Integrating Variable Renewable Energy in Electric Power Markets:

Best Practices from International Experience, Summary for Policymakers

Jaquelin Cochran, Lori Bird, Jenny Heeter, and Douglas J. Arent

NATIONAL RENEWABLE ENERGY LABORATORY

Joint Institute for Strategic Energy Analysis

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Abstract

Many countries—reflecting very different geographies, markets, and power systems—are successfully managing high levels of variable renewable energy on the electric grid, including that from wind and solar energy. This document summarizes policy best practices that energy ministers and other stakeholders can pursue to ensure that electricity markets and power systems can effectively coevolve with increasing penetrations of variable renewable energy. There is no one-size-fits-all approach; each country studied has crafted its own combination of policies, market designs, and system operations to achieve the system reliability and flexibility needed to successfully integrate renewables. Notwithstanding this diversity, the approaches taken by the countries studied all coalesce around five strategic areas: lead public engagement, particularly for new transmission; coordinate and integrate planning; develop rules for market evolution that enable system flexibility; expand access to diverse resources and geographic footprint of operations; and improve system operations. This study also emphatically underscores the value of countries sharing their experiences. The more diverse and robust the experience base from which a country can draw, the more likely that it will be able to implement an appropriate, optimized, and system-wide approach.

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Introduction

Economic, environmental, and security concerns associated with conventional fuel supplies have strengthened support for clean energy technologies among governments and the private sector on a global scale; yet questions persist about how to effectively integrate large amounts of variable renewable electricity generation.[1] Renewable energy (RE) accounted for nearly half the estimated 194 gigawatts of new capacity in 2010—an investment equal to $211 billion (REN21 2011). Variable renewables, in particular, have achieved significant penetration in many countries, and issues associated with grid integration are increasingly gaining attention among a broad range of stakeholders.

The depth of experience in various countries—situated in diverse geographical and market contexts—provides insights for decision makers interested in increasing the penetration of variable RE into the power sector. This study documents the diverse approaches to effective integration among six countries, and it summarizes policy best practices that energy ministers and other stakeholders can pursue now to ensure that electricity markets and power systems can effectively coevolve with increasing penetrations of variable RE.

Approach

Many countries—reflecting very different geographies, markets, and institutional structures—are already demonstrating success in managing high levels of variable RE on the grid, such as from wind and solar. The Clean Energy Ministerial,[2] which seeks to advance clean energy globally, identified the value in learning from this diverse set of experiences, so that these lessons can be applied elsewhere. The energy ministers participating in the Clean Energy Ministerial requested a review of the approaches taken, lessons that can be learned from this process, and actions that energy ministers and other stakeholders can take to create supportive markets, institutions, and power systems.

The cases selected for this study—Australia (South Australia), Denmark, Germany, Ireland, Spain, and the United States (Colorado and Texas)—all have relatively high penetrations of RE but reflect different system and market characteristics.

[1] Variable renewable energy is defined as renewable energy that cannot be stored prior to electricity generation; it includes primarily wind and solar PV but also technologies such as tidal power and run-of-river hydropower.
[2] The Clean Energy Ministerial, launched in 2010, is a high-level forum to promote policies and programs that advance clean energy technology, to share lessons learned and best practices, and to encourage the transition to a global clean energy economy

Key Findings—Actions for Ministers

Actions that ministers can take to integrate higher penetrations of variable RE:

1. Lead the advancement of the technical, institutional, human capital, and market institutions required to enable RE integration
2. Develop visionary goals and plans at national and regional levels, and empower appropriate leadership to bring the visions to fruition.
3. Lead the public engagement to communicate goals and actions needed to attain them.
4. Engage in international coordination to share best practices and strengthen technical, human and institutional capabilities to achieve higher levels of RE penetration.

Five Areas of Intervention to Accommodate High RE Penetration

Analysis of the results from the case studies conducted for this study reveals a wide range of mechanisms that can be used to accommodate high penetrations of variable RE (e.g., from new market designs to centralized planning). Nevertheless, the myriad approaches collectively suggest that governments can best enable variable RE grid integration by implementing best practices in five areas of intervention:

A. Lead public engagement, particularly for new transmission
B. Coordinate and integrate planning
C. Develop rules for market evolution that enable system flexibility
D. Expand access to diverse resources and geographic footprint of operations
E. Improve system operations.

Figure 1 illustrates, within each of these areas, when actions typically need to be implemented as a country transitions from low to high RE penetration. For each of the five areas of intervention, the following sections summarize the rationale, best practices, and challenges and actions to implementing best practices. Text boxes highlight the diversity of approaches as revealed through the case studies. Additional details on the case studies and best practices associated with these five areas can be found in Cochran et al. (2012).[3]

[3]Cochran et al. (2012) includes case studies provided by Hugo Chandler (New Resource Partners), Jenny Heeter (National Renewable Energy Laboratory), Craig Oakeshott (Sinclair Knight Merz), David Pérez Méndez-Castrillón (Spanish Ministry of Industry, Energy, and Tourism), and David Swift (Australian Energy Market Operator).

	Public Outreach	Planning	Market Rules	Expanded Access	System Operations
At LOW RE Penetrations	Involve public stakeholders in planning	Evaluate system flexibility, penetration scenarios, transmission needs, and future flexibility needs	Evaluate market design and implications for higher penetrations of RE	Assess renewable energy resources and options for encouraging geographic diversity	Build capacity of grid operator staff; review regulatory changes needed to require advanced forecasting
At MEDIUM RE Penetrations	Communicate to public why new transmission is essential	Regulatory and legislative changes needed to accommodate revised scenario planning, such as laws to support renewable energy zones (REZs)	Ensure that market design and pricing environment aligns with technical needs, such as accessing flexibility, minimizing uncertainty, and managing risk	Make necessary regulatory, market, or institutional changes	Implement grid codes to accommodate high penetrations of variable RE
At HIGH RE Penetrations		Monitor and review effectiveness of actions; revise	Ensure broad systems solutions are sought, including smart grid/demand response, storage, and complementary flexible generators		

Figure 1. Key activities in transitioning from low to high RE penetration

A. Lead Public Engagement, Particularly for New Transmission

Rationale

High penetrations of variable RE may require expanded transmission capacity—to accommodate diverse RE locations and locations far from load, to enlarge balancing areas, to reduce nodes of transmission congestion, and to fully access flexible resources (generation, storage, and demand response). Installing this transmission, however, is a challenge; stakeholders may express concerns over land use changes, environmental damage, decreased property values, or health concerns. Negotiating the balance between new transmission and public unease requires political leadership.

> **Text Box 1. Approaches to Public Engagement**
>
> **Texas**: New transmission lines designed to serve 18.5 gigawatts of new capacity at remote and varied wind sites were key to integration. Line construction, often resisted, was successful due to extensive and varied opportunities for public feedback.
>
> **Germany**, to facilitate new transmission, uses legislation that 1) gives priority to extra-high voltage transmission projects that reduce north/south congestion and 2) shortens planning and permission process by consolidating responsibilities at the federal level.
>
> **Denmark**, to address public concerns about aesthetics, plans to bury its entire high-voltage grid by 2030.
>
> **California**'s Renewable Energy Transmission Initiative has the objective to facilitate siting and permitting for RE generation and transmission projects. A diverse, credible 30-person steering committee is committed to engaging and incorporating feedback from diverse stakeholders, work in good faith to achieve consensus on key issues, and publicly support outcomes.

Best Practices

1. Involve from the outset of planning public stakeholders that reflect many perspectives; engage them throughout the process
2. Use a transparent process for developing routing options[4]
3. Explain the objectives for grid expansion, especially as it relates to public concerns (e.g., reliability, electricity prices, RE goals, employment)
4. Clearly describe the types and distribution of costs and benefits, as well as costs of inaction or suboptimal actions (REALISEGRID 2011)
5. Create a publically approved, transparent process for evaluating property values and compensation
6. Create a regulatory approach that is accessible to the public and minimizes burdens on applicants
7. Require support from national political bodies for international projects to proceed; authorization for such projects could follow a simplified process, possibly at only the national level (REALISEGRID 2011).

Challenges to Implementing Best Practices

Integrating the meeting-intensive stakeholder process that drives decisions at the local level with a streamlined and expedited process for approving large transmission projects—especially international projects—represents a challenge.

Actions to Improve Public Support

1. Lead public engagement and communicate with the public about why new transmission is essential.
2. Encourage the adoption of approaches that can facilitate new transmission builds

[4] Tools such as Structured Public Involvement offer a process for quantifying community values (Jewell et al. 2009).

B. Coordinate and Integrate Planning

Rationale

Planning is a critical element of all power systems, but this is especially the case with variable RE, which requires a flexible system—one that can respond to expected and unexpected changes in demand and supply. Coordinated and integrated planning helps decision makers anticipate how variable RE might impact the grid and its operations, and what options would optimize costs across a system. Planning that is segregated by type (generation, transmission, and system performance) or geography adversely impacts the ability to employ best practices to accommodate RE, including diversifying RE locations, enlarging balancing authorities, and increasing system flexibility. Plans for ensuring physical capacity are also often considered independent of alternative institutional or market structures. These alternatives, however, could significantly increase access to existing and planned capacity, and they could lower the overall costs of accommodating variable RE.

Best Practices

1. Clarify planning objectives (e.g., cost minimization for entire system vs. discrete areas)
2. Assess ability for variable RE to contribute to system reliability and adequacy (NERC 2009)
3. Ensure institutions and markets are designed to enable access to physical capacity
4. Build from local and regional planning to better integrate information across jurisdictions

> **Text Box 2. Approaches to Planning**
>
> **Australia** uses market-based cost differentials to guide generation and transmission development, and draws from a national, rather than regional, examination of network development. The Australian Energy Market Operator develops a National Transmission Network Development Plan to inform developers of the most economically efficient locations, but there are no requirements to build here. To guide investments, complex spot market pricing provide further signals on economic efficiency. Pricing includes location-specific multiplier on regional price to reflect losses; connection costs; and congestion-based pricing.
>
> **Texas**: Centralized planning has guided decisions. Competitive Renewable Energy Zones allow generation and transmission to be developed in coordination. Ratepayers, not developers, absorb financial risk.

Challenges to Implementing Best Practices

- Coordinating multiple jurisdictions, especially when planning objectives and impacts of integration differ across a region
- Ensuring that each institution has the capacity to communicate with and integrate planning materials from multiple jurisdictions
- Reconciling the planning for a specific generation target while also planning for transmission that reflects a range of possible outcomes

Actions to Improve Planning Coordination

1. Share best practices and guidelines for adapting advancing planning capabilities to accommodate high penetrations of variable RE
   - Enhance capacity of institutions to increase integration, complexity, and coordination of—and stakeholder participation in—planning
2. Convey to all stakeholders the need to review existing rules and methods for planning, design, and operation to accommodate higher penetrations of variable RE, including:
   - Utilities, regional transmission organizations, and others: develop tools that enable system planning to incorporate requirements for flexibility and present recommendations
   - Regulatory commissions: Use rewards and punishments (e.g., rate recovery, rules) for coordination

C. Develop Rules for Market Evolution that Enable System Flexibility

Rationale

Markets help minimize power system costs, and for systems using variable RE in particular, they can facilitate access to a range of options that increase system flexibility. Higher penetrations of variable RE require increased flexibility from the power system to manage the variability and uncertainty of the generation. Flexibility can be achieved through changes in market operations, increased transmission, or the addition of flexible resources to the system, such as more flexible generating units, storage, and demand response. While flexibility is of high value to the system and can reduce the need for new capacity, it may come at a cost to power suppliers. Increased ramping of units that are not adequately designed for cycling can result in maintenance issues or reduce the lifetime of units. Also, conventional generators may experience profit margins that are insufficient to maintain their long-term financial viability if variable generators depress wholesale market prices and generators are only compensated for energy production. Therefore, market rules and operations may need to be modified over time to achieve operational efficiency in systems with increasing penetrations of variable RE.

> **Text Box 3. Approaches to Markets and System Flexibility**
>
> **Denmark**
>
> - A large power pool provides greater flexibility, (e.g., Norway's hydropower is critical to accommodating high wind penetrations).
> - A regulating power market operates up to 15 minutes before delivery.
> - Negative pricing provides an economically efficient way to reduce output during excess generation.
> - Combined heat and power is required to participate in the spot power market.
>
> **Australia**: Sub-hourly (5 min.) dispatch intervals reduce the need for ramping and improve forecast accuracy. Nodal and negative pricing encourage market efficient location strategies.
>
> **Germany** has implemented mechanisms to encourage energy storage. There is a €200 million ($261 million) budget for storage research and development up to 2014, and new storage facilities are exempt from grid charges and the levy required by the German renewable energy act in 2000.
>
> **Texas**: Demand response for frequency regulation has been important for a small, isolated system like Texas. Participating load moves up and down automatically to maintain frequency at 60 HZ; participates in non-standard reserves by being able to ramp load in 30 minutes; and is able to respond within 10 minutes to provide "spinning" (responsive) reserves. In February 2008, when anticipated wind and traditional generation fell short, and demand ramped up more quickly than anticipated; 1,108 megawatts (MW) of demand response were activated in 10 minutes.

Best Practices

Use markets to support the most cost-effective solution to increasing flexibility, which could include:

1. Flexible generation
   a. Encourage sub-hourly scheduling and dispatch intervals (5- or 15-minute) and shorter gate closure periods to improve system efficiency (EWIS 2010)
   b. To increase system reliability, use capacity markets to help address concerns about declining wholesale electricity prices
   c. Use zonal or nodal pricing to help manage congestion on the system and encourage development of resources where needed
   d. Develop equitable rules for curtailment of variable generators during periods of excess renewable generation on the system (NERC 2011)
   e. Design imbalance payment rules so that they do not unduly penalize variable generators

   f. Consider hybrid market solutions to increase flexibility in areas without organized markets
   g. Require flexibility in resource planning or provide financial incentives to ensure new capacity is as flexible as possible
2. Flexible storage
   a. Ensure optimal use of storage, for example, supporting entire system rather than dedicated to a single generator (NERC 2010)
   b. Allow ancillary markets to raise the value of fast-discharge storage and thereby increase its cost-competiveness (NERC 2010, Delille et al. 2010)
   c. Consider non-electric demand, such as combined heat and power for sources of flexibility (Kiviluaoma and Meibom 2010)
3. Flexibility of load through demand response and smart grid
   a. Support short-term balancing; reduce ramping and curtailments (IPCC 2011, Kirby and Milligan 2010, Kirby 2007)
   b. Provide frequency regulation at high penetrations or in isolated grids
   c. Participate in capacity markets (Wattles 2011)
   d. Ensure adequate communication infrastructure between system operators and load (IPCC 2011)
4. Improved use of existing transmission: Consider pricing of transmission congestion in day-ahead markets to encourage efficient dispatch and use of transmission, as efficient siting decisions

Challenges to Implementing Best Practices

- Physical solutions to increase flexibility are straightforward; institutional, legislative, and market barriers will be the challenge
- Adjusting market rules is a time-consuming and stakeholder-intensive process. Various stakeholders have different economic interests, but it is important to develop solutions that lead to greater system efficiency overall while allowing regulatory flexibility to distribute gains equitably
- Implementing solutions for areas without organized wholesale electricity markets can be costly, and obtaining consensus among diverse stakeholders to implement partial market-based solutions may be challenging.

Actions to Use Markets to Enable System Flexibility

1. Lead development and innovation of market design options for enabling higher penetrations of variable RE generation (e.g., identify potential impacts of variable generation on electricity markets and generator compensation and identify needs)
2. Encourage market operators to adopt rules to improve system efficiency with higher penetrations of variable RE work with regulators to educate stakeholders about best practices
3. Play a leading role in negotiating a framework for integration that optimizes flexibility across regions
4. Partner with the private sector to advance development and demonstrate technologies and tools that increase flexibility (e.g., fast ramping, storage, smart demand response) all in coordination with market design innovation

D. Expand Access to Diverse Resources and Geographic Footprint of Operations

Rationale

One of the concerns about integrating variable RE is vulnerability of the power system to weather events. Integration studies have consistently found that expanding access to diverse resources reduces this vulnerability. This can be achieved in two ways: enlarging effective balancing areas and diversifying the location and types of RE generation.

By enlarging balancing areas, the relative variability and uncertainty in both the load and RE generation will be lowered, smoothing out differences among individual loads and generators. This in turn reduces the need for reserves and lowers overall integration costs. Larger balancing areas may also provide access to a greater amount of flexible generation.

Greater geographic distribution of renewable resources reduces the variability of RE because weather patterns are less correlated across large geographies, reducing the relative magnitude of output changes. Greater diversity of technologies similarly reduces the correlation among generators and thus has an effect that is similar to that of increasing geographic diversity.

Text Box 4. Approaches to Diverse Resources

Ireland has twice sought both to reduce its vulnerability to weather variability and to strengthen its power system through expanding regional integration:

- Single Electricity Market with Northern Ireland: required for all electricity >10 MW sold and bought in Ireland; no bilateral transactions permitted
- 500 MW East-west interconnector to U.K. (under construction)

The **U.S. West** lacks an organized wholesale electric market, but an energy imbalance market has been proposed to allow balancing areas to share reserves and—through this broader diversity—reduce the system-wide variability of RE.

Best Practices

1. Create larger balancing areas to help integrate higher penetrations of variable RE generation on the system (NERC 2011), for example, the Nordic system's balancing area allows flexible hydropower in Norway and elsewhere to accommodate the variability of wind in Denmark
2. Interconnect isolated, small systems with neighbors to be able to access generation sources from larger grids
3. For areas without organized markets and with small balancing areas, use hybrid market solutions to achieve balancing area cooperation and reserve sharing; these cooperative mechanisms can result in cost savings from sharing reserves without the need to create a fully organized market structure (King et al. 2011, WECC 2011)
4. Because transmission access often influences where RE generators are located, use renewable energy zone planning to help identify diverse areas of RE resources and encourage transmission planning to those resources (e.g., Texas and the western United States)
5. Provide economic incentives to encourage renewables to be sited in locations that minimize the overall system cost (i.e., the total cost transmission plus generation). Policies can encourage geographic distribution of resources, but this is only worthwhile when the increased cost of diversifying to poorer resource areas is less than the savings associated with reduced costs for transmission upgrades to better resource areas
6. Include an assessment of the location of the resource and its potential impact on the system in project bid evaluations, thereby encouraging a mix of resources on the system

Challenges to Implementing Best Practices

- There are significant institutional challenges to achieving balancing area cooperation or consolidation. Many stakeholders with different objectives and concerns about consolidation may be involved.
- Another challenge for areas with multiple balancing areas and without organized markets is shared telemetry. There is a need to determine what information is shared, what is automated, and how to address the cost.
- Diversifying locations may necessitate operating in regions that are not as cost-effective (i.e., projects in less windy areas).

Actions to Expand Access to Diverse Resources

1. Support study and evaluation of methods to increase balancing area size or balancing area cooperation, particularly for areas with small or disaggregated balancing areas
2. Convene stakeholder discussions to evaluate options and identify needs for overcoming institutional challenges in merging or increasing cooperation among balancing areas
3. Support cooperation among transmission system operators[5]
4. Lead the renewable energy zone planning process for transmission to different resource zones; this could be done to encourage diversity
5. Ensure resource assessment is state-of-the-art for all RE resources
6. Encourage utilities to consider and evaluate the location of new RE generators and encourage diversity through the bid evaluation process

[5] For example, Europe's creation of the ENTSO-E, which is creating a ten-year network development plan. The ENTSO-E has significantly increased common network planning among European transmission system operators.

E. Improve System Operations

Rationale

Beyond market and institutional changes to system operations described in earlier sections (e.g., faster scheduling, enlarged balancing areas), system operations can be improved by adopting advanced forecasting techniques and changes to grid codes.

Using advanced forecasting techniques helps reduce the amount of system flexibility needed to integrate variable RE generation. Renewable energy generation can be variable, changing with the time of day and weather patterns, and uncertain because of the inability to predict the weather with perfect accuracy. Using forecasts in grid operations can help predict the amount of wind energy available and reduce the uncertainty in the amount of generation that will be available to the system.

Revising grid codes to address issues related to variable generation (e.g., concerns about frequency control and other disruptions to network stability) both allows hardware and procurement agreements to be designed in advance to support the power system and reduces the financial burdens of retroactive requirements. Creating a model grid code can serve as a guide for each system to evaluate what changes are needed.

Best Practices

1. Advanced forecasting
    a. Integrate forecasts into fast market operations, the control room, and other standard operating practices of the system operator or market operator. Forecasts are more accurate the closer they are to real time. System operators use accurate forecasts to determine unit commitment and reserve requirements; this can minimize movements on fossil plants and the need for reserves—a cost savings (NREL 2010).
    b. Ensure RE plants continually provide updated data on power, wind speed, and turbine availability to system operators to improve the accuracy of the forecasts they use
    c. Use multiple forecasts to benefit system operations; the use of balancing area and project-level forecasts can improve accuracy and encourage better decision-making by generators (in bidding) and system operators (Holttinen et al. 2009). Having project-level and balancing area forecasts improves how transmission flows are managed on the system
    d. Continue to evaluate and improve forecasting methods to facilitate more efficient operations and help address higher penetrations of variable generation (Holttinen et al. 2009)

Text Box 5. Approaches to System Operations

Spain

- The Control Centre for Renewable Energies monitors RE installations real-time.
- Wind farms with capacities greater than10 MW and solar photovoltaic installations with capacities greater than 2 MW provide reactive power support
- Most wind farms (97.5%) have fault-ride through capability.
- New operational procedures have been proposed to maintain optimal voltage control.

Australia: Market operators use a forecasting model that integrates forecasts from a variety of sources.

Denmark: The system operator uses multiple and advanced forecasts in planning, congestion management, dispatch, and to assess the need for regulating power.

2. Grid codes
    a. Create a roadmap of system reliability requirements based on an integrated review of needs and capabilities (i.e., integrate knowledge of plants, large farms, advanced forecasting, among others)[6]
    b. Require fault ride-through capabilities (Holttinen et al. 2011, IPCC 2011)
    c. Require turbines to provide reactive power, and, in some cases, voltage and frequency control
    d. Distinguish what needs to be addressed at the project level (e.g., wind farms) from what needs to be addressed at the generator level

Challenges to Implementing Best Practices

- The use of forecasts requires operational change. Grid operators need to be aware and convinced of the benefits of integrating forecast data in daily operations.
- Optimal grid codes to accommodate variable RE require sophisticated information and communication infrastructure. Decision-making systems need to be updated, and new programs are required to develop institutional capacity.
- Although codes set in advance minimize retroactive requirements to generators, codes set when penetration is low can unnecessarily burden variable RE technologies. Striking a balance in this timing represents a challenge in providing sufficient notice of new code requirements.
- Using new codes that reflect state-of-the-art engineering-based practices may be better than building from existing codes that draw from older and out-of-date practices.
- Every system is different, which prevents a uniform recommendation and adoption of a model grid codes. System-specific analyses are still needed.
- Jurisdictions have differing standards (e.g., in the United States, NERC requires one standard, WECC might require a higher standard, and a small balancing area can be even stricter). This lack of uniformity challenges manufacturers to serve multiple areas.

Actions to Implement and Improve System Operations

1. Develop national or regional forecasting systems
    - Identify advanced forecasting methods and their benefits
    - Provide public support for research and development to improve forecasting methods and put them in the public domain
    - Support outreach on forecasting benefits and training on best practices for grid operators
    - Encourage efforts to research and continually improve forecasting techniques
    - Work with regulators to require that all generators participate in forecasting, which necessitates that generators provide frequently updated data
2. Lead development of codes and standards that meet interregional and international needs to enable greater penetration of variable RE generation
    - Support work with regulatory commissions to evaluate model grid codes, recommend changes, and implement recommendations

[6] For examples, see NERC (2009) *Accommodating High Levels of Variable Generation*, and subsequent task reports.

System-wide Approach to Areas of Intervention

Areas of intervention are distinct but interrelated; taking a system-wide approach will ensure that not only are individual interventions more effective but also that the system as a whole will be more robust. Figure 2 shows one example of how each area of intervention might relate to others.

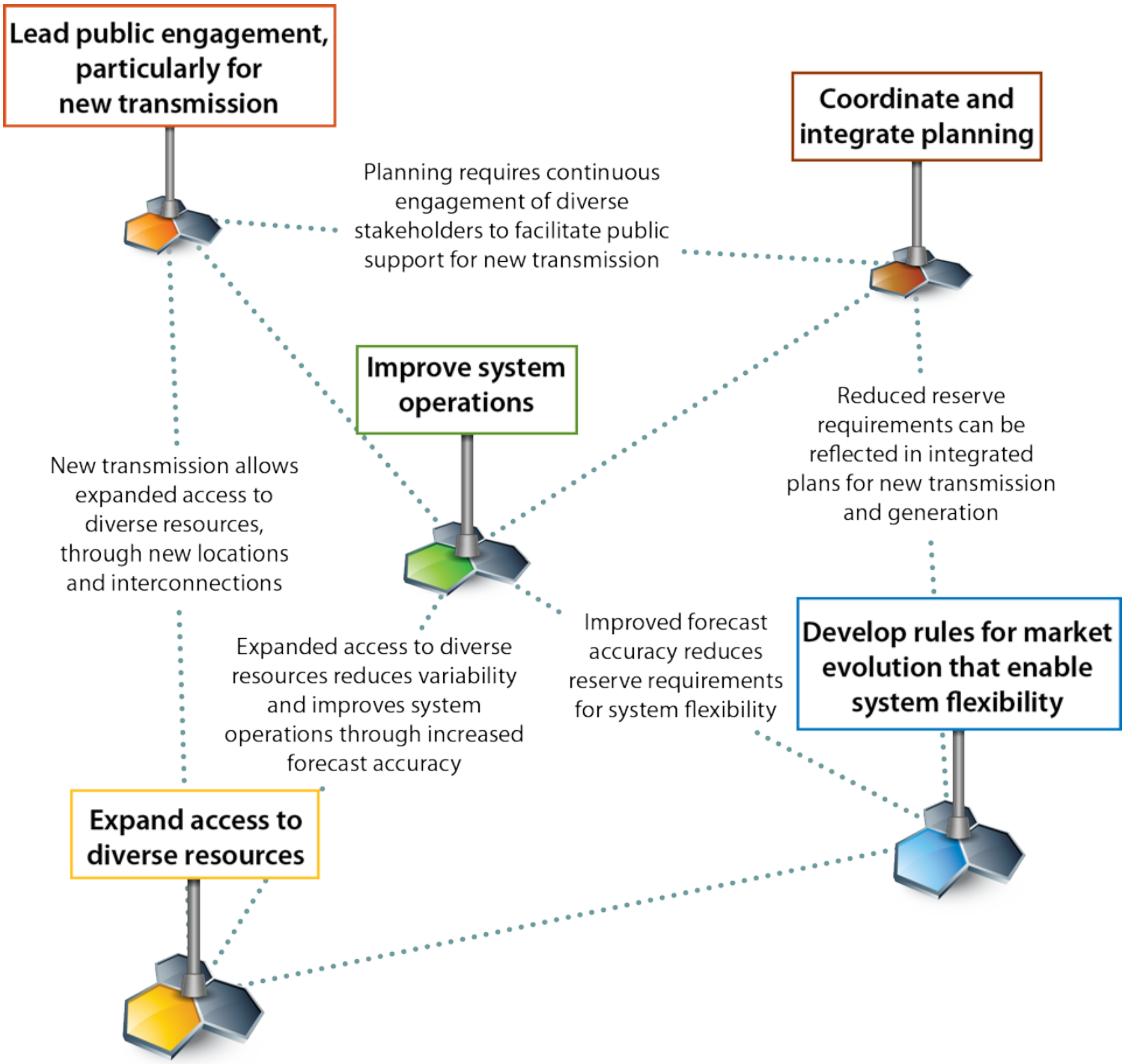

Figure 2. Example of interrelationships among areas of intervention

Costs of Integrating High Penetrations of Variable RE

Calculating the cost of integrating high penetrations of variable RE is very difficult; however, recent integration studies have demonstrated that the costs are manageable (Bird and Milligan forthcoming). Integration costs can be divided into three categories: those that relate to transmission extension and reinforcement (not including the cost of linking to the grid); those incurred in the balancing of increased volatility in the power system; and those that may be incurred to maintain the adequacy of the power system (i.e., its ability to cover peak demand). Milligan et al. (2011) note that all generation sources, including non-renewable sources, have associated integration costs.

Several studies, including the Eastern Wind Integration and Transmission Study (NREL 2011), the European Wind Integration Study (EWIS 2010), and the Greennet study (summarized in Holttinen et al. 2009) have examined integration costs. The Eastern Wind Integration and Transmission Study found that among various scenarios, the interconnection-wide costs excluding transmission costs for integrating large amount of wind were less than $5 per megawatt-hour (MWh). The European Wind Integration Study examined both costs and benefits of incorporating high penetrations of wind, finding that the costs of managing the variability of wind ranged from €2.1to €2.6 ($2.7 to $3.4) per MWh, less than 5% of the calculated wind energy benefits.

The Greennet study estimated wind power balancing costs in Denmark at 28% market share amounted to €1-€2 ($1.3-$2.6)/MWh (Holttinen et al. 2009). The estimated values are similar to real world experience in West Denmark, where costs have been €1.4-€2.6 ($1.8-$3.4)/MWh at 24% wind penetration. These real world costs actually overestimate the balancing costs because the system operator collects more revenues than are actually required to pay the balancing resources used by the system, but they are nevertheless indicative of the magnitude of these costs. The Greennet study determined that additional balancing costs in Germany, at around 10% penetration, would be around €2.5 ($3.3)/MWh (Holttinen et al. 2009).

Conclusion

The cases reviewed for this analysis illustrate considerable diversity, not only of the electricity systems—and their supporting markets, institutions, and renewable resources—but in the actions each country has taken to effectively integrate high penetrations of variable RE. The cases reveal that there is no one-size-fits-all approach; each country has crafted its own combination of policies, market designs, and system operations to achieve the system reliability and flexibility needed to successfully integrate RE. Notwithstanding this diversity, the approaches coalesce around five strategic areas of intervention:

- Engage with the public, particularly in developing new transmission
- Optimize features of the power system over a broad geographic area through system wide comprehensive planning and the use of markets
- Adopt market designs that help support system flexibility
- Expand the diversity of resources—both in type and through expanded effective balancing areas
- Improve system operations, including integration of advanced forecasting to reduce the impact of RE variability, and grid codes that ensure system reliability.

The best practices associated with these five strategic areas benefit all power systems, not just those with high penetrations of variable RE. Yet these strategies are particularly instrumental in accommodating variable renewables where they minimize the impact of RE's variability and allow more options to cost-effectively strengthen the ability of a power system to respond to change. Advancements in energy efficiency and smart grids, when conjoined with higher RE integration, further strengthen the efficacy of any power system.

The study also emphatically underscores the value of countries sharing their experiences. Any country's ability to successfully integrate variable RE depends on a wide array of factors—technical requirements, resource options, planning processes, market rules, policies and regulations, institutional and human capacity, and what is happening in neighboring countries. The more diverse and robust the experience base from which a country can draw, the more likely that it will be able to implement an appropriate, optimized, and system-wide approach. This is as true for countries in the early stages of RE integration as it is for countries that have already had significant success. Going forward, successful RE integration will thus depend upon the ability to maintain a broad ecosystem perspective, to organize and make available the wealth of experiences, and to ensure that there is always a clear path from analysis to enactment.

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