Flexibility in 21st Century Power Systems

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Introduction

Flexibility of operation—the ability of a power system to respond to change in demand and supply—is a characteristic of all power systems. Flexibility is especially prized in twenty-first century power systems, with higher levels of grid-connected variable renewable energy (primarily, wind and solar).

All power systems have some inherent level of flexibility—designed to balance supply and demand at all times. Variability and uncertainty are not new to power systems because loads change over time and in sometimes unpredictable ways, and conventional resources fail unexpectedly. Variable renewable energy supply, however, can make this balance harder to achieve. Both wind and solar generation output vary significantly over the course of hours to days, sometimes in a predictable fashion, but often imperfectly forecasted.

To illustrate how variable renewable energy can increase the need for flexibility, Figure 1 demonstrates how variable wind output impacts power system operation. The figure introduces the concept of "net load" which represents the demand that must be supplied by the conventional generation fleet if all of the renewable energy is to be utilized. The yellow area in the graph represents demand, and shows the daily variability of demand on an hourly basis for one week. The green shows wind energy, and the orange represents the demand-less-wind energy that must be supplied by the remaining generators, assuming no curtailment of wind energy. The graph shows that the output level of the remaining generators must change more quickly and be turned to a lower level with wind energy in the system. Solar energy will cause qualitatively similar impacts on the power system.

Because it can take several years to design and build new generators and transmission lines, the planning process is the first critical activity to ensure that the power system of the future possesses sufficient flexibility to accommodate the growth of variable renewable generation. In regulated paradigms, this function may resemble a central-planning model in which some combination of industry and government jointly assesses potential futures. In areas with competitive markets, there must be sufficient investment signals regarding the potential need for flexibility. In the absence of either sufficient planning or investment clarity, the resulting power system may not have sufficient flexibility to operate efficiently.

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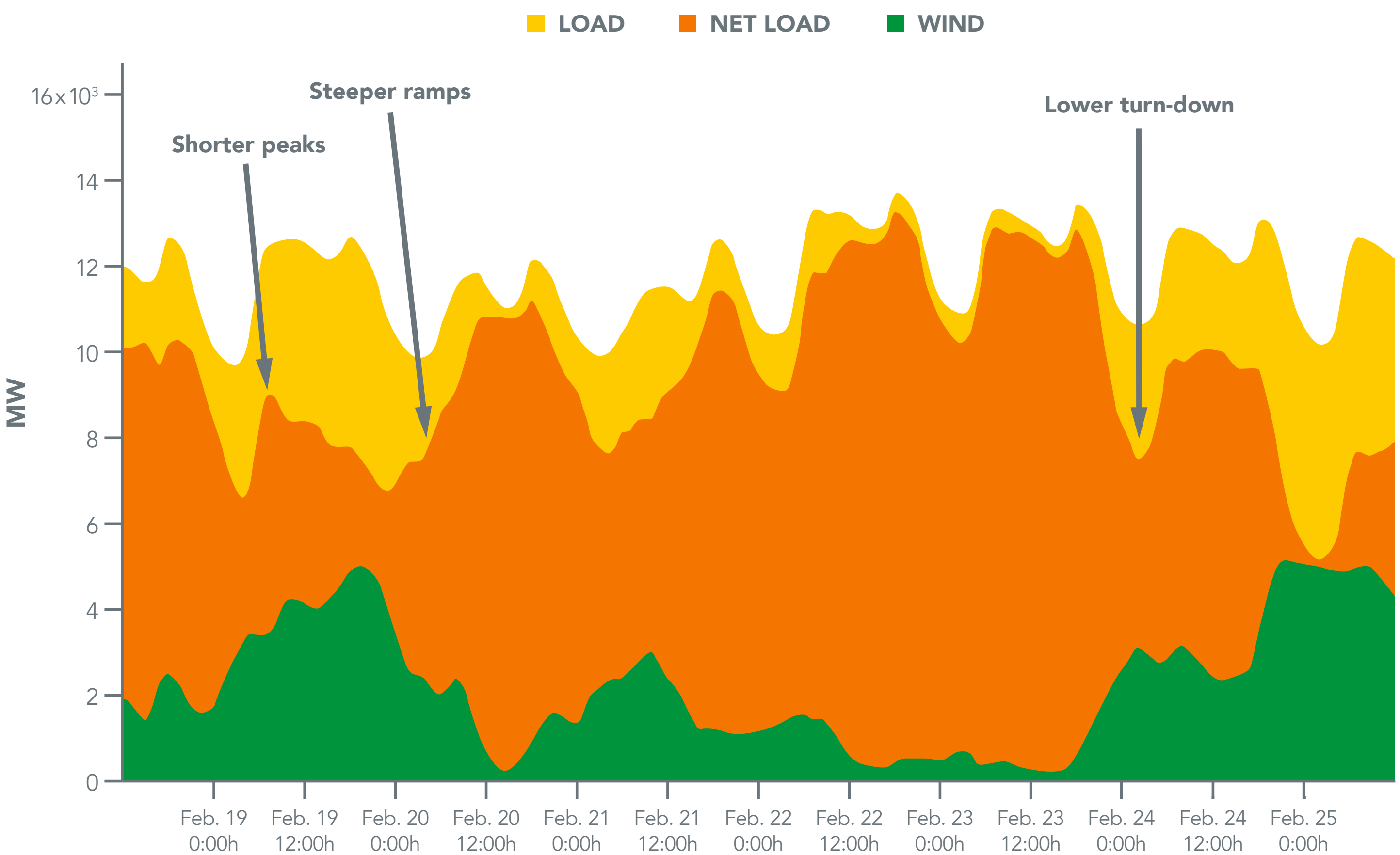

FIGURE 1: GREATER NEED FOR FLEXIBILITY

Wind and solar generation can create the need for more flexibility. The figure illustrates how wind generation can lead to steeper ramps, deeper turn downs, and shorter peaks in system operations.

Ramps - the rate of increase or decrease in dispatchable generation to follow changes in demand. Ramps can be steep if wind generation is decreasing at the same time that demand rises.

Turn-downs - operation of dispatchable generators at low levels. High wind output during periods of low demand creates a need for generators that can turn down output to low levels but remain available to rise again quickly.

Shorter peaks – periods where generation is supplied at a higher level. Peaks are shorter in duration, resulting in fewer operating hours for conventional plants, affecting cost recovery and long-term security of supply.

Source: Milligan (2011). Capacity Value of Wind Plants and Overview of U.S. Experience. www.nrel.gov/docs/fy11osti/52856.pdf.

As power systems evolve to incorporate more renewable energy and responsive demand, regulators and system operators are recognizing that flexibility across all elements of power systems must be addressed by ensuring:

- Flexible generation: power plants that can ramp up and down quickly and efficiently and run at low output levels (i.e., deep turn-downs)
- Flexible transmission: transmission networks with limited bottlenecks and sufficient capacity to access a broad range of balancing resources, including sharing between neighboring power systems, and with smart network technologies that better optimize transmission usage
- Flexible demand-side resources: incorporation of smart grids to enable demand response, storage, responsive distributed generation, and other means for customers to respond to market signals or direct load control

- Flexible system operations: practices that help extract flexibility out of the existing physical system, such as making decisions closer to real time and more frequently, improved use of wind and solar forecasting and better collaboration with neighbors.[1]

Without sufficient flexibility, system operators may need to frequently curtail (decrease the output of) wind and solar generation. Although low levels of curtailment (e.g., less than 3%) may be a cost-effective source of flexibility,[2] significant amounts of curtailment can degrade project revenues and contract values, impact investor confidence in renewable energy revenues, and make it more difficult to meet emissions targets.

The concept of flexibility often arises when policymakers ask system planners how much wind and solar generation can be reliably added to the power system.[3] The question can lead to debate about how flexible a power system is and the corresponding impacts of adding variable renewables.

Flexibility is system specific. For example, all else being equal, systems with many fuel options (e.g., natural gas, wind, demand response, and pumped storage) will be more flexible than ones dominated by coal or nuclear. Flexibility in power systems is also inherently tied to the regulatory and market rules that help shape operations.

An agreed-upon methodology to measure flexibility can help inform policy, assess needed changes to system operations, increase stakeholder acceptance of renewable energy targets, and increase investor confidence that the power system can integrate renewable energy without significant curtailments.

Investments in new flexibility come at a cost, thus careful planning is required to understand how much flexibility might be needed and of what type. Finding the optimal investment level requires consideration not only of short-term operational requirements (e.g., a plant that can deliver rapid ramping and deep turn-downs), but long-term viability to recover costs (e.g., a plant that is not too capital-intensive).

Power systems in developed and emerging economies may take very different paths to increasing flexibility. Many emerging economies have rapidly growing power systems characterized by, for example, increasing demand growth and transmission build-outs. In such cases, investment is already required, making it easier to build flexible plants to balance variable renewable generation. In more mature systems like those in many developed countries, increasing flexibility tends to involve early retirements and increased cycling (starting up, shutting down, ramping, operating at part-load) of conventional generation. In these cases, the associated costs place more of the burden on existing generators and may incentivize investment in new flexible resources.

This paper aims to help clarify debates about flexibility by summarizing the analytic frameworks that have recently emerged to measure operational flexibility, and by clarifying some of the key concerns and misperceptions of the term. We also consider the importance of flexibility, beyond operational reliability, as discussed in the following section.

1 Operating practice and market structures are often grouped into a category called "institutional factors." Having sufficient physical flexibility in the power system is a pre-requisite for efficient operation of the grid, however, institutional constraints, if present, can impede access to this flexibility.

2 For example, ERCOT (Texas, USA) assumed 2% wind curtailment in its analysis to optimize transmission expansion to support new wind generation. ERCOT (2006). Analysis of Transmission Alternatives for Competitive Renewable Energy Zones in Texas. http://www.ercot.com/news/presentations/2006/ATTCH_A_CREZ_Analysis_Report.pdf.

3 Flexibility is one element to reliability and as defined here is a subset of frequency stability; other stability impacts such as voltage stability can arise when integrating wind and solar into power grids. This paper focuses exclusively on flexibility.

Why Does Flexibility Matter?

In addition to enabling supply to match demand at all times, power system flexibility can facilitate the transformation toward 21st century power systems by improving investment climates, lowering consumer prices, and reducing emissions.

By reducing the frequency of curtailments and negative market prices (see Text Box 1), system flexibility improves the investment climate for new generation. Curtailment of variable renewable energy reduces the capacity factor and potentially the revenue stream of a plant. Likewise sustained negative wholesale prices, such as can occur in systems with generators that cannot turn down to low outputs, also reduce the attractiveness of investments in new generation—conventional or renewable. Banks assessing power projects may assume high levels of risk and therefore increase the cost of financing a project.[4] More flexible power systems decrease the risk of curtailment and negative pricing, and increase the confidence in revenue streams.

Flexibility can also reduce overall system costs and consumer prices, via more efficient power system operation. Flexibility might also improve environmental impacts of power system operations via increased optimization of demand response, more efficient use of transmission, and reduced renewable curtailments.

4 Miller, M., Bird, L., et al. (2013). *RES-E-NEXT: Next Generation of RES-E Policy Instruments*. International Energy Agency's Implementing Agreement on Renewable Energy Technology Deployment (IEA-RETD).

TEXT BOX 1: Signs of Inflexibility

Sometimes examples of inflexibility are easier to document than flexibility. Signs of inflexibility include:

- **Difficulty balancing demand and supply**, resulting in frequency excursions or dropped load.
- **Significant renewable energy curtailments**, occurring when generation is not needed routinely or for long periods (e.g., nights, seasonally), most commonly due to excess supply and transmission constraints.[1]
- **Area balance violations**, which are deviations from the schedule of the area power balance. Such deviations can indicate how frequently a system cannot meet its electricity balancing responsibility.

1 Bird, L., Cochran, J., Wang, X. (2014). "Wind and Solar Energy Curtailment: Experience and Practices in the United States." NREL Report No. TP-6A20-60983.

And in wholesale power markets:

- **Negative market prices**, which can signal several types of inflexibility, including conventional plants that cannot reduce output, load that cannot absorb excess supply, surplus of renewable energy, and limited transmission capacity to balance supply and demand across broader geographic areas. Negative prices can occur in systems without renewable energy but may be exacerbated as renewable energy penetration increases.
- **Price volatility**, swings between low and high prices, which can reflect limited transmission capacity, limited availability of ramping, fast response, and peaking supplies, and limited ability for load to reduce demand.[2]

2 Cochran, J. Miller, M., et al. (2013). Market Evolution: Wholesale Electricity Market Design for 21st Century Power Systems. NREL TP-6A20-57477.

Analytic Frameworks to Measure Flexibility

Analytic frameworks can help answer the questions, 'Does my system have enough flexibility to match generation and load at all times, including under scenarios of projected renewable energy generation growth and changes to demand profiles? How can I modify my system to improve flexibility?'

The importance of power system flexibility is generally agreed upon. This section reviews three types of frameworks, reflecting different levels of complexity. Frameworks for measuring flexibility are still evolving.

GETTING STARTED: QUICK ESTIMATES

What types of flexibility does my system have?

A simple summary of major sources of flexibility, such as capacity levels of dispatchable plants, pumped-hydro storage, demand response, and interconnection to neighboring systems, can provide a snapshot of system flexibility.

One example of this framework is the "flexibility chart" in Figure 2. The charts summarize capacities of a subset of different types of physical sources of flexibility: dispatchable plants (hydropower, combined cycle gas turbine (CCGT), combined heat and power (CHP)), pumped-hydro storage, and interconnection. Each of these can in theory contribute to a power system's ability to balance.

Using the flexibility chart, non-technical audiences (e.g., policy makers, journalists) can make quick comparisons of countries' (or specific power systems') relative strengths in flexibility, and how much wind each country currently integrates with that flexibility.

Metric to measure flexibility: Percent of GW installed capacity of generation type relative to peak demand

Simple summaries can be quick and insightful, but they have limitations. A limited number of characteristics can be measured, and the chart does not provide enough information to evaluate the overall level of flexibility. The flexibility chart restricts the comparison to capacities in order to employ common units across the variables, and excludes aspects of flexibility that cannot be reduced to capacity (e.g., market designs).

Moreover, capacity is not a proxy for flexibility. Some CCGT plants have limited ability to cycle. Combined heat and power could be operated inflexibly. Pumped-hydro storage

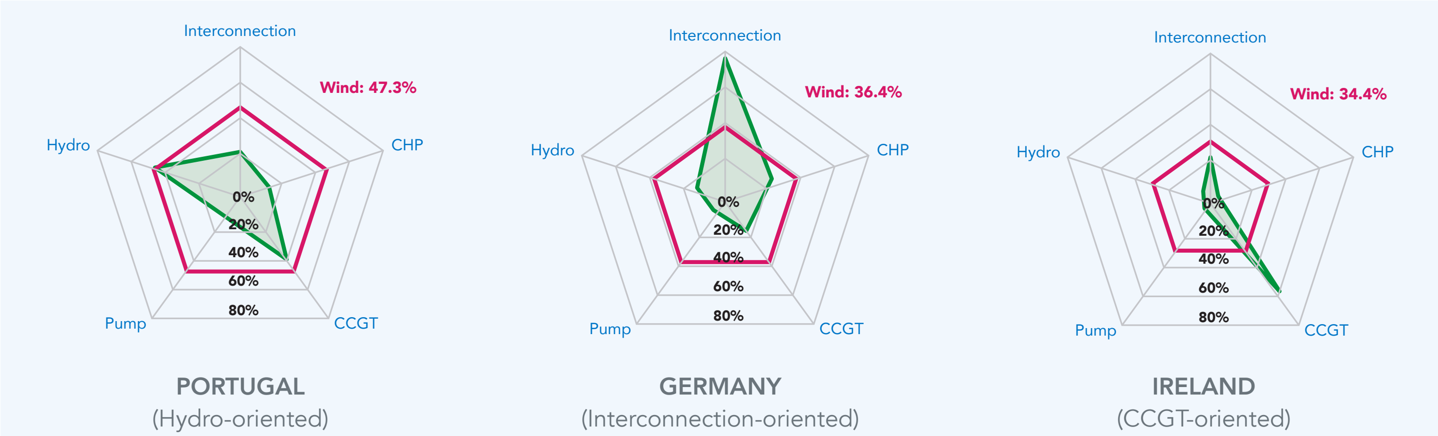

FIGURE 2. Frameworks and metrics for measuring power system flexibility are evolving. These flexibility charts, developed by Yasuda et al.,[1] provide a snapshot overview of what types of generation-based flexibility each country has, and the maximum share of wind power (red text) during one hour relative to demand. The charts show in green the percentage of installed capacity of each potential source of flexibility relative to peak demand, i.e., high installed capacity translates to a possible source of flexibility. However, since capacity does not map directly to flexibilty, the size of the green area relative to red does not have a direct meaning. Instead, the charts only highlight potential flexibility sources.

1 Yasuda, Y. 2013. "Flexibility Chart: Evaluation on Diversity of Flexibility in Various Areas." Wind Integration Workshop. London. 22 October.

may be full when it is most needed to absorb renewable energy generation. Limited natural gas fuel supply could render large capacities of CCGT inoperable. Operational practices could restrict access to existing flexibility. Interconnection is only valuable if the neighboring power system can contribute to system flexibility.

Figure 3, a second example of a visually oriented snapshot of flexibility, was created for the third phase of the Grid Integration of Variable Renewables (GIVAR III) project.[5] This figure scores power systems according to properties relevant to the grid integration of variable renewable energy.

In comparison to the flexibility charts, the GIVAR visual presents a broader range of power system properties and types of measurement. For example, dispatchability of the portfolio can include capacity *and* assumptions about fuel supply and specific analyses of cycling capabilities.[6] Likewise interconnection is scored based on both actual and potential interconnection. This added breadth and nuance comes at the cost of increased computation and lack of the common metric (percent capacity of peak demand) used in the flexibility charts. Nevertheless, neither of these visuals provide enough information to evaluate a system's overall flexibility relative to need.

The strengths of simple visualization tools are that they are easy to create, allow a comparison of flexibility across power systems, and serve as a communication tool for non-technical audiences, but they contain limited information and should be used prudently.

5 For more information on the IEA GIVAR project, visit www.iea.org/topics/renewables/givar/

6 The "offline" flexibility index is one example of a quantitative metric to analyze the cycling capabilities of the thermal fleet. Calculation of the metric is simple, using minimum turn-down levels, ramp rates and maximum plant outputs to create a single index that can be used to compare fleets. For more information, see: Ma, J., Silva, V., Belhomme, R., Kirschen, D. S., & Ochoa, L. F. (2013). Evaluating and Planning Flexibility in Sustainable Power Systems. *IEEE Transactions on Sustainable Energy*, 4(1), 200–209.

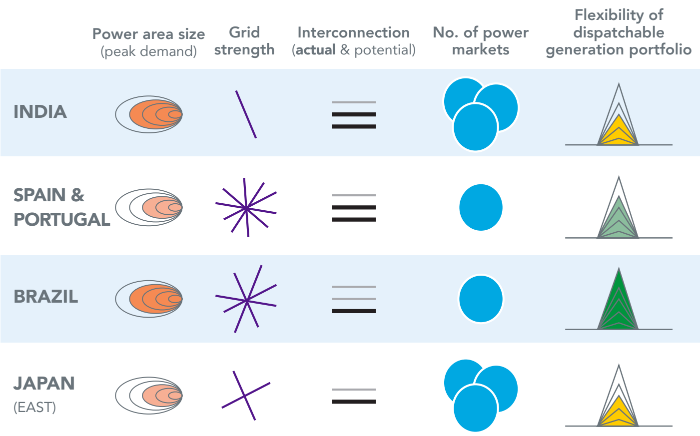

FIGURE 3. GIVAR III Flexibility Scoring Framework, in which power area size, grid strength, interconnection, number of power markets, and flexibility of dispatchable generation portfolio serve as proxies for flexibility. Recent developments in India (e.g., creating an all-India synchronous grid) have improved grid strength.

GETTING SERIOUS: FIRST-CUT ANALYSIS USING TIME-SERIES DATA

Will my power system at all hours of the year be technically able to meet demand at a given level of variability and uncertainty (assuming no renewable energy curtailment)?

In practice, power system flexibility is a time-specific quality. Much can depend on what generation is operating, the shape of the load, and seasonal and diurnal characteristics of wind, solar, and hydro resources, among other factors. Measurements of flexibility that account for time-based properties provide a more meaningful picture of what challenges the system might face and how to address them.

An example of a tool that uses time-series data is the revised Flexibility Assessment Tool (FAST2).[7] The tool assesses the technical ability of a power system to integrate increasing penetration levels of variable renewable energy. It does this by measuring the maximum magnitude of change in the supply/demand balance that a power system can meet at a given time. FAST2 matches existing physical capacities (generation, demand response, storage, and interconnection) with demand, time-synchronized with wind and solar PV generation.

Sample graphical outputs of FAST2 are shown in Figure 4. The figure shows the share of hours with insufficient flexibility relative to the share of variable renewable energy for given dispatchable generator minimum output levels, providing a snapshot of how much variable renewable energy the power system can integrate under existing physical constraints.

Metric to measure flexibility: Maximum upward or downward change in the supply/demand balance that a power system is capable of meeting over a given time horizon and a given initial operating state (i.e., operation level of different power plants). This maximum change can be constrained either by the speed at which power plants or load can react or by the minimum amount of dispatchable generation that must be operating at any point in time.

The data requirements for this tool can be significant: hourly time-scales of wind and solar resource data over at least one year are needed and may not be available for all countries, particularly for emerging economies. Additional data requirements include information on conventional generators, such as ramp rate capability and minimum load, as well as data concerning interconnection with other power systems and possible demand response capabilities. Nevertheless, with this time synchronized data, the tool can offer a more rigorous albeit complex initial assessment of power system flexibility, and has the potential to alleviate some concerns about the ability of the power system to meet renewable energy targets.

The IEA has used the FAST2 methodology to compare the system flexibility of six case study power systems.[8] The obtained results are in line with the underlying differences of the power systems with regard to the installed power plant mix, the presence of interconnection, and the

7 International Energy Agency (IEA). (2014). *The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems*. OECD, IEA, Paris.

8 International Energy Agency (IEA). (2014). *The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems*. OECD, IEA, Paris.

amount of installed storage. More general assumptions are made on demand response capabilities. While the tool can provide useful preliminary information to guide more in-depth analysis, it makes a number of simplifying assumptions. In particular, the electrical grid is assumed to be able to to accommodate all dispatch scenarios (no congestion) and the flexibility of the installed power plants is used to its technical maximum, which can be costly to achieve. A FAST2 or similar analysis can lay the ground for more analytical work and inform initial policy debate; it cannot substitute for a more detailed integration study.

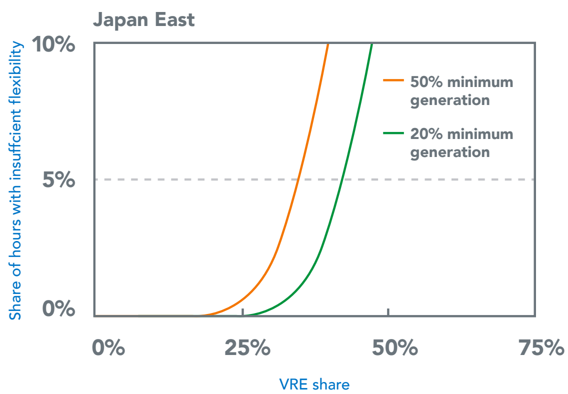

FIGURE 4. Example visual output of FAST2: Shares of hours in a year with insufficient flexibility relative to variable renewable energy (VRE) share, based on two operational assumptions about minimum conventional generation output levels—50% and 20%. The example shown is for Japan East.

GETTING VERY SERIOUS: FLEXIBILITY ASSESSMENTS IN THE CONTEXT OF DETAILED POWER SYSTEM PLANNING

How will increased variable renewable energy and dynamic loads impact the operation of my power system, how much more can I incorporate, and what changes can I make to the system, markets, and operations to improve reliability?

A third tier of evaluation is to measure flexibility in its full power system context, including:

- Physical characteristics, such as transmission constraints, balancing area size, characteristics of the renewable energy resource and generator (e.g., type, intensity, diversity, plant design, correlation with demand)
- Institutional characteristics such as
  - » System operation practices, such as forecasting accuracy, scheduling, thermal cycling
  - » Economic and market contexts, to assess incentives and costs to provide flexibility[9]
- Integration with other energy systems, such as transportation and CHP heat.

As illustrated by the breadth of system context under evaluation, the data requirements to calculate flexibility in this manner are significant. In fact, the array of data required and simulation complexity is comparable to the substantial data needs of full grid integration studies, which seek to assess the impacts of variable renewable energy on networks and the operation of generators.[10] Integration studies provide details on options to optimize operations and investments for many objectives, one of which is flexibility. Flexibility assessment would therefore be a component of these larger analyses. These assessments evaluate a future point in the system, assume what it might look like, and characterize flexibility.

Using robust, engineering-based metrics for assessing flexibility as a component of a grid integration study can help system operators make informed judgments about the economically optimal amount and mix of flexibility measures to procure. The flexibility assessments can also inform broader investment priorities for generation and transmission capacity expansion, and new methods have been developed to quantify the relationship between transmission and flexibility.[11] Figure 5 illustrates how flexibility (in orange) can be considered as part of a utility's planning process.

9 In some regions it is possible that the terms of certain power purchase agreements may constrain the physically flexibility that could otherwise help balance the system with large amounts of variable renewable energy sources. This is another example of potential institutional inflexibility.

10 For a review of the types of data needed for a grid integration study, see the *Expert Group Report on Recommended Practices: 16. Wind Integration Studies*, which was developed by members of Task 25 of the International Energy Agency Implementing Agreement for Cooperation in the Research, Development, and Deployment of Wind Energy Systems (Holttinen 2013). www.ieawind.org/index_page_postings/100313/RP%2016%20Wind%20Integration%20Studies_Approved%20091213.pdf

11 Lannoye, E., Flynn, D. and O'Malley, M.J. (2014, in press). "Transmission, Variable Generation and Power System Flexibility." IEEE Transactions on Power Systems.

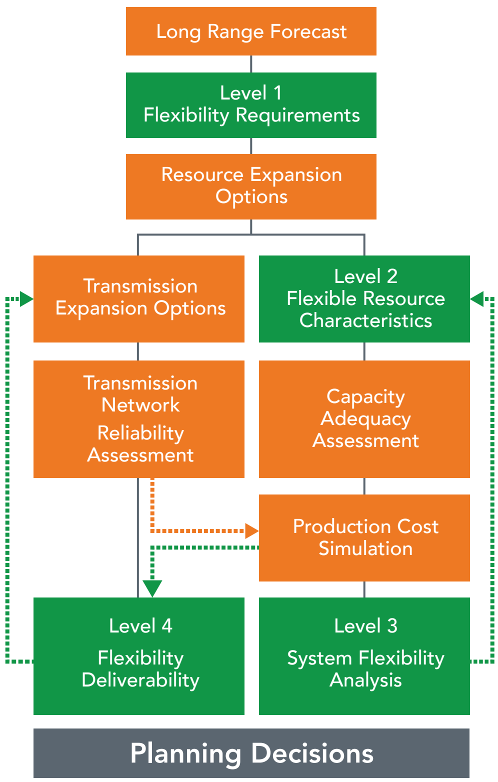

FIGURE 5. Flexibility is relevant to many aspects of the utility planning process. The traditional processes involved in power system planning, the orange boxes, are focused on ensuring sufficient generation and transmission capacity to reliably meet demand during peak conditions. The green boxes highlight how new processes can be included at the planning stage to ensure that systems can also meet and deliver the flexibility required for successful operation.[12]

Given the complexity, these techniques may be more appropriate for analyzing systems that might be flexibility challenged. Flexibility challenges could arise with higher penetration levels of renewable energy, when flexibility is likely insufficient, or with low levels of renewable energy being integrated into a portfolio of inflexible conventional generation (e.g., Japan, Alberta). Carbon emission limits and water restrictions can also limit the achievable flexibility of a power system, encouraging the use of these more complex analyses at lower levels of renewables.

Many engineering-based flexibility tools and metrics have been developed in recent years and implemented in detailed power system studies.[13,14] One example metric which might be implemented during system planning activities is Insufficient Ramping Resource Expectation (IRRE).[15] This metric complements generation adequacy studies to assess whether planned capacity allows the system to respond to short-term changes in net load. Figure 6 provides an example graphical output of IRRE. The value of IRRE is that the tool highlights time horizons of most risk, and measures the flexibility of the overall power system, not just the generation resources.

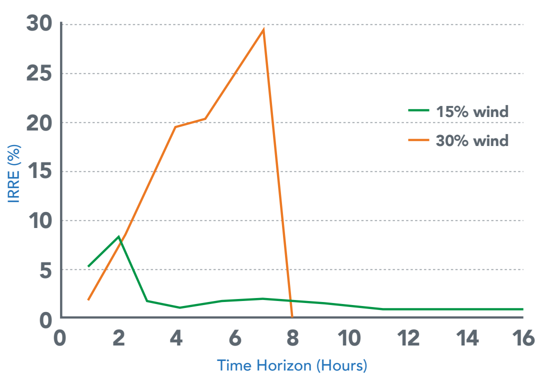

FIGURE 6. Example visual output of IRRE. The IRRE highlights the risk that a system will not be able to meet the expected upward ramping requirements as a function of wind generation over a variety of time horizons. The IRRE can be used to identify the key time horizons (e.g., 2 hours in the 15% wind penetration case and 7 hours in the 30% case) where flexibility is an issue and additional flexibility is required.[15]

Metrics to measure flexibility (example IRRE): expected percentage of incidents in a time period when a power system cannot cope with changes in net load.

12 EPRI. (2013). *Power System Flexibility Metrics: Framework, Software Tool and Case Study for Considering Power System Flexibility in Planning*. EPRI, Palo Alto, CA. 3002000331.

13 Palmintier, B. (2013). *Incorporating Operational Flexibility into Electric Generation Planning: Impacts and Methods for System Design and Policy Analysis* (PhD Dissertation). Massachusetts Institute of Technology, Cambridge, MA.

14 Bulk System Flexibility Index (BuSFI), in Capasso et. al. (2014). "Bulk Indices for Transmission Grids Flexibility Assessment in Electricity Market: A Real Application." *International Journal of Electrical Power & Energy Systems*. 56(0).

15 Lannoye, E., Flynn, D., and M. O'Malley. (2012). "Evaluation of Power System Flexibility." *IEEE Transactions on Power Systems*. 27(2).

A recent review of the modeling tools currently being used to carry out studies in California relating to system flexibility found that there are multiple methods employed to assess flexibility sufficiency there. Some methodologies focus on stochastic analyses, attempting to examine system operations over a wide range of conditions. Others do detailed simulation of one year. All of the analyses use underlying unit commitment and economic dispatch simulation, with differences in how variability and uncertainty are represented, how shortfalls are assessed, and how the requirements are considered.

TABLE 1. ANALYTIC FRAMEWORKS TO MEASURE FLEXIBILITY

Minimal | Moderate | Significant

	GETTING STARTED	GETTING SERIOUS	GETTING VERY SERIOUS
Purpose	Simplified communication tool Comparison across jurisdictions	Screening tools to evaluate need for further flexibility analysis	Flexibility-adapted resource planning
Complexity of Execution	Simple analytical framework	Required data may not exist Data curation and tool customization may be required	Requires advanced analysis techniques and data requirements
Example Data Requirements	Existing capacity of power system Capacity mix and availability of interconnect systems	Renewable resource assessments Various time series data sets Ramping capabilities of dispatchable units	Comprehensive suite of power system data Operational rules and market and policy context
Limitations on Execution	Existing capacity and interconnection data is generally available in all jurisdictions	May be infeasible if renewable resource assessments are unavailable	May be infeasible without significant data and modeling and analytical expertise
Limitations on Results	Does not evaluate whether system is sufficiently flexible May exclude aspects of flexibility that cannot be reduced to capacity Ramping capabilities of individual generators not considered	Simplified treatment of dispatchable generators Presumes fully built-out transmission	While analysis results are always qualified, this tier of tools and metrics provide the most robust of those outlined in this paper
Usefulness of Tool Relative to Generation and Load Variability	Preliminary and comparative analyses	Systems which are evaluating need for more robust flexibility assessment (e.g., generation levels of 5-15% wind or solar)	Systems which already utilize all 'no-regrets' sources of flexibility
Metric	Flexibility Charts (Figure 2) GIVAR III visual (Figure 3)	FAST2 (Figure 4)	Insufficient Ramping Resource Expectation (IRRE) (Figure 6) Bulk System Flexibility Index (BuSFI)[14]

How Can Policymakers and Regulators Help Increase Flexibility?

In transitioning from evaluating to increasing flexibility, regulators and system operators can draw from a suite of options, as illustrated in Figure 7. The types of intervention span physical (e.g., storage, transmission), operational

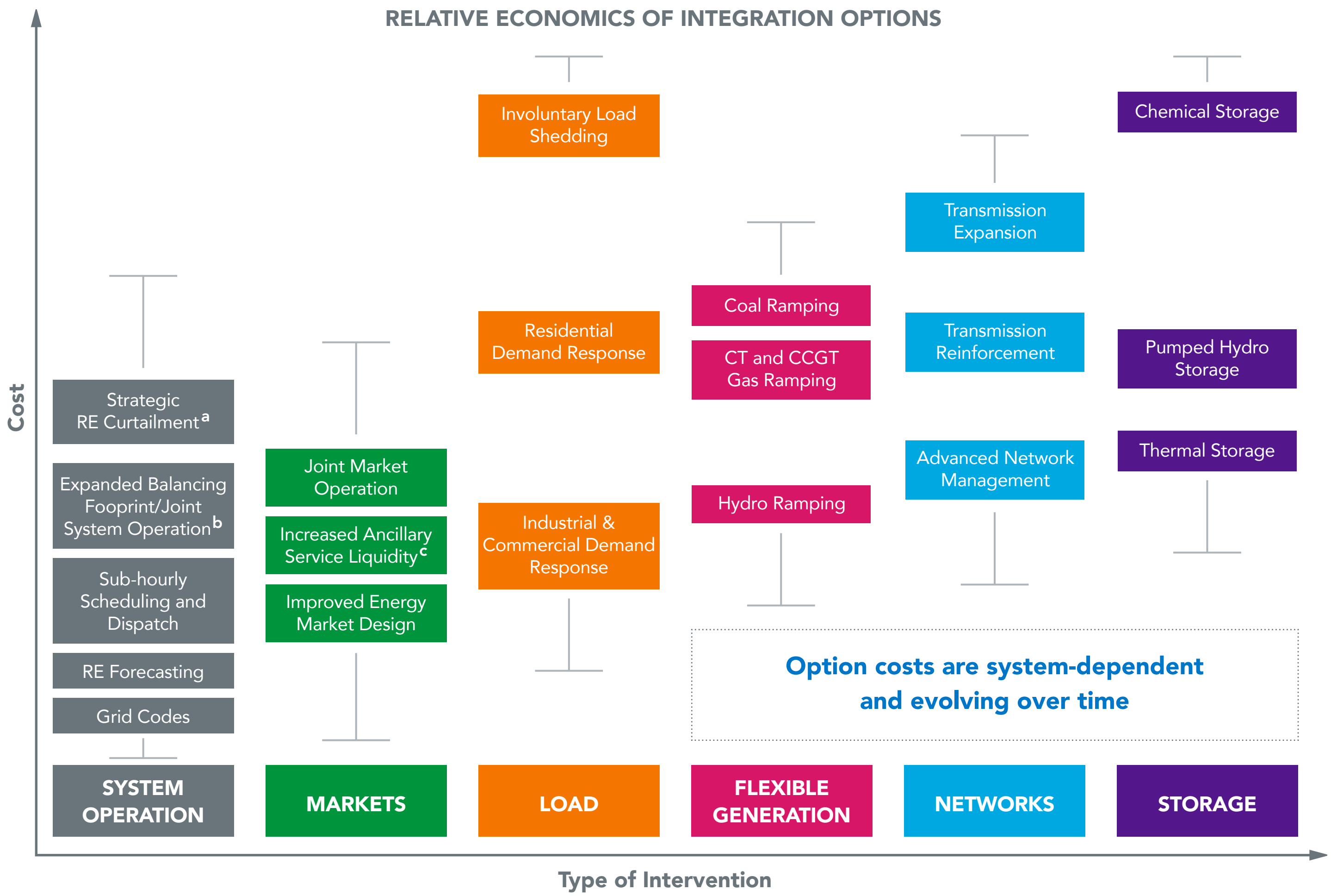

FIGURE 7: Example integration options. Relative costs are illustrative, as actual costs are system dependent.

a There is a tradeoff between costs of flexibility and benefits of reduced (or no) curtailment, hence a certain level of curtailment may be a sign that the system has an economically optimal amount of flexibility.

b Joint system operation typically involves a level of reserve sharing and dispatch co-optimization but stops short of joint market operation or a formal system merger.

c Wind power can increase the liquidity of ancillary services and provide generation-side flexibility. Curtailed energy is also used to provide frequency response in many systems, for example Xcel Energy, EirGrid, Energinet.dk.

(e.g., cycling thermal fleets, forecast integration), and institutional (e.g., new market designs, integration of demand response). Country experiences demonstrate a wide range of approaches to addressing flexibility, reflecting system-specific contexts. These experiences also demonstrate that while system operators might be cautious about increasing variability based on valid concerns about feasibility, experience suggests that system operators have been very innovative in discovering new approaches once they take up this challenge.

Although options and associated costs to increase flexibility are very system-specific, in general tools that help access existing flexibility through changes to system operations and market designs are cheaper than those that require investments in new sources of flexibility. While requiring less capital investment, changes to system operation and market design do have implementation costs and may entail changes to institutional relationships.

A detailed discussion of these interventions is beyond the scope of this paper, but for more complete discussions of how to increase system flexibility, see the publications listed in Text Box 2.

TEXT BOX 2: Selected References on Policy Tools to Increase Flexibility

Cochran, J. et al. (2012). Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A00-53732. www.nrel.gov/docs/fy12osti/53732.pdf.

Holttinen, H. et al. (2013). "The Flexibility Workout: Managing Variable Resources and Assessing the Need for Power System Modification." IEEE Power & Energy. 11(6):53-62.

Holttinen, H. et al. (2013). Design and Operation of Power Systems with Large Amounts of Wind Power. Final summary report, IEA WIND Task 25, Phase two 2009–2011. VTT Technology. www.ieawind.org/task_25/PDF/T75.pdf.

IEA. (2014). "The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems." Paris: OECD, IEA.

Miller, M. et al. (2013). RES-E-NEXT: Next Generation of RES-E Policy Instruments. International Energy Agency's Implementing Agreement on Renewable Energy Technology Deployment (IEA-RETD). iea-retd.org/wp-content/uploads/2013/07/RES-E-NEXT_IEA-RETD_2013.pdf.

Milligan, M. et al. (2012). Markets to Facilitate Wind and Solar Energy Integration in the Bulk Power Supply: An IEA Task 25 Collaboration. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-56212. www.nrel.gov/docs/fy12osti/56212.pdf.

Schwartz, L., ed. (2012). Meeting Renewable Energy Targets in the West at Least Cost: The Integration Challenge. Western Governors' Association. www.uwig.org/variable2012.pdf.

Key Principles in Thinking About Flexibility

All power systems have some inherent level of flexibility, designed to accommodate variable and uncertain load, and contingencies related to network and conventional power plant outages. Thus many of the tools to access flexibility, such as spinning reserves, automatic generation control, and short dispatch intervals, are in use in systems even without significant renewable generation.

Using this existing set of tools, power system operators have proven effective at incorporating increased variability and uncertainty without substantial new investment in system flexibility, such as new storage, demand response, or transmission. Especially at low penetration levels of wind and solar, large-scale investments in additional flexible resources might not be needed.

This paper aims to help address the question "How much flexibility does my system have and how much renewable energy can I add and still maintain reliability?" The various analytic frameworks explored in this paper help answer these questions, but they range widely in their complexity. The simplest tools—such as the flexibility charts—are useful for explaining relative strengths and weaknesses in the system to support flexibility. Adding temporal and spatial dimensions to data inputs—such as in FAST2—can help confirm whether further investigation is warranted on specific system issues, which is often not the case at low wind and solar penetration levels. Engineering measurements—such as IRRE—build from broad and high-resolution data, and not only robustly measure flexibility, but also help evaluate options to improve access to that flexibility, such as changes to system or market operation.

This detailed level of evaluation becomes more critical as penetration levels increase. Nevertheless, the early stages of variable renewable penetration levels are an important time for policymakers to establish the institutional capacity to collect data and model flexibility.

Key messages for policymakers about power system flexibility are summarized in Text Box 3.

TEXT BOX 3: Key Messages for Policymakers about Power System Flexibility

- Power systems are already flexible, designed to accommodate variable and uncertain load.
- In many power systems, sufficient flexibility exists to integrate additional variability, but this flexibility may not be fully accessible without changes to power system operations or other institutional factors.
- In sufficient quantities, renewable energy will change the shape of dispatch requirements so that system flexibility must be reassessed, and increases in the levels of renewable energy may require increasing levels of flexibility.
- A wide range of power system elements impact system flexibility, ranging from transmission assets to generation characteristics and operational practices.
- While there are many emerging flexibility metrics and assessment methods, there is no standard metric for measuring flexibility to date, and metrics continue to evolve.
- There are several approaches to improving grid flexibility, including improving ramping capabilities of the dispatchable generation fleet, increasing demand-side and distribution-level participation, and increasing coordination across multiple markets or balancing areas.
- Finding the optimal investment level requires consideration not only of short-term operational requirements, but long-term viability to recover costs. Uncertainty regarding the level, timing, and type of renewable energy deployment will complicate the problem of finding the optimal levels of investments.
- Based on investment needs independent of variable renewable energy and smart grids, power systems in developed and emerging economies may take very different paths to increasing flexibility.
- Flexibility considerations can be integrated into the design of procurement policies for new renewable energy generation (e.g., feed-in tariffs, subsidies), for example, by basing support on location of generation, provision of frequency support, alignment with demand, and/or integration into dispatch optimization.
- Policy incentives can be designed to anticipate flexibility needs and support system flexibility.

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