMF), total explicit and implicit fossil fuel subsidies were \$5.9 trillion, or 6.8 percent, of GDP in 2020. Cutting these subsidies would reduce projected global fossil fuel CO₂ emissions to 36 percent below baseline levels in 2025 (<https://www.imf.org/en/Topics/climate-change/energy-subsidies>).
2. According to recent work from the International Energy Agency, existing clean technologies in the market could deliver more than 80% of the carbon emission reductions in a net zero pathway to 2030 relative to 2020, and more than half of savings until 2050 (Roadmap: A Global Pathway to Keep the 1.5C Goal in Reach, IEA 2023).

To address these challenges, innovative solutions have been developed and implemented, both in developed and developing countries, and will be described in the following sections. This brief introduction highlights five key topics that are crucial for maximizing the benefits and minimizing the challenges associated with the integration of VRE sources: (1) energy storage technologies, (2) proactive spatial planning, (3) regional grid interconnection, (4) renewable energy forecasting, and (5) permitting.

Energy storage technologies play a pivotal role in facilitating the integration of VRE into power networks. By storing excess energy during periods of high generation and releasing it when needed, energy storage systems provide grid stability and flexibility. This helps to address the intermittency and variability of renewable energy sources, enabling a more reliable and efficient power supply.

Proactive spatial planning is a key to preventing the most frequent problems encountered in the construction and operation of energy projects. By strategically identifying suitable locations for renewable energy installations, such as wind farms and solar arrays, spatial planning ensures optimal resource utilization and minimizes environmental impacts. This practice involves considering factors such as land availability, transmission infrastructure, environmental considerations, resilience to extreme weather events exacerbated by climate change, and community engagement.

Regional grid interconnection is a key enabler for the integration of VRE sources. By connecting diverse regions and balancing the fluctuations in renewable energy generation, regional grid interconnection allows for greater sharing of resources, increased system resilience, and improved energy market dynamics. This practice promotes a more efficient utilization of renewable energy and enhances grid stability across larger geographical areas.

Accurate renewable energy **forecasting** is one of the most cost-effective ways to integrate VRE into power grids. By leveraging advanced data analytics, meteorological models, and machine learning algorithms, renewable energy forecasting enables operators to predict the expected output of renewable energy sources with greater precision. This information is crucial for effective grid management, optimal dispatch of generation resources, and efficient integration of renewable energy into the power system.

Lastly, streamlining the **permitting** process is essential for the smooth and rapid integration of VRE sources. Clear and transparent procedures, along with standardized guidelines, can expedite the approval and construction of renewable energy projects. By reducing bureaucratic barriers and promoting a predictable regulatory environment, streamlined permitting facilitates the timely deployment of renewable energy infrastructure.

Each topic is organized in the following manner: a description of the challenge at hand, the benefits associated with addressing the challenge, existing solutions including the technological factors that enable them, and examples of successful experiences that can be replicated, along with key references for further information.

1. ENERGY STORAGE TECHNOLOGIES

1.1 Challenges

Energy system decarbonization requires the rapid scale-up of renewable energy sources such as wind and solar that are variable. This variability demands the implementation of storage and balancing solutions and system-level optimization efforts to improve the utilization of these VRE assets and thus, the bankability of these projects. Among the most important challenges for a massive deployment of energy storage technologies are:

- **Costs of deployment:** Storage technologies (e.g., battery storage and pumped storage hydropow-

er) have high upfront capital costs.³ This has limited their deployment at a larger scale and faster pace to complement wind and solar projects and provide grid support. Despite the cost of battery storage coming down in recent years,⁴ its cost-benefit ratio is yet to be better understood as its full potential and long-term gains are yet to be realized. While another difficulty is selecting the most suitable storage technology when the same type of service can be provided by several storage technologies, the levelized cost of storage (LCOS) can serve as a good indicator for comparison. However, several other aspects, such as the level of dispatchability, shift of generation being considered, spread between peak, off-peak time tariffs, and sources of generation, impact the final cost. With a decent level of partial dispatchability where there is good wind and/or solar resource, hybrid plants, such as wind and/or solar plus storage can economically compete with fossil fuel generation.

- **Operational challenge:** Storage batteries are considered a new technology in many markets and are not well understood or operationalized technically, and knowledge and capacity building in grid management of storage is urgently needed. Optimization of storage requires high levels of technical and operational capacity for energy systems and forecasting capacity of wind and solar farms, which are often lacking in many developing countries. However, this challenge can also be seen as an opportunity since additional energy storage in the system could improve dispatchability of renewable generation and minimize duplication of generation capacity with fully dispatchable assets, such as fossil fuel generation.
- **Lack of standardization:** International technical and implementation standards for battery storage are lacking. This creates a challenge for the long-term compatibility and continuity of many storage projects and increases the trans-

action costs for scaling up their deployment. To date, there is also a lack of production certification standards for a sustainable battery storage supply chain. The high mineral resource requirement for some battery storage technologies can cause ESG concerns if not properly managed.

- **Lack of policy support and market design:** Regulatory policy is lagging and the energy storage technologies, knowledge, and learnings that exist today are slow to be disseminated across countries and regions.
- **Innovation and critical mineral constraints:** Research and development on batteries is being driven by efforts to increase energy density, reduce cost, reduce critical material usage, and develop new battery chemistries with readily available materials. For example, lithium-ion batteries such as Lithium Iron Phosphate (LFP) batteries and 3-1-1 Nickel Manganese Cobalt (NMC) batteries, reduce and eliminate the use of critical materials, such as cobalt, in batteries, while increasing energy densities, storage, and range. At the same time, battery manufacturers, research institutions, and university laboratories are developing and piloting new chemistries with readily available materials, such as Sodium-Ion batteries, Lithium-Sulphur batteries, Metal-Air batteries, molten metal batteries and flow batteries, for different applications in both mobility and pure stationary storage. These new chemistries are likely to be introduced commercially around the year 2025 and are expected to play a significant role in the large-scale development of energy storage solutions with cheap and readily available materials. The selection of the battery technology and particular chemistry will depend on the application and local requirements of the electrical systems.

3. Ini, "Large-Scale Solar LCOE Fell 3% to \$0.049/Kwh in 2022, Says Irena."

4. BloombergNEF, "Top 10 Energy Storage Trends in 2023."

1.2 Solutions

A holistic and comprehensive approach and a conducive ecosystem for storage implementation and integration in the energy system are required. The following key steps should be taken by government departments, regulators, system planners and operators, and project developers to incentivize storage integration and system optimization to increase project bankability:

- **Government guarantee and support:** Strong involvement from governments and government agencies to provide financial support for initial demonstration projects to incentivize private sector participation, as well as to ensure long-term offtake through government guarantees.
- **Streamline grid connection for battery storage:** Easy and streamlined process to obtain approval for grid connection projects when adding batteries to an existing wind or solar farms.⁵ Shortened construction time will increase the economic value of both the wind and solar farms and battery storage facilities.
- **Reform ancillary service:** Enable battery storage as a Fast Frequency Response capability to assist with frequency control and system security support by rapidly responding to emergency imbalance events.
- **Improve regulatory ecosystem:** Include storage batteries in medium- and long-term plans for system expansion; define clear regulations for the ownership and operating models of storage to enable a wide range of revenue streams; develop accounting, billing, and metering methods for battery storage systems; and recognize battery storage as demand side response resources for system reliability and stability.
- **Achieve technical efficiency:** Smart management software to optimize and co-manage wind/solar plus storage facilities to maximize the economic

value and smart battery management software to protect the battery and act as a site controller to implement the charging and discharging algorithms.

- Increase revenue streams:
- Allow battery value to be recognized as generation capacity, for example, to be reflected in solar PV feed-in-tariffs or to receive capacity payment.
- Increase economic value in providing frequency and regulation control, for example, in ancillary services, black start services, and flexible ramping.
- Recognize the economic value of battery storage and demand side response through avoided costs from the deferred investments in grid reinforcement and peak generation investment.
- Market-based settlement regime reform to adopt a five-minute market settlement approach that increases the value of fast acting services, such as battery storage and demand side response.
- Incentivize long-term offtake contracts, including long-term PPAs, contracts for difference, or guarantees from governments and utilities for a clearly defined revenue stream over the amortization period of projects.

1.3 Successful Replicable Experiences

Although there are diverse storage technologies for fast response and/or long duration storage in successful operation, this section focuses on examples of pioneering projects that offer different grid services with lithium battery technology:

- **Dalrymple ESCRI-SA battery project:** A 30 MW/8 MWh battery in Yorke Peninsula, South Australia. It is grid-connected but during an outage, it

5. Clean Energy Council, "CHARGING FORWARD."

can operate with the 90 MW Wattle Point Wind Farm and rooftop solar PV in islanded mode.⁶ Its revenue streams include lowering the marginal loss factor at the Wattle Point Wind Farm, revenue from expected unserved energy, frequency control ancillary services, and market trading opportunities. Under contingency conditions, the Dalrymple substation and downstream load can operate in islanded mode, with the battery storage expected to cover the islanded load with 100% renewable energy.

- **Limay BESS in Bataan, the Philippines:** A 60 MW capacity packaged BESS solution purposely designed and installed to strengthen the reliability and stability of the grid, and to support the integration of renewable energy on the main island of Luzon. This facility helps to avoid large frequency and voltage deviations that can result in costly equipment damage and disruptive power system failure. Operating within the Philippine Wholesale Electricity Spot Market it allows operators to optimize the electricity system by leveraging peak shaving and load-lifting to reduce overall system costs, and therefore benefit its citizens with lower cost of electricity.
- **Hornsedale Power Reserve:** The world's first big battery storage in the world balances and supports over 65% of wind and solar capacity in the generation mix in the state of South Australia. The 150 MW battery reserve includes Tesla's Virtual Machine Mode, enabling the battery to provide inertia support services to the electricity grid, as well as regulation control ancillary services, frequency control ancillary services, and energy arbitrage. It has saved South Australian consumers over \$150 million since 2017.
- **Virtual Reservoir:** The world's pioneering Virtual Reservoir merges a lithium-ion battery bank with a run-of-the-river hydroelectric facility. Implemented at Chile's 178 MW Alfafal I plant,

this innovation captures surplus energy during low-demand periods, storing it for release during peak demand, delivering 5 hours of power. With a 10 MW capacity, Virtual Reservoir matches the energy supply of 4,000 homes. Noteworthy for optimizing hydroelectric output and bolstering generating capacity, it also offers flexibility, enabling ancillary services like frequency regulation and voltage control.

- **Kiamal Solar Farm:** A 256 MW solar PV project located in Victoria, Australia. The 190 MVAR Kiamal Synchronous Condenser, the largest synchronous condenser installed in Australia, contributes system strength into the NW Victorian grid to help maintain network stability. It is co-located with Stage 1 of Kiamal Solar Farm and connected into TransGrid's Kiamal Terminal Station. However, the bankability of this project increased when it was combined with a 100 MW/380 MWh battery storage system, which allowed the project to provide dispatchable power to the grid.
- **Crimson Storage in California:** A 350 MW/1400 MWh battery storage project, by far the second-largest energy storage project in the world.⁷ A solar farm will be constructed later to deliver power to around 87,500 homes through the Southern California Edison Colorado River Substation. Crimson Storage holds two long-term contracts with local utilities: a 200 MW/800 MWh 14-year and 10-month contract with Southern California Edison and a 150 MW/ 600MWh 15-year contract with Pacific Gas and Electric.
- **Moss Landing Battery Storage Project in California:** At 400 MW/1,600 MWh capacity, it is currently the world's biggest battery storage facility.⁸ Vistra Energy, an integrated retail electricity and power generation company based in Texas, USA, developed the project in two phases under two separate resource adequacy agreements with

6. ElectraNet, "Dalrymple ESCRI-SA Battery Project."

7. Lewis, "The World's Largest Single-Phase Battery Is Now up and Running."

8. NS Energy, "Moss Landing Battery Storage Project, California, US."

the Pacific Gas and Electric Company. Vistra secured a \$1.3 billion construction loan from a group of lenders including JPMorgan Chase, Bank of America, and MUFG Union Bank. In addition, the project is partially funded through the California Public Utilities Commission's Resource Adequacy Program, which pays energy storage facilities to maintain a certain level of capacity on the grid.

2. PROACTIVE SPATIAL PLANNING FOR RE INFRASTRUCTURE (RESOURCE CO-LOCATION AND OPTIMIZATION)

2.1 Challenges

Efficient energy system decarbonization requires better utilization of local and regional resources from both the supply and demand sides, as well as collaborative planning and management approaches at the regional level supported by policy makers, system planners, project developers, and local communities. Such cooperation plays a critical role in addressing the following key challenges.

- **High costs of grid connection:** The best and most resource-efficient renewable energy sites are often situated in remote areas, far from the existing grid infrastructure. This has limited the development of these renewable energy sites to achieve energy decarbonization goals, due to the high costs of establishing new grid connections.
- **Co-development challenge:** Due to generally different geographic and temporal weather patterns, achieving overall local efficiency of renewable energy resources often requires that different technologies are co-located and optimized across the planning, development, and operational phases. These local projects often have different development and technological requirements, and diverse ownership schemes, which create complications in coordination for better development, asset utilization, and management to achieve greater efficiency.
- **Incoherent and insufficient co-optimization policy support:** Governments often are relied upon to provide guidance and policy and planning tools for the development of local/regional zones in order to help achieve more efficient and optimal outcomes for developers and financiers with different expertise and objectives. However, hybrid generation policy frameworks and regulations are still lacking in many countries, causing delays in their development and implementation. Long permitting processes and inadequate planning and management frameworks for co-location and co-optimization can deter the development of high renewable energy resource sites for onshore and offshore wind and solar farms.
- **Lack of local/regional energy system planning capacity:** Local/regional energy system planning has yet to be sufficiently incorporated into local urban or regional planning efforts to better align development and economic objectives across different scales. This means that centralized system planners tend to not be sufficiently informed of local objectives and are thus unable to coordinate a collaborative decision-making process for improved local outcomes. For example, in some jurisdictions, the rapid uptake of distributed generation at the household level has triggered the curtailment of their outputs due to network constraints, which could be avoided via the alignment of local and regional planning.

2.2 Solutions

The following approaches can be considered for better local optimization to increase RE bankability based on local contexts and conditions:

- **Co-location of wind-solar-storage technologies, hydro-floating solar, or other hybrid technologies, including nuclear, geothermal, etc:** There are production and cost efficiencies that can be achieved in sharing sites, grid connection, and HV transmission lines. For example, in many locations, merging wind and solar power technologies increases generators' capacity

factor and decreases their intermittency at the connection point. Adding storages will further increase the dispatchable power generation capacity and the value of the bundled projects. For example, a study found that wind and solar potentials for Europe are anti-correlated at seasonal and monthly timescales.⁹ Through co-location, renewable power generation would be available more than 70 per cent of the time in southern Europe, and more than 50 per cent of the time in the intermediate latitudes of Europe.

- **Co-location of generation and load centers:** This approach is best demonstrated, for example, by renewable energy powered mining sites and green hydrogen production sites. The co-location of generation and load centers will reduce or eliminate the costs for major grid extension projects and minimize the transmission costs and losses. These sites can be either on-grid or off-grid depending on the situation. Many municipalities considering net zero emissions are also utilizing distributed energy technologies to better satisfy local demand through local generation. Local supply tends to be more resilient, especially when there is major disruption in the main system.
- **Special renewable energy zones:** These zones support the green economy and demand expansion.¹⁰ Renewable energy zones can be used as a planning tool to make sure new renewables can be coordinated together with transmission and demand, while combining generation, transmission, and storage to achieve better economic efficiency. Coordinated action and government leadership are needed to help achieve more efficient and optimal outcomes for developers, industry, and communities. They also provide opportunities for thousands of clean jobs to be

created, mostly in regional areas, whilst reducing a country's reliance on fossil fuels to fight climate change.

2.3 Successful Replicable Experiences

- **Zhangbei National Energy Storage and Transmission Demonstration Project:** This project provides frequency regulation, ramping, renewables capacity firming, and renewable energy time shift.¹¹ The project includes 100 MW of wind generation, 40 MW of solar PV, and 20-36 MW of battery storage. The project reported to have significantly smoothed and balanced power production, although the use of large-scale power storage may well have contributed to this claim rather than the complementary nature of the solar and wind resources.
- **Da Mi hydro-floating Solar Hybrid Project:** A 47.5 MW floating solar project, generating 70,000 MWh of electricity.¹² The project cost \$66.44 million, consisting of 143,940 modules, each with 330 W nameplate capacity spreading over an area of 50 hectares. Potential benefits of coupling floating PV with hydropower include reduced transmission costs by linking to a common substation and balanced generation from the two technologies—solar power with better potential during dry seasons, hydropower with better opportunity during rainy seasons. Pumped hydropower storage can also be developed to store excess solar generation.¹³
- **Renewable energy industrial precincts:** Some Australian governments and regulators developed precincts where renewables could be co-located with industrial development, with the aim of streamlining approvals, maximizing the use of the electricity infrastructure, facilitat-

9. Bossonot and Schlosser, "Characterization of the Solar Power Resource in Europe and Assessing Benefits of Co-Location with Wind Power Installations."

10. Christiansen and Lam, "CO-LOCATION INVESTIGATION."

11. Power Technology, "Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project I - Bess, China."

12. Larkin, "ADB, DHD Deal to Provide First Large-Scale Floating Solar PV in Viet Nam."

13. Macknick, et al., "The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study."

ing innovation, as well as improving community consultation and regional employment opportunities.¹⁴ These precincts help the country's manufacturing industry capitalize on the growing global demand for low-emissions products. They are attractive locations for energy-intensive businesses, such as aluminum smelting, steel and other metals processing, hydrogen production, chemical production including pharmaceutical supply chains, recycling, advanced manufacturing, and data centers.

- **Agrivoltaics:** Although it is not the optimization of two renewable technologies, the innovative practice of combining agriculture with solar energy production, called agrivoltaics, provides a double benefit by maximizing land-use efficiency.¹⁵ This approach not only generates clean solar power, but also enhances agricultural productivity through optimized land utilization, reduced water evaporation, and improved crop yields. By integrating solar panels into farming landscapes, agrivoltaics present a sustainable solution to bolstering power networks, while promoting ecological harmony and food security.¹⁶
- **Solar Hybrid Project in the mining sector in Egypt:** The project consists of a 36 MW solar farm and a 7.5 MW battery storage system.¹⁷ Both subsystems were integrated into the gold mine's existing diesel power plant during ongoing mine operations. JUWI Hybrid IQ micro-grid technology enables the integration of the solar and battery system into the existing off-grid network and supports the operation of the existing power station.

3. REGIONAL GRID INTERCONNECTION

3.1 Challenge

Regional power system integration is a process that requires work across a range of technical, economic, policy, and social issues. In different countries, power systems may have evolved separately, with different standards, technologies, and even divergent institutional and administrative features. Despite the challenges in interlinking national power grids, the technical and economic benefits are becoming more explicit under the necessary global transition to low-carbon power systems.

Regional grid interconnection involves connecting electric power grids of different regions or countries to allow for the exchange of power among them. This has many benefits such as improving system reliability, improving overall efficiency, and increasing renewable energy utilization. However, it also presents several challenges:

- **Financial:** Significant investments are required to establish regional grid interconnections. This can involve financing new or upgrading existing infrastructure. Harmonizing regulations and market design is needed for efficient operation of regional interconnected grids.
- **Technical:** Interconnecting grids with different frequencies or transmission voltages can be technically challenging. The design of the interconnection system and the associated infrastructure requires careful planning and coordination to ensure efficient and reliable operations.
- **Operational:** Effective operation of the interconnected regional grid requires ongoing coordination and communication among various stakeholders, such as system operators, regulators,

14. BZE, "Ambitious Research to Drive Australia's Economy Forward."

15. Colorado Agrivoltaic Learning Center, "Agrivoltaics 101: Colorado Agrivoltaic Learning Center: United States."

16. NREL, "News Release: Untapped Potential Exists for Blending Hydropower, Floating PV."

17. Renewable Energy Industry, "Lighthouse Project: Juwi Commissions World's Largest Mine-Hybrid Power Plant in Egypt."

and market participants. This can be challenging in the context of different languages, cultures, and operation protocols.

- **Regulatory:** Different countries or regions may have different regulatory frameworks and market rules, making it difficult to establish a consistent approach to grid interconnection. This can create issues around transmission pricing, market design, and operational standards.
- **Political:** Political considerations can also present challenges to grid interconnection. Some countries may be hesitant to depend on power supplies from other countries due to the concern of national security risks.
- **Economical:** Some countries are exporting to neighboring countries electricity from other sources than renewables. A larger regional integration based on increased interconnection with countries that have important renewable resources could be considered a threat to their commercial balance relating to electricity trade.

3.2 Solutions

In the last 30 years, multiple shifts in the global energy landscape have created a number of drivers for increased cooperation to develop regional power grids: the rising cost competitiveness of variable renewable energy sources such as wind and solar PV, pressing need to decarbonize the energy systems, cost and efficiency improvements in long distance transmission technologies, growing number of relevant regional and intercontinental integration projects and entities, and availability and sophistication of digital technologies for smarter and more flexible power grids.

A combination of technical, economic, social, and political strategies may be implemented to advance cooperation in power systems integration (UNESCAP, 2020):

- Political-level support;

- Develop a master plan for regional power grid connectivity, including coordination of cross-border transmission planning and system operations;
- Develop and implement Intergovernmental Agreements, creating a broader institutional framework;
- Coordinate, harmonize, and institutionalize policy and regulatory framework;
- Move towards multilateral power trade and create competitive markets for cross-border electricity trade;
- Mobilize investment in cross-border grid and generation infrastructure;
- Encourage capacity-building and sharing of information, data, and best practices;
- Ensure that energy connectivity initiatives are compatible with the SDGs.

3.3 Benefits

The interconnection of power grids has many potential benefits, including:

- **Improving reliability and pooling reserves:** Sharing reserve capacity within an interconnected network can reduce the amount of capacity needed by individual networks to ensure reliable operation.
- **Reduced investment in generation:** Shared generation resources can reduce or postpone individual generation capacity build. Power interconnection can even open new markets for resource-rich countries, while providing countries with high or growing demand or limited potential the opportunity to develop renewable resources domestically, as well as access to sources of low-cost, low-carbon electricity.
- **Improving load factor and increasing load diversity:** Systems can improve poor load factors by

interconnecting to other systems with different types of loads, or loads with different daily or seasonal patterns that complement their own.

- **Economies of scale:** Sharing resources in an interconnected system can allow the construction of larger facilities with lower unit costs.
- **Diversity of generation mix and supply security:** Interconnections between systems that use different technologies and/or fuels to generate electricity provide greater security in the event that one kind of generation becomes limited.
- **Economic exchange:** Interconnection allows the dispatch of the least costly generating units within the interconnected area, providing overall cost savings that can be divided among the component systems.
- **Environmental dispatch and new plant siting:** Interconnections can allow generating units with lower environmental impacts to be used more and units with higher impacts to be used less.
- **Coordination of maintenance schedules:** Interconnections permit planned outages of generating and transmission facilities for maintenance to be coordinated, so that overall cost and reliability for the interconnected network is optimized.
- **Power system flexibility increases:** Regional integration and multilateral power trading can expand balancing areas, allowing for efficient resource sharing, particularly for renewable resources, ultimately helping to increase power system flexibility and resilience.

3.4 Technology Enablers

The technologies have a pivotal role in promoting the advancement of regional interconnection, of which current attention should be paid to power transmission from high-voltage to ultra-high-voltage

(HV/UHV PT), voltage source converter (VSC), electricity submarine cable (ESC), and advanced operation, simulation, and control technologies (AOSCT). HV/UHV PT provides the essential physical infrastructure for effective long-distance and low-loss power transmission. VSC technology enhances the flexibility and efficiency of access, delivery, and distribution of variable renewable energy. ESC facilitates efficient underwater power transmission, particularly for countries situated across the sea. AOSCT significantly enhances precision control and reliability levels of power grids.

3.5 Successful Replicable Experiences

- **Central American Electrical Interconnection System (SIEPAC):** The electrical interconnection of Central American countries has been promoted for several decades as a fundamental instrument for economic development and integration in the region. Initial planning and negotiations can be dated back to 1976, however, the first operations started in around 2010. The purpose of this electrical interconnection is to use the energy resources of the Central American Isthmus (Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama) in an optimal, rational, and efficient way, and to benefit from the development and coordinated operation of an interconnected electrical system. Efforts to progress in regional electricity integration have moved forward through the design and execution of the Central American Electrical Interconnection System (SIEPAC) project, the construction of the first regional transmission system and launch of a competitive electricity market in which all Central American countries participate.¹⁸
- **Lao PDR–Thailand–Malaysia–Singapore Power Integration Project (LTMS-PIP):** Operational in 2022, the LTMS-PIP is considered a historic milestone, serving as the first multilateral cross-border electricity trade scheme involving four ASEAN countries, and providing the first renewable energy import into Singapore. It comprises the

18. Barrera, “Central American Electrical Interconnection System (SIEPAC).”

import up to 100 MW of renewable hydropower from Lao PDR to Singapore via Thailand and Malaysia using existing interconnections. Power trade in the region started at the bilateral level and is envisioned to scale up to trade within three subregions — north (ASEAN countries in the Greater Mekong Subregion), south (Malaysia and Singapore), and east (BIMP-EAGA countries).

- **The European Cross-Border Power Grid:** Covers thirty-six countries and is one of the world's largest regional power grids. It contains four sub-regional AC power grids connected by DC lines, including Continental Europe, Northern Europe, the UK & Ireland, and Baltic States. In addition, the Continental European grid is connected to the grid of North Africa via double-circuit Spain-Morocco submarine lines.¹⁹ Regional power grids allow surplus renewable energy from northern and southern Europe to replace coal power in the west and east. Transnational transmission capacity can be utilized during peak demand periods to improve flexibility, reducing the need for traditional power construction. It also supports the consumption of renewable energy resources in conjunction with carbon markets.
- **Trans-Borneo Power Grid Sarawak–West Kalimantan Interconnection Project:** Starting operations in 2016, this is a 275-kilovolt grid-to-grid transmission line between Sarawak in Malaysia and West Kalimantan in Indonesia on the island of Borneo. The next challenges will be adding submarine cables from Singapore to Sumatra, Kalimantan, Malaysia, Sabah, Sarawak, and Brunei to the Philippines.
- **Sustainable Electricity Trade (SET) Roadmap:** Recognizing the numerous benefits of regional electricity market integration, France, Germany, Morocco, Portugal, and Spain are designing the rules and conditions for the integration of electricity markets based on renewable energy. The SET consortium includes Artelys, Castalia,

Ernst and Young, and Fraunhofer ISI. The first market that has been integrated is the Green Cross-Border Corporate PPA. The integration of other markets, such as the wholesale market or the primary reserve, are being studied. The main challenges that are slowing down markets' integration in the frame of the SET Roadmap are: countries' hesitation to extend interconnection with neighboring countries and countries' hesitation to fully open their market to competition from other countries in order to protect monopolies.

4. MANAGING VARIABLE RENEWABLE ENERGY: FORECASTING

4.1 Challenge

Managing VRE in power networks can be challenging because the output of sources, such as wind and solar power, can fluctuate rapidly and unpredictably due to changes in weather conditions. This can make it difficult to ensure a stable and reliable power supply, as well as to balance supply and demand on the grid, especially at high VRE penetration levels.

4.2 Solutions

Advanced forecasting is one of the most cost-effective solutions to improve the integration of solar and wind energy into power networks because it allows utilities and grid operators to predict the amount of renewable energy that will be generated over different time horizons, which in turn enables them to balance supply and demand more effectively on the grid. With accurate forecasting, utilities and grid operators can anticipate when renewable energy generation will be high or low and adjust their operations accordingly. For example, if a forecast predicts that solar generation will be high during the middle of the day, the utility or grid operator can schedule maintenance on conventional power plants during that time or

19. Ladislav and Naimoli, "Transforming the U.S. and EU Electric Power Sectors."

increase imports of power from neighboring grids. Similarly, if a forecast predicts that wind generation will be low overnight, the utility or grid operator can schedule power generation from other sources to make up for the shortfall. Recent use of artificial intelligence (AI), cloud computing, big data, and machine learning in forecasting has contributed to more accurate predictions, better decision making, increased grid stability and reliability, and cost savings.

4.3 Benefits

Improved forecasting of renewable energy in power networks can provide several benefits, including:

- **Increased grid stability and reliability:** With accurate forecasting, utilities and grid operators can anticipate changes in renewable energy generation and take steps to maintain a stable and reliable power supply.
- **Reduced costs:** Improved forecasting can help utilities and grid operators reduce the need for expensive fossil fuel-based power generation, and to optimize the use of energy storage systems, which can help to lower overall costs.
- **Improved energy market efficiency:** Accurate forecasting can enable utilities and grid operators to better predict supply and demand on the grid, which can lead to more efficient energy market operations.
- **Increased integration of renewable energy:** Improved forecasting can help utilities and grid operators integrate renewable energy more effectively into the power network, which can help to increase the overall penetration of renewable energy sources in the grid.
- **Better management of transmission systems:** Accurate forecasting can help utilities and grid operators predict power flows in the transmis-

sion systems, allowing them to better manage the network and avoid congestion.

- **Better use of energy storage:** With accurate forecasting utilities, grid operators can optimize the use of energy storage systems to better manage the supply and demand of electricity in the grid, reducing costs and increasing the penetration of renewables.

4.4 Successful Replicable Experiences

- **National Grid, Great Britain:** Renewables are playing an increasingly important role in the power system in Great Britain. In May 2019, the Electricity System Operator (ESO) reported the first two-week system operation period without coal-fired generation. The ESO aims to be able to operate a zero-carbon electricity system by 2025, using machine learning to build a solar forecasting system which is 33% more accurate by analyzing large amounts of historical data and identifying patterns that can help predict future energy generation.²⁰ Additionally, the ESO has been experimenting with the use of deep learning algorithms, which can learn to identify patterns in data that are not visible to the human eye to improve the accuracy of its renewable energy forecasts even further.
- **Xcel Energy, USA:** Xcel Energy is the largest clean energy provider in the United States, with 11.2 GW installed capacity of solar and wind plants in the power grid. In 2020, the utility generated about 35% of its electricity from renewable sources, primarily wind and solar, and has committed to sourcing 100% carbon-free energy by 2050. The utility worked with several research labs to improve their wind forecasting system specific to each wind farm site, based on measured wind speeds at wind turbine hub heights and updates of 15 minutes for a period of 7 days.²¹ The improved operation of their wind farms using the new system that represented a

20. ESO, "ESO and the Alan Turing Institute Use Machine Learning to Help Balance the GB Electricity Grid."

21. Baskin, "Xcel Tames Variability of Wind Power."

one-time investment of US\$3.8 million generated their customers US\$60 million in total savings in electricity bills over a period of 7 years.

- **Electricity Market Administration ADME, Uruguay:** Since 2016, Uruguay ranks second worldwide in terms of the highest share of wind energy in power systems, only behind Denmark.²² In 2020 and 2021, wind electricity accounted for 42.2% and 32.3% of the country's total electricity generation, respectively. The PRONOS project, carried out by the Uruguayan Electricity Market Administrator (ADME), worked to include wind and solar resource forecasts in the optimal operation tools of the Uruguayan National Interconnected System (SIN), which until then only considered the availability of fuel for thermal power plants and water for hydroelectric plants.²³ This new real-time model allows the estimation of solar and wind output for the next 7 days and energy prices for the next 72 hours, optimizing the use of available energy.²⁴ The incorporation of forecasts using this tool into the strategies used for programming future operations has facilitated power exports to Brazil and Argentina, which has translated into benefits estimated to be in the order of US\$20 million per year.
- **Wind Capacity Forecasting, Texas, USA:** The Electric Reliability Council of Texas (ERCOT) is responsible for managing the power grid in the state of Texas. Wind power is a significant source of energy in the ERCOT grid, with over 30 GW of installed wind capacity. Wind capacity forecasting is essential for the efficient and reliable integration of wind power into the ERCOT grid.²⁵ ERCOT performs an Intra-Hour Wind Power Forecast (IHWPF) by wind region that provides

a rolling two-hour, five-minute forecast of ERCOT-wide wind production potential. This report is posted every 5 minutes and includes system-wide and geographic regional 5-minute averaged solar power production for a rolling historical 60-minute period.²⁶

5. ACCELERATING RE DEPLOYMENT: PERMITTING

5.1 Challenge

Permitting constitutes nowadays one of the most important roadblocks to a faster energy transition. Challenges associated with lengthy and complex frameworks for project siting and development, stakeholder opposition, permitting timelines and costs, lack of standardized processes, limited permitting agency capacity, land use and access issues, and grid integration can collectively hinder the speed of the energy transition by delaying the approval and development of renewable energy projects. Addressing these challenges and streamlining the permitting process for renewable energy projects can help accelerate the transition to a more sustainable and low carbon energy future.

In 2021, the EU Commission sponsored a study on RES development barriers and on 18 January 2022, the EU Commission published a Call for Evidence and an open public consultation to gather stakeholder feedback on the permit-granting processes for renewable energy projects.²⁷ The results of this public consultation confirm that administrative processes (e.g., via bureaucratic burdens, lack of legal coherence, and lack of spatial planning), access to the grids, conflict of public goods (environmental regulation and land-

22. In 2019, Uruguay ranked third, after Denmark and Ireland, due to an especially dry season and low availability of hydropower, which is the main source of electricity for the country.

23. Cisneros, "Las Ganancias En Eficiencia Energética Del Sistema Eléctrico Uruguayo."

24. Proyecto PRONOS, "Monitor de Generación ERNC."

25. ERCOT, "Combined Wind and Solar."

26. ERCOT, "Intra-Hour Wind Power Forecast by Geographical Region."

27. Tallat-Kelpšaitė, J., Brückmann, R., Banasiak, J. et al. "Technical support for RES policy development and implementation"; European Commission, "DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL," May 2022.

use conflicts), and third-party opposition are key bottlenecks for the acceleration of renewable energy deployment.

5.2 Solutions

Improving permitting requires a multi-faceted approach and coordination between several agencies at the national, federal or state level. Some of the measures that can be implemented by governments include:

- **Streamlining regulatory frameworks:** Simplifying and streamlining regulatory frameworks associated with renewable energy projects can help reduce complexity and shorten permitting timelines. This could involve harmonizing federal, state, and local regulations; creating clear and consistent guidelines; and standardizing permitting processes across jurisdictions. It may also involve conducting comprehensive reviews of existing regulations to identify and remove unnecessary barriers to renewable energy project development, while maintaining appropriate environmental and safety protections.
- **Stakeholder engagement and collaboration:** Engaging and collaborating with stakeholders, including local communities, environmental groups, and other interest groups, early and throughout the permitting process can help address concerns and build support for renewable energy projects. This can involve proactive communication, public outreach, and meaningful engagement to understand and address stakeholders' concerns and incorporate their feedback into project design and mitigation plans.
- **Enhancing permitting agency capacity:** Increasing the capacity of permitting agencies through additional staffing, expertise, and resources can help expedite the review and approval of renew-

able energy projects. This may involve allocating adequate resources to permit review, hiring qualified personnel with relevant expertise, and providing training and support to permitting agencies to enhance their efficiency and effectiveness.

- **Standardizing or digitalizing permitting processes:** Developing standardized permitting processes and requirements for renewable energy projects at all levels can provide clarity and consistency, reduce duplication, and streamline the permitting process. This may involve developing best practices, digitalizing application templates and guidelines for permit applications, environmental assessments, and other permitting requirements, while ensuring that environmental and safety standards are maintained.
- **Improving coordination among agencies:** Coordination among different agencies involved in the permitting process, such as environmental, energy, and land management agencies, can help streamline the permitting process and reduce delays. This may involve setting up “one-stop-shops,”^{28,29} creating interagency task forces, improving communication and coordination mechanisms, and establishing clear lines of responsibility and accountability among agencies.
- **Integration of grid access and spatial planning:** Incorporating environmental analysis tools, such as Strategic Environmental Assessments (SEA), and other land restrictions early in the grid integration project development process can help identify and address potential challenges and unforeseen issues upfront. This may involve conducting grid studies, identification, and allocation of low environmentally sensitive areas for project development. Federal or local governments can then issue specific regulations to speed up processes or waive certain require-

28. In order to have an integrated approach of facilitating the permitting process, avoiding the mobilization of land that has other public interest (such as agriculture), and avoiding land speculation, it is important to have a unique public agency that purchases land and de-risks the best locations. This agency would handle all the permitting processes and lease the land to developers, which could optimize the end-cost of electricity by transferring both the land and permitting risk to the public.

29. Danish Energy Agency, “The Danish Energy Agency as a one-stop-shop authority.”

ments for renewable energy projects asking for development and grid interconnection permits in those designated areas or prioritized “renewable energy zones.” Additionally, federal, and local governments should require SEA for their National Energy and Climate Plans (NECPs). The SEA should result in an *a priori* definition of suitable areas for RES project development. Those suitable areas for RES should be included in the NECPs, ensuring the necessary means to achieve national contributions to renewable energy targets.

- **Environmental and Social Impact Assessment (ESIA):** To identify positive and negative impacts caused by project implementation from the design phase and throughout project construction, operation, and decommissioning. Best practice guidelines help project developers facilitate and streamline the accomplishment of both mandatory stages (environmental licensing, waste management permitting, and planning consent) and dialogue with stakeholders to increase engagement and reduce potential risk of opposition. An ESIA is a legal requirement in many countries, although national legislation and local requirements vary. In some circumstances, for example, this is a requirement where international funding is being sought for project development.

5.3 Successful Replicable Experiences

- **Texas, USA:** The Texas Competitive Renewable Energy Zones (CREZs) were established in 2005 by the state government to prioritize renewable deployment and transmission infrastructure in areas with high wind potential and energy demand.³⁰ By 2013, the project was operational, surpassing the initial target of 18.5 GW with over 30 GW of renewable energy capacity today. Curtailment, which refers to unused renewable energy due to grid constraints, dropped significantly from 17% in 2009 to 0.5% by 2014. The project also stimulated a solar boom in Texas, with over 100 GW of solar projects in the pipeline. The CREZ project can be considered a success as wind energy integration was achieved by moving forward regulatory processes and technical planning analyses in parallel.
- **India:** The country launched the Development of Solar Parks and Ultra-Mega Solar Power Projects scheme in 2014 to assign and de-risk available land (“solar parks”) for renewable energy development.³¹ These areas were provided permitting clearances and included transmission infrastructure, water access, road connectivity, and communication networks, facilitating rapid development and installation of solar farms. 25 solar parks with a combined capacity of over 20 GW were identified as part of this scheme. As of 2022, India has approved 40 GW capacity and commissioned 10 GW within solar parks, including the world’s largest solar farm, the 2,245 MW Bhadla facility in Rajasthan. Solar parks have become preferred locations for developers, with auction tenders within solar parks being more heavily subscribed compared to those outside of solar parks. Another project that was part of the scheme, the 750 MW Rewa solar project in the state of Madhya Pradesh, was the first project in India to reach a renewable energy tariff below grid parity (a tariff lower than the cost of electricity produced across the grid) after a successful bidding process.³² Part of this lower tariff was attributed to the public de-risking phase, as developers had lower target returns on equity and lower cost of capital, being able to decrease their bids by approximately 5% due to the previous clearance process in terms of permitting and grid connection.
- **Spain:** The Ministry for Ecological Transition and the Demographic Challenge created an online zoning tool in early 2021 to identify the best

30. Public Utility Commission of Texas, Docket NO. 33672.

31. Ministry of New and Renewable Energy | India, “Schemes.”

32. Blackridge Research, “All You Need to Know about Rewa Ultra Mega Solar Project.”

areas in Spain for solar and wind energy projects.³³ The environmental zoning tool consists of two layers of information (one for wind energy and the other for solar photovoltaic energy) that show the value of the environmental sensitivity index existing at each point on the map (five different sensitivity grades), and the environmental indicators associated with that point. The tool is not exempt from the pertinent environmental assessment procedure to which each facility must be submitted, and it provides a guiding methodological approach for knowing from the environmental conditioning factors associated with the locations of the projects in the early stages.

- **EU:** REPower EU Plan is a set of measures to rapidly end the EU's dependence on Russian fossil fuels, accelerate the clean transition, and join forces for more resilient energy systems.³⁴ It also promotes the revision of the Renewable Energy Directive and introduces the designation of “the renewable acceleration areas” (RAAs) and other ways to shorten and simplify permitting, while minimizing potential risks and negative impacts on the environment.³⁵ An RAA, as defined in the REPower EU Plan, refers to a specific location, whether on land or sea, which has been designated by a Member State as particularly suitable for the installation of plants for the production of energy from renewable sources other than biomass combustion plants. The EU Parliament amended the Draft Directive in September 2023 and the adoption by the EU Council is expected by the end of 2023.
- **USA:** SolarAPP+ is a software tool launched in 2019 through an award to the National Renewable Energy Laboratory (NREL).³⁶ Getting a permit to install residential rooftop solar panels and solar-plus-storage systems used to be a logistical burden that could take several weeks.

The free SolarAPP+ app allows instantaneous approval and can be used by cities, counties, and other jurisdictions. Today, 27 communities across the United States are using SolarAPP+ and more than 475 have expressed interest in doing so. Since launching, SolarAPP+ has issued over 10,000 permits, approved more than 60 MW of clean power, and eliminated 40,000 days of delays. SolarAPP+ projects have shorter timelines, too, with permits, installations, and inspections occurring about 13 days sooner than traditional projects (32 days versus 45).

- **Morocco:** Masen (the Moroccan Agency for Sustainable Energy) is the main public institution monitoring the development of renewable energy in Morocco. Masen is also in charge of the land allocation, performing RE potential assessments across the country and identifying the best locations for RE power plants. By law, lands are acquired or transferred to Masen who performs all the land qualification, social, and environmental studies. The lands are then leased to developers through a transparent tender process. For Morocco, this solution avoids speculation on lands and the destruction of other public interests.

33. Ministerio para la Transición Ecológica y el Reto Demográfico, “Zonificación Ambiental Para Energías Renovables: Eólica y Fotovoltaica.”

34. European Commission, “REPowerEU Plan.”

35. European Commission, “DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL,” July 2022.

36. Energy.gov, “EERE Success Story — SolarAPP+ Rips Red Tape Off Approval Process for Rooftop Solar Panels.”

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CEET SUBJECT MATTER EXPERT

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