Power Sector Transformation Pathways

Exploring Objectives, Factors, and Technology Innovation to Inform Power Sector Pathway Decisions

Sadie Cox,[1] Thomas Bowen,[1] Owen Zinaman,[1] Karlynn Cory,[1] Tim Reber,[1] Kaifeng Xu,[1] Robin Burton,[1] Ron Benioff,[1] Johannes Eskstein,[2] and Jakob Wachsmuth[2]

1. National Renewable Energy Laboratory
2. Fraunhofer Institute for Systems and Innovation Research

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List of Acronyms

AGC	automatic generation control
APAEC	ASEAN Plan of Action for Energy Cooperation
APG	ASEAN Power Grid
API	Application Programming Interfaces
ARENA	Australia Renewable Energy Agency
ASEAN	Association of Southeast Asian Nations
BA	balancing area
BIMP-EAGA	Brunei-Indonesia-Malaysia-Philippines East ASEAN Growth Area
BMG	Brooklyn Microgrid
CAPEX	capital expenditures
CEER	Council of European Energy Regulators
DER	Distributed Energy Resource
DERMS	Distributed Energy Resources Management System
DeX	Distributed Energy Exchange
DG	distributed generation
DPV	distributed PV
DSO	distribution system operator
EIM	Energy Imbalance Market
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EV	electric vehicle
FACTS	Flexible AC Transmission System
IoT	Internet of Things
IRP	integrated resource plan
KETRACO	Kenya Electricity Transmission Company Limited
LCOE	Levelized Cost of Energy
LEDS GP	Low Emission Development Strategies Global Partnership
NDC	Nationally Determined Contributions
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OPEX	operational expenditure
PST	power sector transformation
PV	photovoltaic
REC	Renewable Energy Certificate
T&D	transmission and distribution
TSO	transmission system operator

Executive Summary

The power and heating sectors are responsible for around 30% of global CO_2 emissions, and this share is likely to grow as countries move towards electrification of the transportation and building sectors. Therefore, enabling forward-thinking, long-term strategies in the power sector is a crucial area for international collaboration and support. The rapid transition of power systems toward modern, low-carbon pathways and technologies will be necessary to meet climate goals, while also enabling other critical objectives such as economic development, energy access, and energy system resiliency, among others. Many developed and developing countries are well-poised to champion power sector transformation (PST); however, additional support can help identify pathways and implement critical near and long-term actions. To provide this support, the Low Emission Development Strategies Global Partnership (LEDS GP) together with an expert team including Agora Energiewende, Energy Innovation, European Climate Foundation, Fraunhofer Institute for Systems and Innovation Research, Prayas Energy Group and LEDS Latin America and Caribbean Platform, developed a framework identifying four potential pathways that can be integrated and combined to support low-carbon PST. These four pathways are: (1) Distributed Energy Resource Revolution; (2) Bulk Power Transformation;(3) Transmission and Distribution Interactivity; and (4) Distributed Transactional Future.

To support exploration of pathways, this study examines country-specific PST objectives and factors that stakeholders may consider as they investigate various pathways to support PST. A framework and complementary tool for considering relative pathway emphasis in a hands-on manner is also presented. The report provides case studies on application of the approach to bring life to the topic. The case studies include Haiti, Kenya, Mexico, Southeast Asia, and the European Union, among others. The report also presents actions to be considered in the near-, medium- and long-term to support the realization of pathways and long-term transformation of the power sector. The report, together with a complementary spreadsheet tool developed under the effort, can be used to enable stakeholder engagement and visioning for the power sector over the long-term, taking into account country-specific factors and potential innovations. It can also be used to understand and inform relevant analysis tools and models based on which pathways are emphasized, and to identify supportive actions in the near- and medium-term to avoid lock-in of carbon-intensive technologies.

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1 Introduction

The power and heating sectors are responsible for nearly one third of global greenhouse gas emissions[2] and this share is likely to grow as countries transition towards electrification of the transportation and building sectors. A rapid transition of power systems toward low-carbon pathways and technologies[3] may be necessary to meet country-specific environmental goals and could also enable other critical objectives such as sustained economic development, energy access, and energy system resiliency, among others. Many developed and developing countries are well-poised to champion power sector transformation (PST), however, further support is needed to identify potential pathways and implement near and long-term actions aligned with those pathways.

Power Sector Transformation Defined

According to the International Energy Agency and 21st Century Power Partnership, power sector transformation can be defined as "a process of creating policy, market and regulatory environments, and establishing operational and planning practices that accelerate investment, innovation and the use of smart, efficient, resilient and environmentally sound technology options".[1]

This paper identifies four possible pathways for PST that could be integrated and combined to support low-carbon power sector transformation in developing countries. Effective PST strategies should seek to identify actions and combinations of pathways that maintain flexibility and keep options open as market conditions shift. Allowing for course corrections and the ability to take advantage of technology breakthroughs is critical. In some cases, this can mean utilities, governments and societies may seek to shift from known technology suites and begin experimenting with newer technologies aligned with broader power sector objectives. For example, a utility may choose to retire a generator before the end of its useful economic life in order to meet other objectives; in so doing, the transformation of the electricity sector can be accelerated.

To support decision makers in exploring unique combinations of potential PST pathways, this paper examines power sector objectives and factors that may lead countries or jurisdictions to place a greater relative emphasis on certain transformation pathways. The paper concludes with insights on potential areas of need or intervention related to each pathway that can inform country and donor collaborative efforts, drawing from case examples around the world. For each of the pathways, the paper also sheds light on near-term actions that countries can take to achieve a low-carbon transition, reaping associated benefits, and avoiding unnecessary stranded assets. Jurisdictions could apply a portfolio of these actions with a greater emphasis on their highest priority pathways; this report and the PST spreadsheet tool (described below) are designed to support decision-makers in identifying a mix of pathways that align most closely with objectives and factors in unique country and jurisdictional settings. Sections below further describe each of the elements of the paper.

[1] (IEA 2019)
[2] (Center for Climate and Energy Solutions 2017)
[3] For the purposes of this paper, low carbon pathways and technologies can encompass renewable energy, nuclear, and carbon capture and storage technologies.

1.1 Four Pathways for Power System Transformation

The pathways described below provide an organizational framework for this report. Countries and jurisdictions could pursue a mix of these pathways based on unique objectives and factors relating to the power sector and presented in upcoming sections.[4]

Distributed Energy Resources (DER) Revolution—Under the DER Revolution Pathway, distributed energy technologies, particularly solar PV, distributed storage, energy efficiency[5], plug-in electric vehicles (EVs) and other grid-edge and digital technologies are significantly scaled up by 2050. When these technologies are optimized simultaneously to support the electric system broadly, they help shape energy demand and provide energy and capacity to the power system. Aggregation, consumer empowerment, and digitalization are key aspects of this pathway and are described in detail in sections below.

Bulk Power Transformation—The Bulk Power Transformation Pathway is focused on integrating utility-scale renewables into the bulk power system, improving bulk power system stability and reliability, and promoting power system flexibility. This pathway could either be adaptive, where a vertically-integrated utility retains their principal role in the power system with a shifting of regulatory framework towards rewarding revenue based on performance, or be reconstructive, taking iterative wholesale power market restructuring lessons learned (over several decades) to achieve power market reforms aligned with renewable integration. The availability of a steady stream of financing to support large-scale infrastructure investments is a crucial aspect of this transformation pathway. The Bulk Power Transformation Pathway could, in many respects, be considered a lower risk approach (relative to DER-focused pathways) and could support large-scale carbon emission reductions in the near-term with available and proven technologies. However, this pathway could lead to greater curtailment of variable renewable energy and distributed energy resources, as well as reduced consumer engagement relative to other pathways. To make informed decisions under this pathway, it is critical to understand the technology availability, scope, and cost of various measures to support grid integration and power system flexibility[6].

Transmission and Distribution Interactivity—Under the Transmission and Distribution Interactivity Pathway, a highly flexible and operationally optimized transmission grid is linked

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[4] It is acknowledged that the paper focuses on generation, transmission and distribution technologies and related pathways. While end use technologies, such as electric vehicles, are considered to some degree under the DER-focused pathways, it is understood that end use technologies (e.g., heat pumps) will play an important role in PST and these technologies could be considered further in follow on reports.

[5] While energy efficiency is not considered explicitly in all cases, it is acknowledged as a key aspect of all of transformation pathways, with the largest energy efficiency benefits likely to occur under pathways which emphasize a greater role for distributed energy resources and related energy efficiency actions. Distributed energy resources are more likely to lead to energy saving opportunities relative to centralized pathways as DERs can reduce line losses by generating power closer to the source of demand. Furthermore, distributed pathways are more likely to encourage wide-scale adoption of demand response initiatives, which can reduce the need for 'standby generators' by more efficiently utilizing generation and transmission assets.

[6] According to the 21st Century Power Partnership and the International Energy Agency, power system flexibility can be defined as "the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply" (IEA 2019).

with the optimized distribution grid, grid-level storage, dispatchable distributed generation, real time monitoring and analytics, and consumer demand interactivity. In this pathway, the transmission and distribution (T&D) systems are each modernized, enabling communication and improved management that includes streamlined communication between the T&D systems. Both planning and operations are flexible and optimized, and grid components are increasingly able to "self-heal," or operate in a fashion that allows faults to be isolated following grid disturbances; power continues to be supplied to as many customers as possible until the fault can be corrected. Utility business models evolve to allow for increased customer ownership of DER and participation in the power market, while providing backup power to participants, reliable power to non-participants, and all-the-while maintaining utility profitability. Utilities will value new grid services that enable a broader monetization of the range of services that modern power system resources are capable of providing, and have a more complex role in operations, communications, and coordination across neighboring regions/systems. Although utility-scale central generation is still highly prevalent under this pathway, DER plays a significant and notable role, and the two systems interact reliably and seamlessly. Many of the circumstances noted in both the DER Revolution Pathway and the Bulk Power Transformation Pathway descriptions are also highly relevant for this pathway.

Distributed Transactional Future—Traditionally, system operators have managed only a couple dozen control points on the electricity supply side, coupled with thousands or millions of passive points of demand. Under the transactional future, this norm shifts in two critical ways:

<u>More nodes and control points</u>—Systems are moving from having dozens of power injection nodes and related grid services, to having potentially millions of control points—each one linked to a distinct DER.

<u>Changing nature of control points</u>—What had formerly been strictly passive demand nodes interacting in a unidirectional way with the grid will now double as supply nodes needing to interact bi-directionally with the grid.

The Distributed Transactional Future Pathway can be understood as a complementary pathway to the three pathways described above as it could support further technical advances through altering the way energy services are planned for, characterized, valued, priced, procured, and transacted. The Distributed Transactional Future Pathway focuses on creating an overall electricity services market and system operation paradigm that will enable innovative power sector resources to operate at maximum value and for that value to be recognized and realized. Under this pathway, an automated, secure, and real-time distributed energy market utilizes emerging distributed network protocols, such as blockchain, and enables transformation in the distributed energy markets and significant scaling of DER. As a comparison, companies such as Uber and AirBnB created new platforms for accessing latent value by maximizing utilization of traditionally underutilized assets (e.g., a car sitting in a driveway or an unoccupied bedroom, respectively). A similar (albeit far more complex) shift to a distributed energy transaction environment enables underutilized DER capacity and related grid services to be marketed through real-time markets hosted on integrated platforms that enable utility sales, peer-to-peer energy transactions, demand response (DR), and grid services.

The Distributed Transactional Future Pathway can be considered a market-based pathway that would primarily support the DER Revolution and T&D Interactivity Pathways, as depicted in Figure 1. However, it should also be noted that the Bulk Power Pathway may also be influenced by the Distributed Transactional Future as the bulk system acknowledges and values DERs to a greater extent. The T&D Interactivity Pathway can be understood as sitting at the intersection of the DER Revolution and Bulk Power Transformation Pathways, also presented in Figure 1. Each of these pathways will be explored in great detail in sections below.

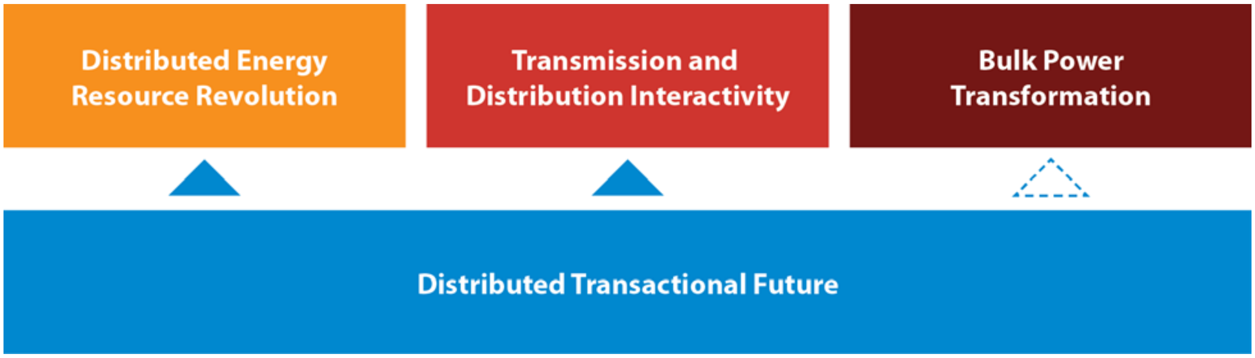

Figure 1. PST Pathways and Interactions

1.2 How Can PST Objectives and Factors Inform Pathways?

Power sector transformation occurs within a unique set of circumstances that relate to high-level objectives for the power sector, as well as country-specific factors relating to resource and land availability, structure of the economy, market organization and context, technical and institutional characteristics of the existing power system, and power system vulnerabilities.[7] These objectives and factors, combined with trends in technology and business model evolution, may lead countries or jurisdictions to place a greater relative emphasis on certain pathways or combinations of pathways. It is also important to note that strong policy and regulatory frameworks, as well as a steady stream of low-cost financing, can facilitate each of these pathways. In this report, policies, regulatory frameworks, and finance mechanisms are considered "actions" or "solutions" to enable the pathways rather than "factors" influencing choice of pathways. It is acknowledged that this could be considered in other ways in future or complementary reports. Figure 2 presents a methodology for the paper aligning with the narrative above and indicating relevant chapters.

[7] While political economy is an absolutely critical aspect of power system transformation, vast literature exists on this topic and it is not considered in detail in this paper.

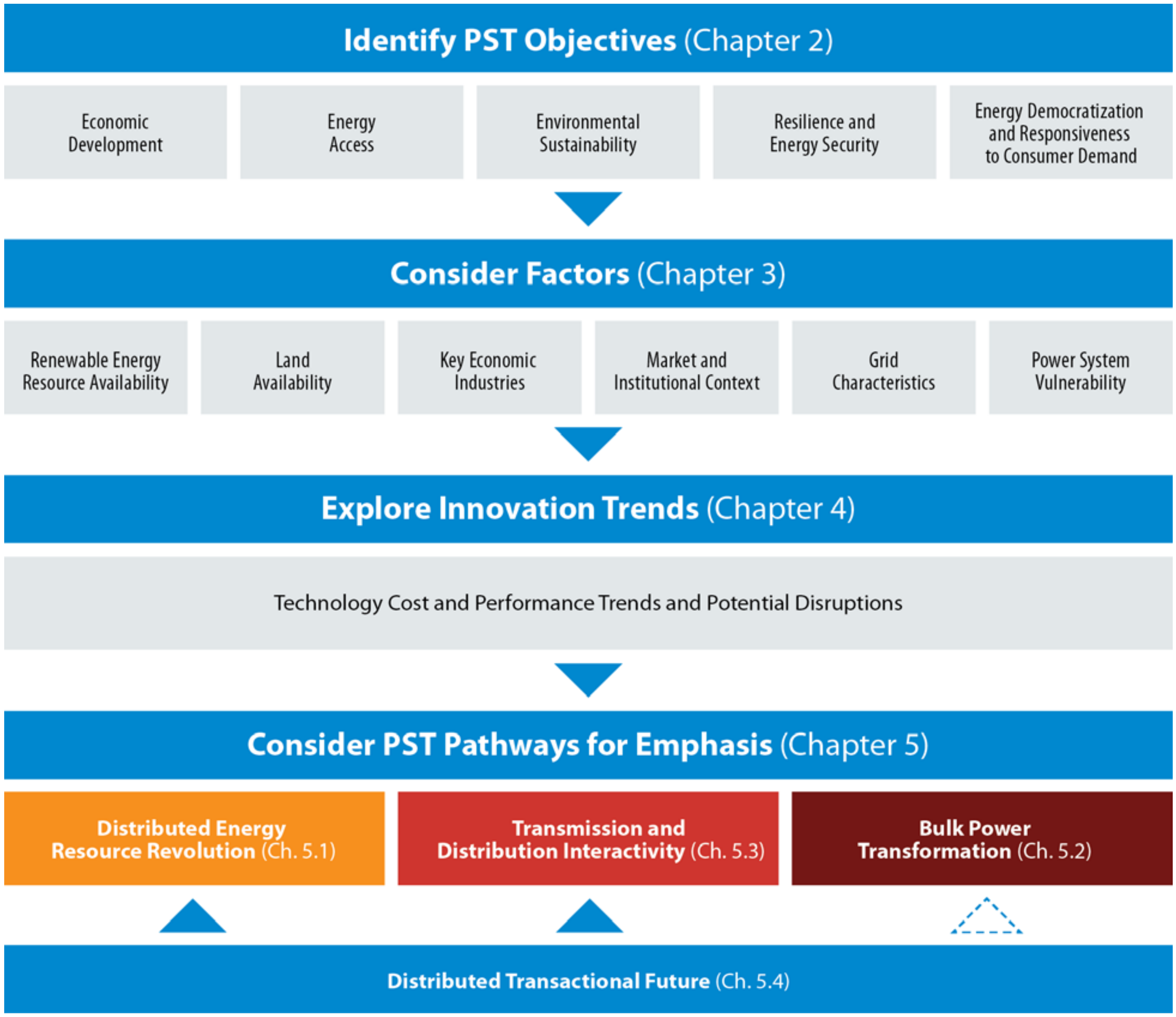

Figure 2. Steps to Inform PST Pathway Emphasis and Alignment with Chapters in the Study

As a complementary resource, the study team developed a spreadsheet tool where country stakeholders can input information on the characteristics of the existing power sector in their country, as well as aspirations and objectives for the future. Table 1 provides a snapshot of the tool.[8] While the underlying relationship determining the alignment between factors, objectives and pathways was put forth by subject matter experts (blue columns in Table 1), users of the tool can represent their country's specific context by changing the orange columns in Table 1. This tool then provides a qualitative representation of combinations of pathways that may be most aligned with their current situation, as well as pathways that may be most aligned with their objectives and aspirations for transformation. Within the spreadsheet tool, users can also place a greater relative emphasis on certain objectives or factors based on their situation and input from diverse stakeholders and experts. The spreadsheet tool is envisioned to be most effectively used within a stakeholder process to support visioning for the power sector over the longer term. As a practical application example, this tool can be used to inform scenario design for power system

[8] For more information on the tool or if you are interested in applying the tool, please email Thomas.Bowen@nrel.gov.

planning. A simplified version of the tool—which does not include aspirational considerations of countries or varied weighting of factors—is also included in the country case sections to offer examples of how the tool can be used.

It is important to note that countries at earlier stages of renewable energy development (i.e., with lower levels of renewable integration with the grid) can design and implement policies or other actions that can be supportive across all pathways. There is vast literature on good practices associated with well-established renewable energy policies internationally (e.g., RE targets, renewable portfolio standards) and many key actions that can be supportive across several pathways are presented on the USAID-NREL Greening the Grid website (https://greeningthegrid.org/).

Building on these foundational policies and actions, this paper and tool are meant to support longer-term visioning exercises for the power sector, while also connecting that visioning back to more specific near term actions that could be taken (in combination with more foundational policies mentioned in the paragraph above) to set the groundwork for particular pathways or combinations of pathways over time. Pathways at earlier stages of maturity, such as the Distributed Transactional Future, will also depend heavily on experience in other countries and scaled-up deployment of disruptive technologies internationally. While the tool may indicate that a country's objectives and factors align with the Distributed Transactional Future pathway, the actions presented in this paper emphasize more basic DER actions in the near term with innovative pilots (and related deployment) scaling up over time and building on international experience. Particularly as countries reach higher penetrations of renewables and, in some cases, 100% renewables, the nuances and related actions across these pathways will become increasingly important to reach these futures.

Table 1. Power Sector Factors and Pathways Alignment Tool with Scoring Included for an Illustrative Country X

	Relevance of factors for country X		Pathways and level of alignment with factors			
	Current relevance of factor	*Relevance based on aspirations, goals or anticipated future*	*DER Revolution*	*Bulk Power Transformation*	*Transmission and Distribution Interactivity*	*Distributed Transactional Future*
Area #1 - Local Power System Transformation Objectives						
Objective: Economic Development		1	2	2	2	2
Objective: Energy Access		1	2	1	1	2
Objective: Environmental Sustainability		0	1	2	1	1
Objective: Resilience and Energy Security		1	1	1	2	1
Objective: Energy Democratization + Responsiveness to Consumer Demand		0	2	0	1	2
Area #2 - Renewable Energy Resource Availability						
Solar	1	1	2	1	1	2
Wind	1	1	1	2	1	1
Offshore Wind	1	1	0	2	1	1
Geothermal	0	0	1	2	1	0
Biomass	0	0	1	1	1	0
Area #3 - Land Availability						
Significant Land Availability	0	0	0	2	1	0
Minimal Land Availability	1	1	2	0	2	1
Dense Urban Area with Suitable Rooftops	1	1	2	0	2	2
Area # 4 - Key Economic Industries						
Established Distributed Energy Resource Installer Market	0	1	2	0	2	2
Established Large-Scale RE Manufacturing Sector (e.g., large wind turbines)	0	0	0	2	1	0
Established DER Manufacturing Sector (e.g., batteries, PV panels)	0	1	2	0	1	2
Significant Industrial Demand	0	0.5	1	2	2	2
Significant Agricultural Demand	0.5	0	2	0	2	2
Area # 5 - Market and Institutional Context						
Decentralized Power Market	0	1	2	0	1	2
Centralized Power Market	1	0	1	2	2	0
Utility Financial Insolvency	1	0	2	0	1	1
Customer Demand for Distributed Energy Resources	0.5	1	2	0	2	2
High Electricity and/or Fuel Prices	1	0	2	1	1	2
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets	1	0	0	2	1	0
Significant Cross-Border Trading Opportunities	0	0.5	0	2	1	0

	Relevance of factors for country X		Pathways and level of alignment with factors			
Significant Cross-Sector Electrification Potential	0	1	2	1	1	2
Area #6 - Grid Characteristics						
Robust Transmission & Distribution Networks	0	1	1	1	2	2
Large Balancing Area	0	0	0	2	1	0
Strong Grid Management Capabilities	0	1	1	2	2	1
Area #7 - Power System Vulnerability						
Dependence on Imported Fuels	1	0	2	1	1	2
High Vulnerability to Natural Threats	1	0.5	2	0	1	1
High Vulnerability to Physical or Cybersecurity Threats	0.5	0.5	0	1	0	1
GRAND TOTAL						
Pathway Score Based on Current Factors:						
Pathway Score Based on Aspirational Factors and Goals:						

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates low or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

1.3 What Actions and Interventions Can be Supportive in Reaching These Pathways?

Building on the sections above and drawing from experiences in countries around the world, this paper also presents actions in the near and longer term that can support progress along each pathway.[9] Again, while all of these pathways seems likely to manifest in most countries,

[9] It is recognized that more foundational policies, such as development of renewable energy targets, can also be integral in enabling low carbon technologies. These foundational policies are not considered in detail within the pathways sections given the availability of vast literature on these topics.

decisionmakers can choose to emphasize a subset of pathways that best align with their country's goals and unique circumstances.

Through looking at country and jurisdiction examples where particular pathways are currently evolving, the paper also presents emerging good practices and possible needs/interventions related to each pathway from individual country perspectives. Building on this piece, the paper concludes with insights on collaborative approaches for enhanced technical assistance and capacity building to support PST in developing countries. These approaches can leverage and complement current development and environmental assistance programs.

2 High-Level Objectives Driving PST

Many countries are currently transforming their power systems to align with several high-level objectives. These objectives are ideally identified through diverse stakeholder processes and serve as the foundation for integrated resource plans (IRP) and other power sector planning activities. Prioritization of objectives, combined with analysis of other factors, can lead to identification of and a relative emphasis on certain PST pathways or combinations of pathways described in the introduction and detailed in this paper. Objectives related to power sector transformation are presented below and will be further described in relation to their alignment with each pathway in later sections of the paper.

Importantly, reliability and affordability are two foundational high-level objectives for power sector planning exercises. Reliability can be understood in simplified terms as the ability of the power system to maintain the delivery of electricity in the face of uncertain operating conditions—it is critical to enabling economic growth, maintaining the operation of critical infrastructure, and the safety and well-being of citizens. Affordability can be defined as the ability of the power system to provide electricity at a cost that does not exceed customers' willingness and ability to pay for those services—it is a similarly critical aspect of power systems.[10] Both reliability and affordability can be well-supported across the transformation pathways discussed in this report, and thus will not be considered in a comparative nature to distinguish among the pathways. However, sections on technology cost projections do shed light on the future affordability of technologies that may align with certain pathways.

Economic Development—Power sector transformation offers many opportunities to support economic development objectives, including targets for growth in GDP and employment. Many countries and jurisdictions are supporting renewable-focused power sector transitions to align with broader economic development goals for job creation, green growth, and industrial development. In 2017, IRENA found that the renewable industry added 500,000 new jobs, with solar PV supporting the highest number of renewable jobs globally.[11] In addition to renewables, power sector transformation has significant prospects for further job growth in the realm of grid-edge technologies, including energy efficiency technologies, buildings, software, EVs and EV infrastructure, and other disruptive technologies yet to come to market. While renewable energy and other PST technologies can enable job growth, it is also critical for countries to consider just transitions and retraining programs for other industries that may lose jobs as certain PST pathways are undertaken. Power sector transformation can also allow countries to reduce reliance on fuel imports and significantly improve the balance of trade for the country. Finally, advanced power systems can provide reliable, low cost, and clean power to support industrial development and broader economic growth.

Energy Access—Energy access is still a critical challenge internationally as nearly 1 billion people are currently without electricity.[12] In many contexts, addressing this challenge is a crucial priority in power sector planning. Decision-makers must analyze options to extend the grid or enable off-grid energy provision. Addressing energy access through various solutions will be an

[10] (Grid Modernization Laboratory Consortium 2017)
[11] (IRENA 2018)
[12] (United Nations 2018a)

integral aspect of power sector transformation in many contexts around the world. The pathways described in this paper can support both off-grid distributed and grid-connected solutions.

Environmental Sustainability—Environmental objectives such as reducing GHG emissions and improving local air quality are significant priorities for many countries and jurisdictions pursuing power sector transformation. Clean power can play a significant role in reducing GHG emissions and mobility at the grid edge, such as EVs, can also support improved air quality through replacing traditional combustion engine vehicles. While not described at length in this paper, different technology pathways including renewables, nuclear, and clean fossil (e.g., through carbon capture and storage) can support environmental objectives.

Resilience and Energy Security—Power systems globally face natural, technological, and man-made threats that can impact infrastructure, systems, and energy supply, and cause power interruptions. When power systems are interrupted by natural disasters, cyber-attacks, or other threats, this can have significant negative consequences across sectors (e.g., healthcare, water, education) and economic activities. Thus, planning for resilient and energy secure power systems through various technical and institutional solutions is a crucial aspect of power system transformation and execution will be unique to individual countries and cities as they face different threats and vulnerabilities that can also evolve over time.

Energy Democratization and Responsiveness to Consumer Demand—In some contexts, policymakers or other energy sector actors are pursuing PST as a response to or to "get ahead of" demand from consumers for distributed energy systems. In other cases, PST decisions are being made to explicitly empower consumers to have more control over their energy decisions. This particular objective may lead decision-makers to place a greater relative emphasis on certain DER-focused pathways described in the sections below. Working directly with consumers and consumer representatives to support grid efficiency and reliability can have significant benefits for the power system if planned in a thorough and detailed manner; there are many steps and approaches that can be taken to support this outcome.

3 Factors to Consider for PST Pathways

Many unique factors may influence the direction taken by countries and jurisdictions in pursuing power sector transformation. While the influence of these factors on power sector planning is extremely nuanced, certain factors may lead to a greater emphasis on particular PST pathways or combinations of pathways. For example, countries with a large amount of land availability, significant wind resources, and a focus on supporting large-scale wind turbine manufacturing may choose to place a greater relative emphasize on the Bulk Power Transformation Pathway, particularly in certain regions of the country where all of these factors are most prevalent. Alternatively, dense urban areas with significant solar resources and a focus on manufacturing certain DER technologies may be more inclined to pursue a DER Revolution Pathway. The aforementioned examples are meant to provide a very simple view of potential emphasis on certain pathways. Looking across all factors described below, in addition to considering relative weighting, would provide a more representative view of possible pathway emphasis based on unique circumstances in countries and jurisdictions. All factors considered as part of the PST framework are described below with simplified examples of how these factors may align with certain pathways. As noted in sections above, countries or jurisdictions could undertake detailed assessments of these factors in unique settings to inform PST pathway emphasis.

Renewable Energy Resource Availability—Availability of certain types of renewable energy resources may lead countries or jurisdictions to place a greater relative emphasis on certain pathways. For example, significant availability of resources such as large-scale wind (onshore and offshore) and geothermal may lend themselves to an emphasis on bulk power-focused pathways. Abundant solar resources are often a central component of a distributed resource-focused pathway but can also play a key role in bulk power transformation through utility-scale solar.

Land Availability—Land availability is an important aspect of power sector planning and transformation. Dense urban areas (and suitable roofs for PV) or areas without access to a large amount of land (e.g., islands) may choose to emphasize a DER Revolution Pathway, while jurisdictions, countries, or regions with vast land availability (within or across borders) may place a greater emphasis on a Bulk Power Transformation Pathway. Country demographics related to land use are also important. Countries with many rural and remote areas, far from the centralized grid system, may place a greater emphasis on distributed resources and off-grid power to support energy access. Furthermore, geographically remote communities might prefer to build systems that allow local or regional interactions supported through a Distributed Transactional Future Pathway instead of interconnecting to the utility transmission system.

Key Economic Industries—Country or jurisdiction economies (hereafter "economies") have different compositions that feature varying degrees of activity in heavy industry and manufacturing, the service sector, and the agricultural sector, among others. A desire to support specific economic sectors may lead countries or jurisdictions to place a greater relative emphasis on certain pathways. For instance, economies with a significant industrial sector may have greater interest in developing local manufacturing capacity for large-scale wind turbines and thus may place a greater emphasis on the Bulk Power Transformation Pathway. Economies with a broader service sector may be more inclined to concentrate on a Distributed Transactional Future Pathway that involves the participation of a range of energy service providers.

Market and Institutional Context—Market and institutional context can also play a key role in informing pathway decisions. As a simplified example, the existence of a centralized, non-competitive power market may lead decision-makers to place a greater emphasis on bulk power transformation, while decentralized markets could lend themselves to DER-focused pathways. As another market example, high consumer demand for distributed technologies or even grid defection (due to high electricity prices or other market factors) may lead to a focus on DER-focused pathways and/or a greater emphasis on improved coordination across T&D.

Grid Characteristics**—**The robustness and coverage of the T&D system, the available set of flexibility resources and grid management capabilities within a jurisdiction or country, as well as size of the balancing areas, are also important factors in assessing pathways for PST. For example, T&D systems that are particularly robust and well-managed may be well suited for the T&D Interactivity Pathway, as well as pathways more focused on grid-connected distributed resources. Larger balancing areas may allow for a greater focus on bulk power transformation. Most cases countries are likely aiming to develop robust T&D infrastructure and grid management practices. If these practices and infrastructure are lacking in the near term, however, a greater emphasis may be placed on the DER Revolution Pathway.

Power System Vulnerability—The vulnerability of the power system to threats (e.g., hurricanes, cyberattack events, etc.) can influence the level of emphasis on each of the PST pathways. Different pathways and associated technology choices may have implications for the ability of the power system to adapt to changing conditions and rapidly recover from disruptions. Distributed generation resources could diversify the energy supply, and technologies such as distributed storage can provide back-up power during outages. This power can also be diverted to critical facilities if the system is designed and built to do so. The presence of larger and more geographically centralized resources may increase system vulnerability in some cases, as the entire system becomes more reliant on a smaller number of power plants. Finally, other grid-edge technologies such as demand response and energy efficiency can support alleviating stress on the system during extreme events, such as heat waves. However, increased numbers of distributed assets can also create more access points for man-made threats such as cyber-attacks. Understanding power system vulnerability requires an assessment of all assets and infrastructure, and it is particularly beneficial to ensure highly distributed pathways are planned in a way that supports resilience and reliability.

4 Technology Costs and Innovation

Technological and manufacturing-related innovations are driving down costs and improving performance characteristics for a range of energy technologies. Many innovations in renewable energy and storage technologies are enabling rapid price declines and performance improvements[13] that support power sector transformation. Such trends can play a key role in informing decisions to emphasize certain pathways. To provide background on costs, an overview of the energy technology innovation landscape is presented in Appendix 2. Sections below explore global estimates of cost projections for selected renewable energy technologies as well as implications for power sector transformation.

Figure 3 and Figure 4 respectively present mid and low technology cost projections out to 2050 for key renewable energy technologies aligned with the bulk power and distributed energy-focused pathways.[14] All technologies presented are projected to see cost reductions out to 2050. The most dramatic declines are expected for solar, wind, and storage technologies, with geothermal following suit. While these cost projections are for the United States, similar studies could be undertaken for specific countries to further inform PST pathway emphasis (e.g., bulk power vs. DER emphasis) in combination with factors and objectives highlighted above.

[13] Performance improvements by technology are not included in this report. There are many other resources that examine the improved performance of different power sector transformation technologies.
[14] Numbers are drawn from the U.S. Annual Technology Baseline study, with a table of values presented in Appendix A.

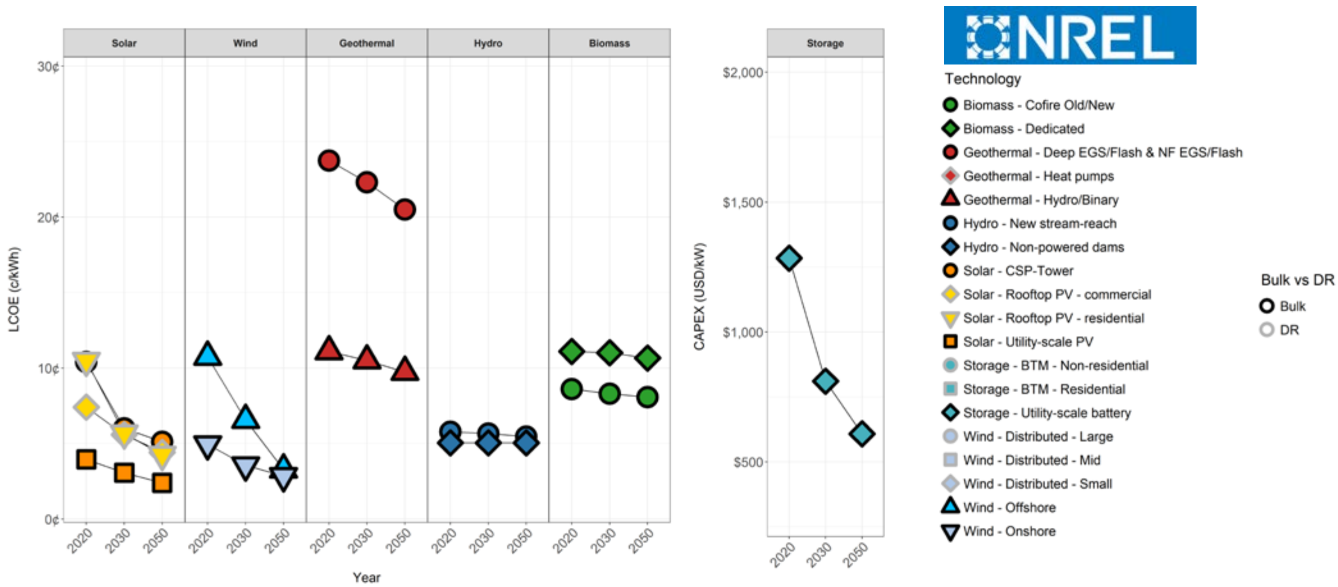

Figure 3. Key technology mid cost projections out to 2050 to inform bulk power and distributed energy-focused pathway decisions

Drawn from U.S. Annual Technology Baseline (See Appendix A)

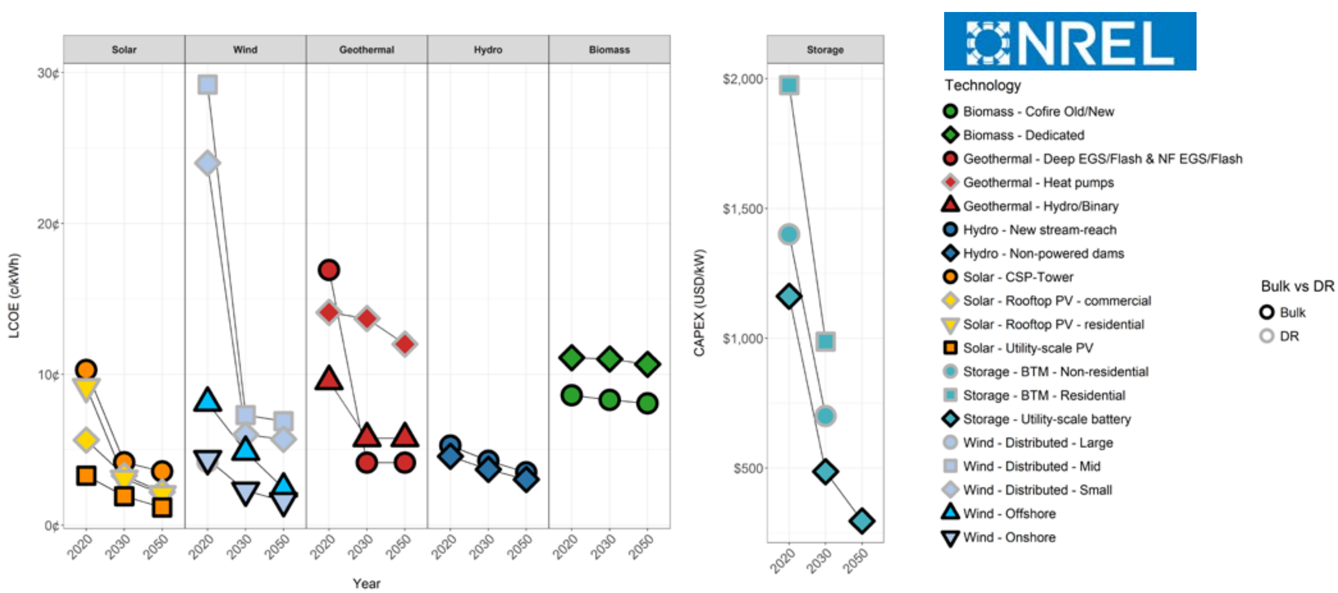

Figure 4. Key technology low cost projections out to 2050 to inform bulk power and distributed energy-focused pathway decisions[15]

Drawn from U.S. Annual Technology Baseline (See Appendix A)

[15] Additional technologies are included in the 'Low Cost' figure due to the availability of data.

In addition to exploring declines in renewable energy cost projections over time, it is important to examine potential sudden shifts in technology adoption over a shorter timeframe (e.g., within one year) due to a major policy or other transformational action. To inform power sector transformation, anticipating these step-wise shifts may be as important as analyzing long-term projected declines in costs. Wachsmuth et al. (2018) analyzes actual cost declines to inform projections, arguing that it could allow for increased ambition of Nationally Determined Contributions (NDCs) due to a potentially higher share of renewable energy in the power system at equal costs. Their findings are summarized here to illustrate the implications of the decline in cost projections.

In order to keep the analysis globally relevant, Wachsmuth and Anatolitis (2018) focus on cost projections of solar PV, wind power, and lithium batteries for EVs. They compare projected values prior to 2014-2015 (just prior to the development of NDCs) to values roughly four years later 2017-2018, with 2025 and 2030 as target years. The study builds on reports from IRENA, the World Energy Outlook, and recent auction outcomes, as well as peer-reviewed articles. Figure 5 gives an overview of the evaluation, with darker colors giving the more up-to-date values. Minimum price projections for 2030 have fallen between 36% for offshore wind and just above 50% for onshore wind, PV, and battery storage. Maximum values for cost projections for 2030 have not decreased as dramatically, but are still 15-20% lower today than five years ago, with a more dramatic drop of more than 40% seen for offshore wind.

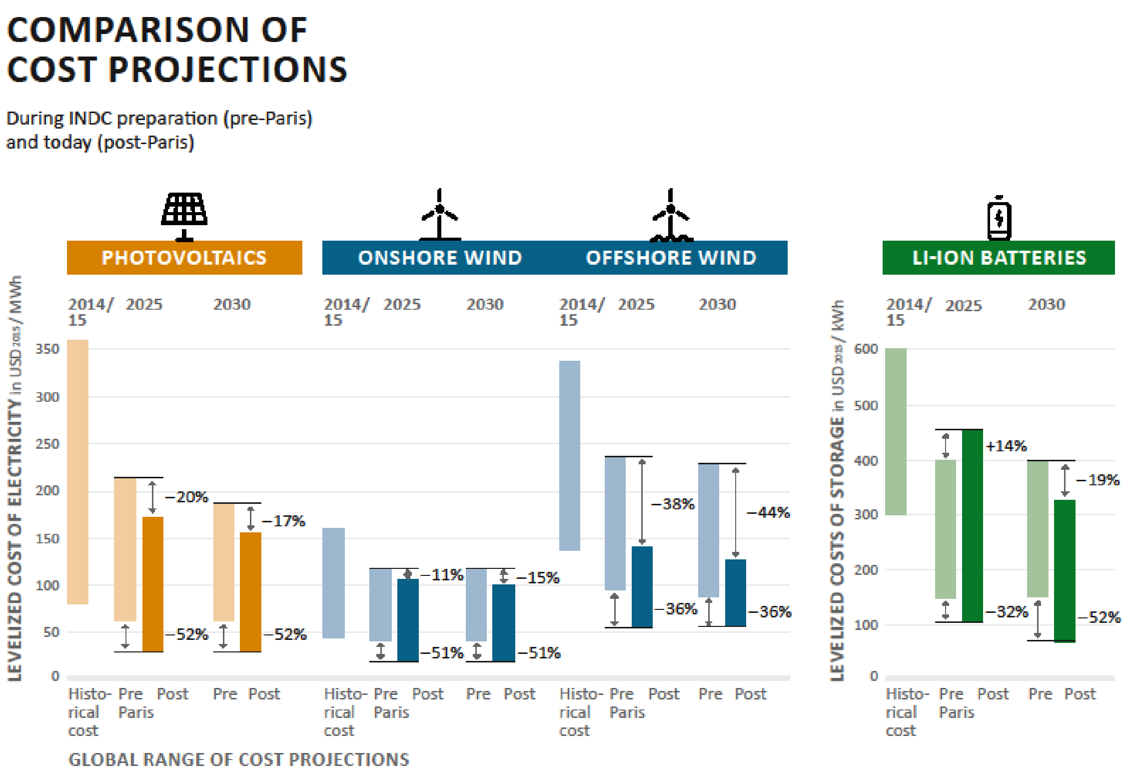

Figure 5. Projections for the levelized costs of energy/storage in 2025 and 2030 for renewable electricity and lithium-ion batteries before and after COP 21 in Paris

Source: (Wachsmuth and Anatolitis 2018)

Considering these values, one can compare how far the same capital investment could go with the updated cost projections. For example, within the study, the same capital investment required to achieve an increase in capacity of solar PV and wind power by 2030 was examined. Comparing the results, cost estimates from 2014/15 result in a baseline capacity, while using more recent cost estimates yields nearly double (90%) the amount of additional capacity. The same phenomenon also holds true for EVs, due to the accelerated steep declines for lithium-ion battery cost estimates. Using the same capital investment between 2014/15 and today could allow for almost double (93%) the number of EVs on the road. An increase in the uptake of these technologies due to faster-than-expected price declines may enable replacement of carbon-intensive technologies, leading to a reduction in GHG and other emissions.

As case study examples, Fekete et al. (2019) and Fekete and Nascimento (2019) applied the methodology of Wachsmuth and Anatolitis (2018) to Canada and Chile. The evaluation of cost projections for Canada returns a cost reduction of 15% to 40% for PV and 8% to 37% for wind, which implies a corresponding increase in the number of installations and total capacity for the same capital investment. For Chile, the respective decrease in cost projections turns out to be slightly larger for PV (47% to 53% reduction) but smaller for onshore wind (4% to 15% reduction).

It should be noted that while this information can provide some insights on particular PST pathways to emphasize, pathway decisions informed by expectations of technology cost and performance improvements will be highly dependent on local technology prices and soft costs, business models at the local level, and other important factors. Individualized analyses of both technology cost projections and potential for disruptive technologies could be undertaken at the country level and even the local level,[16] to build on the analysis and graphics presented in this section. This type of targeted analysis could provide further insights on pathway emphasis at the country level based on technology innovation trends, relevant renewable energy resources, and other country-specific factors described in the section above and throughout the paper.

Building on the technology cost projections above and moving to the topic of innovation, it is clear that innovation is required across all pathways and cannot be controlled by any single jurisdiction. Innovation takes scientific discoveries, new and improved manufacturing processes, new technology and engineering ideas, and creative procurement mechanisms, and transfers them to industry to get impactful products and processes on the market and in the field. Innovation is, and will be, critical for all four PST pathways. The jurisdiction-specific level of innovation in advancing, adopting, and deploying innovative technologies, manufacturing, engineering, and procurement will impact how quickly a new technology is adopted and how quickly the PST evolution occurs. Simultaneously, global innovation will also impact the ability to emphasize the highest priority PST pathways, and how all PST pathways advance. Thus, innovation is seen as fundamental to all PST pathways, and is assumed to be necessary, but is not explicitly addressed as a key enabling factor in this study. From a higher level, and in the section below, this report sheds light on technology and engineering innovations, although many other innovations will support PST advancement across unique settings.

[16] Local-level project economics may be important, particularly when considering energy access or project development on land with mountainous terrain.

Figure 6 presents potential technology disruptions relevant to the DER Revolution (and other distribution-focused pathways) and Bulk Power Transformation Pathways,[17] based on current expectations of the number of years until their widespread use, as well as their potential for helping to transform the power sector. While this graphic presents a global, qualitative perspective, an analysis of potential disruptions (including possible timing and impact) could be undertaken at the country level to inform pathway decisions. This graphic was developed based on expert opinion of the authors and can be considered illustrative based on many uncertainties regarding disruptive technologies.

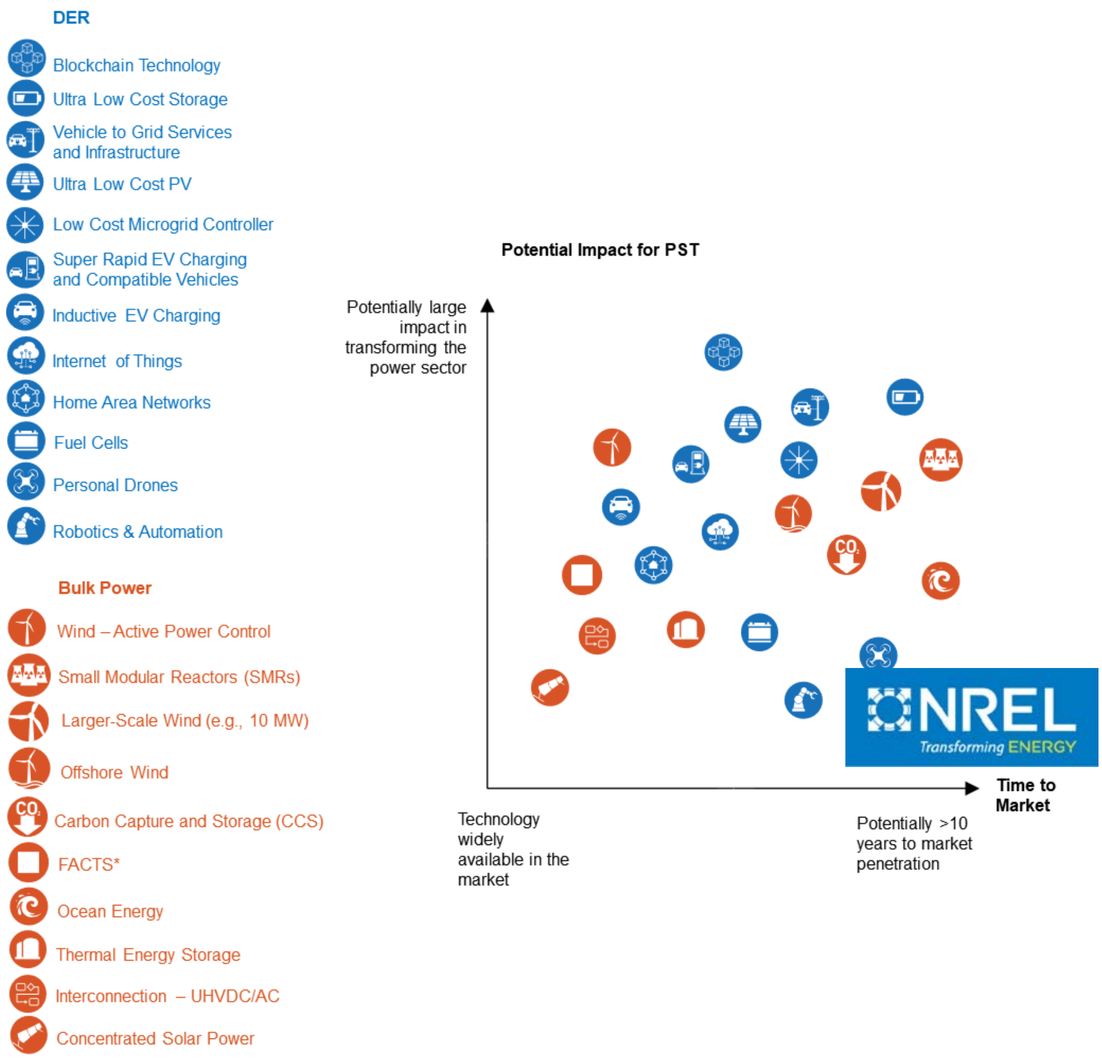

Figure 6. Illustrative view of disruptive technologies and potential alignment with DER Revolution and Bulk Power Transformation Pathways

*Flexible AC Transmission System (FACTS)[18] refers to the use of power electronics to provide rapid, highly controllable reactive power to the system. This improves voltage quality and increases system stability and power transfer capability.

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[17] All technologies included could be seen as relevant for the T&D Interactivity Pathway.
[18] (Csanyi 2011)

Technological advances are happening rapidly in the power sector. Therefore, developing and frequently updating planning goals and processes, strategies, and investment approaches may help power systems adapt to quickly changing technology trends and paradigms (see Figure 6 for examples). While in some cases, past energy infrastructure investment decisions may “lock in” technologies for long periods of time, this is not always the case as countries may choose to move forward with generator retirement policies and actions. Revisiting strategic planning exercises with the most recent cost curves and technology performance metrics can improve decision-making processes and enable course corrections as new options arise.

In all cases, business models will be crucial in advancing the technologies presented in this section. The sections below present key business models within each pathway that can support the technologies described in this section.

5 Diving into the Four PST Pathways

Each of the four PST pathways offers unique characteristics and approaches to support power sector transformation. With strong political leadership and vision, robust institutional capacity, and policy and regulatory certainty[19], these pathways can be emphasized and combined in complementary ways to enable power system transformation. While certain pathways may be emphasized within a country or jurisdiction, in many cases there will be some mix of all four pathways to support PST. Sections below provide a detailed description of each of the pathways including key characteristics, issues for consideration, enabling business models, and near and longer term actions to support the pathways.

5.1 Distributed Energy Resource Revolution Pathway

The DER Revolution Pathway integrates distributed generation and storage, energy efficiency, EVs, and other technologies at the grid-edge[20] to support low carbon PST. This pathway is characterized by a future that includes:

broad-scale deployment of DERs, in particular distributed photovoltaics (DPV) and distributed storage

significant enrollment of consumers as flexible demand response resources as well as sources of energy, system flexibility, and ancillary services through both market-based and utility-led approaches

innovative policy and regulatory constructs that support business model innovation to enable the broad enrollment and aggregation of DER

an increased emphasis on integrated distribution-level planning which is integrated into broader utility-led resource planning activities

development of market-appropriate incentive schemes to promote DER deployment

a strong emphasis on seizing deep grid-edge,[21] or at the individual customer level, energy efficiency opportunities;

This pathway is also enabled by large growth in consumer demand for distributed energy and empowerment of consumers to produce their own energy and participate more actively in the power system through automated approaches, such as home energy management software. The role of end-use consumers expands significantly, as they become a primary source of capital for investment in distributed energy resources (including PV + storage), participate in demand response programs to schedule their energy use through smart appliances, and increase demand through EVs which are enrolled in smart EV charging schemes. Third-party aggregators work with individual customers to become a force within competitive wholesale power markets.

[19] See Zinaman et al. (2019) for a review of principles for PST in emerging economies.
[20] According to GreenTech Media, "The Grid Edge comprises technologies, solutions and business models advancing the transition toward a decentralized, distributed and transactive electric grid." (Chen 2017)
[21] Grid-edge opportunities could include avoiding line losses through more locally generated energy or utility-supported efficiency efforts, such as upgrading outdated appliance equipment.

Customers (or their aggregators) utilize energy management systems that attempt to minimize customer bills while providing and monetizing valuable services to the power system. Energy management systems also allow customers (or aggregators) to interact with their neighbors (also a key element of the Distributed Transactional Future Pathway highlighted below), at the grid, wholesale, or retail markets (potentially at all three levels). Retail customers actively participate in demand response programs and markets. Key DER services are harnessed to enable resilience to natural and man-made threats, and DER continues to play a key role in supporting global 100% energy access goals.

Based on country and jurisdictional experience around the world, Figure 7 presents supportive actions that could enable the DER Revolution Pathway out to 2050. Specific actions and policy and regulatory areas are not covered in detail, as there is vast literature available on many of these topics.

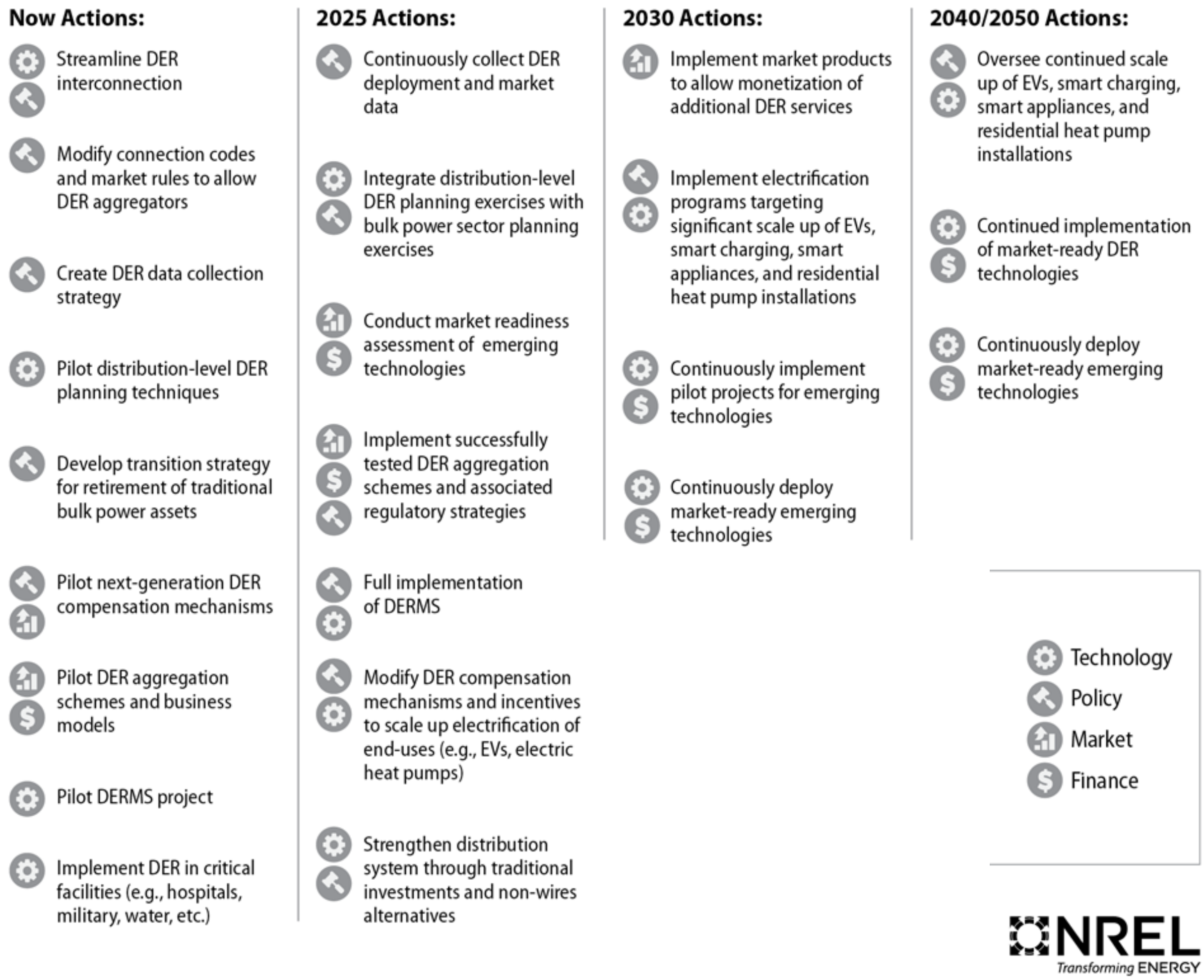

Figure 7. DER Revolution Illustrative Pathway out to 2050 – Supportive Actions

*DERMS—Distributed Energy Resources Management System

Topics to consider in pursuing the DER Revolution Pathway are presented in Section 5.1.1. Countries or jurisdictions may consider emphasizing this pathway to align with high-level objectives or goals for PST, as well as factors unique to their specific setting (as presented in Sections 5.1.2. and 5.1.3).

5.1.1 Issues for Consideration - DER Revolution Pathway

Countries and jurisdictions exploring emphasis on a DER Revolution Pathway can consider the topics described below to support progression along this pathway.

Aggregation—The growth of DER creates an opportunity for these assets to contribute to the reliability and energy needs of distribution systems, as well as transmission systems (as discussed in more detail in the T&D Interactivity Pathway section). Aggregated DER assets have the potential to reliably bid into competitive energy and ancillary services markets[22] to meet both system-wide and local reliability requirements. The additional revenues earned from providing

[22](Trabish 2017)

energy and services to the larger power system could greatly improve the economics of these systems, driving their continued adoption. As DER deployment increases and opportunities for such aggregation grow, issues concerning the rapid and secure communication between the system operator (and ideally the distribution system operator) and DER will need to be addressed. Furthermore, market rules will need to be developed and refined to ensure an open, transparent, and technology-agnostic process for market participation and utility procurements. Questions concerning utility and third-party ownership and operation of distributed, aggregated resources will need to be addressed to safeguard consumer rights while also promoting competition. Box 1 discusses a potential "tipping point" for DER technologies which could be significantly enabled by aggregation.

Box 1: DER Tipping Point

Aggregation of DERs could provide a critical mechanism for reaching a tipping point for DER technologies. As indicated in Figure 8, the period between 2025 and 2030 is anticipated to be a potential "tipping point" for many grid-edge technologies relevant for all pathways that see a larger role for DER. Figure 8 presents this potential tipping point occurring around 2025 and then rapid advancement leading to around 80% penetration of grid-edge technologies perhaps by 2040 or sooner. The assumption of a tipping point around this period informs many of the illustrative projections for DER deployment and penetration level within Figure 7 presenting installed capacity mix out to 2050. This potential tipping point will require a significant shift in power market constructs and operational paradigms as indicated in several key actions in Figure 7 and in other sections, particularly the Distributed Transactional Future section.

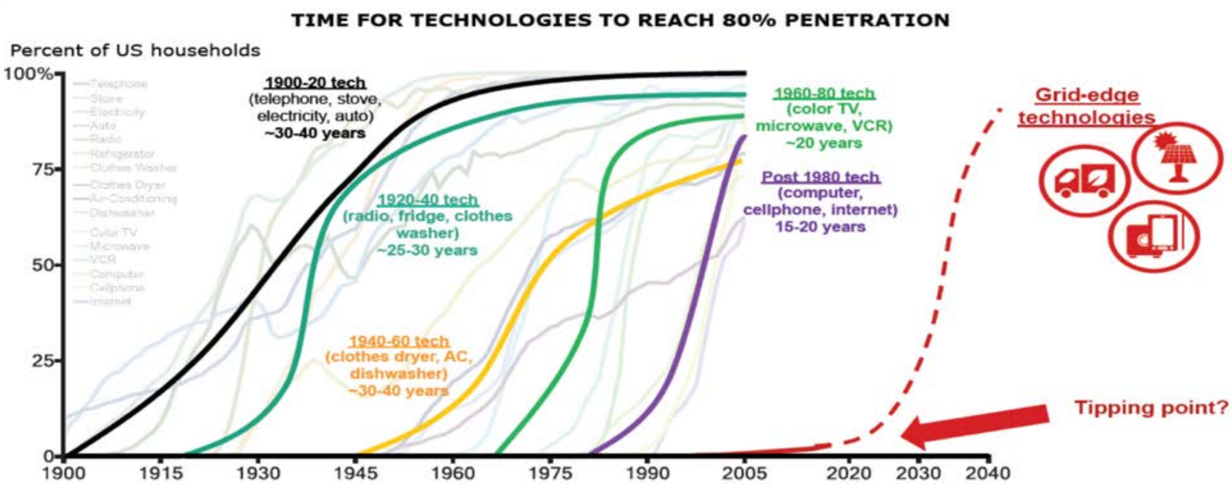

Figure 8. Potential tipping point for grid-edge technologies (Astarloa et al. 2017)

Consumer Demand and Empowerment—Consumer demand for distributed energy resources (e.g., distributed generation and storage, EVs and smart appliances) is growing in many jurisdictions around the world. At the same time, many consumers are increasingly able to manage their energy consumption and production (e.g., with smart meters, digitalization, etc.). With this in mind, decision-makers and utilities are considering new ways to engage and transact with consumers, and these approaches, if desired, can facilitate the DER Revolution Pathway. Figure 9 presents some categories of energy-empowered consumers and some "value propositions" that can be considered in relation to these consumers to scale up a DER-focused PST Pathway. Each country and jurisdiction context will vary significantly, but utilities and decision-makers can consider these value propositions as they work to scale up DER.

Availability of Financing for Consumers—With individual consumers increasingly investing in DER, the issue of financing availability to prospective DER customers may grow in prominence. While early adopters may rely on self-financing, a lack of attractive financing options may inadvertently hinder the pace and ultimate realization of a DER Revolution Pathway. Fostering an environment of abundant, low-cost financing for DER investments is no trivial task, and will benefit from stable policy and regulatory frameworks, educational efforts with financing institutions, and perhaps even changes to laws that might allow utilities, aggregators, and/or installers to provide financing to (and/or sign leases with) prospective DER customers.

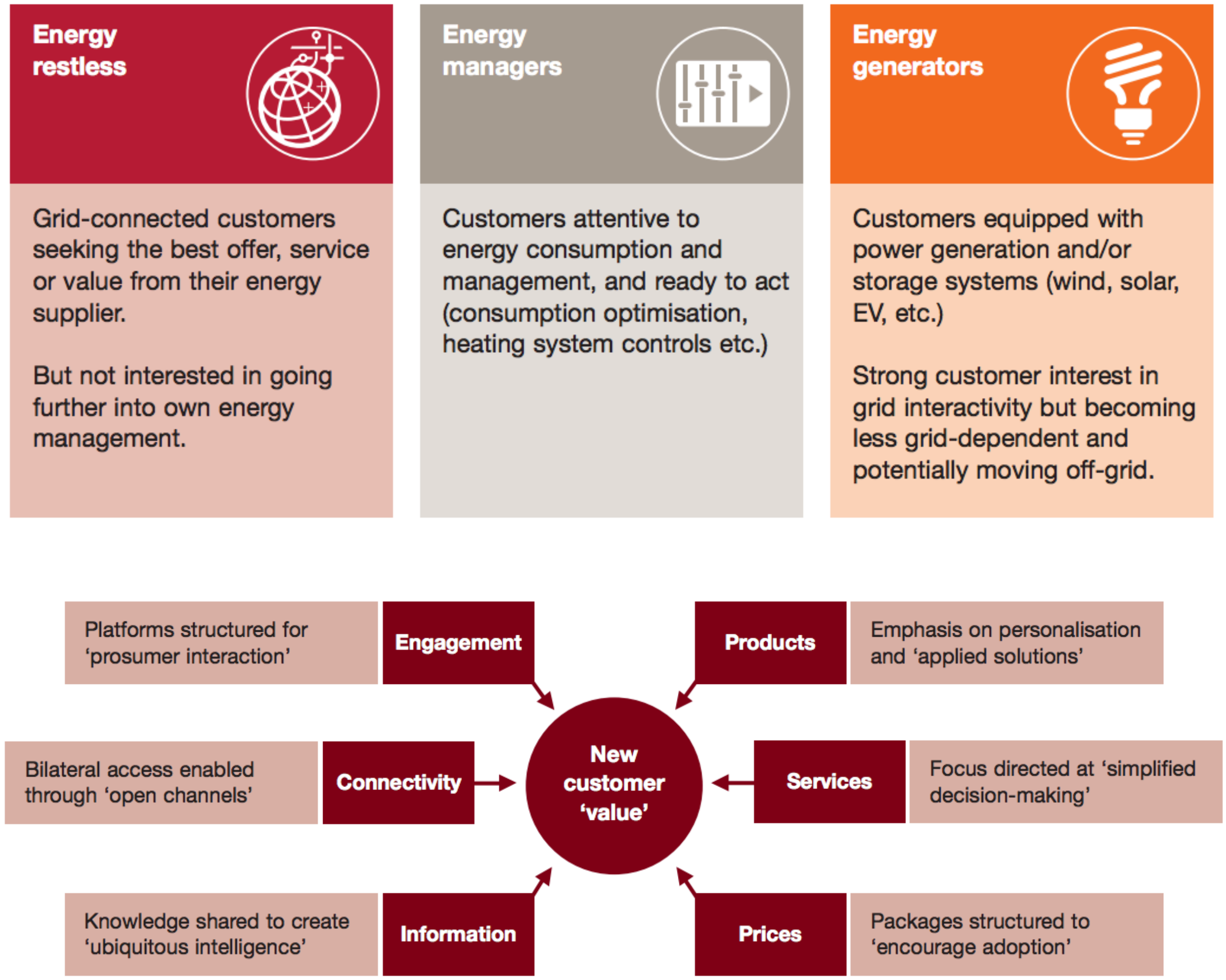

Figure 9. Categories of consumers that will have an influence on the DER Revolution Pathway and opportunities to create value for these consumers

Source: (PwC 2016)

Digitalization—Realization of the DER Revolution Pathway may add significant complexity to the operation and management of the power system, as decentralized resources are scaled up within the electricity markets. Digitalization will be critical to manage these resources efficiently and reliably and can enable improvements to the power system.[23] In particular, with increased digitalization, DER technologies can interact more efficiently, and the responsiveness of demand can be significantly streamlined. Customers will be further empowered with real-time data and automated home energy management systems to make efficient energy decisions benefiting both the consumer and the broader power system. Particularly, as presented in the Distributed Transactional Future Pathway section, digitalization will be a critical enabling factor for supporting the buying and selling within a transactive energy market which may be pursued in many contexts to support PST. Box 2 (pg. 36 of this report) presents further information on the role of digitalization in supporting DER business model innovation.

[23] (Smith 2018)

5.1.2 PST Objectives and Alignment With DER Revolution Pathway

Broader PST objectives, such as supporting energy access or empowering consumers, may lead decision-makers to place a greater relative emphasis on the DER Revolution Pathway. PST objectives that align with the DER Revolution Pathway are presented in Table 2, along with country and jurisdiction examples related to these objectives and the DER Revolution Pathway.

Table 2. PST Objectives and Alignment with DER Revolution Pathway

Objectives	DER Revolution Pathway Alignment	Country and Jurisdiction Examples
Economic Development	The development and installation of DERs is a job-intensive endeavor relative to utility-scale projects. For instance, a 2018 survey of solar jobs in the United States estimated that residential installations require 38.7 jobs per MW of installed capacity, whereas utility-scale solar installations require 3.3 jobs per MW.[24] Beyond project development and installation activities, DER can enable economic development in several other ways: operation and maintenance, software development, and operation and oversight of virtual DER assets, among others. DERs can also play an important role in providing power to large-scale manufacturing facilities, a key economic engine in many countries.	California's DER action plan objective of "economic prosperity" Hawaii microgrid bill with objectives of workforce and economic development[25]
Energy Access	DER, particularly distributed generation and storage, are critical tools for enabling energy access in areas where extension of transmission is cost prohibitive or where other benefits of DG outweigh costs of grid extension. For more information on energy access benefits of DG, please see Cox et al. (2016).	Microgrid policies in Nigeria[26] Power Africa and NREL microgrid support in Sub-Saharan Africa[27]
Environmental Sustainability	Renewable distributed generation can support reductions in GHG emissions through reducing use of centralized fossil generation, directly mitigating emissions.[28] In addition, with DER being closer to load, losses associated with the delivery of electricity can also be avoided. Further, the DER Revolution Pathway is focused on significant scale-up of EVs. When combined with low-carbon electricity, EVs can support further air pollution and GHG emission reductions by replacing traditional combustion engine bus fleets, fleet vehicles and personal vehicles. For more information on environmental benefits of DG please see Cox et al. (2016).	Alignment of California's DER Action Plan with Senate Bill 350 and 32[29]
Resilience and Energy Security	DER can support resilience and energy security in several ways. For example, modularity of systems can allow for greater spatial diversification than large-scale centralized power generation, which are more vulnerable to disasters occurring in a single location. As another example, when	Hawaii Microgrid Bill (2018) to support security of Hawaii's power system[30]

[24] (The Solar Foundation 2019)
[25] (Lee et al. 2018)
[26] (Castalia Strategic Advisors 2017)
[27] (Booth et al. 2018; Reber et al. 2018; Weston et al. 2018; Lockhart et al. 2018)
[28] (Cox et al. 2016)
[29] (CPUC 2017)
[30] (Lee et al. 2018)

Objectives	DER Revolution Pathway Alignment	Country and Jurisdiction Examples
	properly configured, distributed generation and storage can be disconnected from the central grid, providing backup power and diversion of energy to critical loads in the event of a disaster. As a final example, smart grid and energy efficiency technologies can be instrumental in reducing peak demand to enable resilience during extreme weather events, such as heat waves or snowstorms. For more information on resilience and energy security benefits of DG, please see Cox et al. (2017).	
Energy Democratization and Responsiveness to Consumer Demand	Many countries and jurisdictions are seeing increased demand from energy consumers for distributed technologies. In some cases, jurisdictions may explicitly describe consumer empowerment to produce their own energy as an objective for power sector transformation. In other cases, responding to this demand in an effective way could be a driving force in pursuing this pathway.	In South Africa, DER deployment has been largely demand driven by consumers as a response to rising electricity prices and grid outages.

5.1.3 Factors to Consider for DER Revolution Pathway

Building on the PST objectives, specific factors within a country or jurisdiction may lead decision-makers to place a greater relative emphasis on the DER Revolution Pathway. Table 3 presents factors that may lead decision-makers in various contexts to place greater emphasis on the DER Revolution Pathway (building on the objectives that also align closely with this pathway presented above).

Renewable Energy Resource Availability—Availability of solar, particularly in dense urban areas, land-constrained areas, or areas far from the central grid could play a key role in placing emphasis on the DER Revolution Pathway. While other renewable energy technologies also have distributed applications such as biomass, wind and geothermal, solar has the greatest potential for wide distributed generation scale-up based on cost projections (presented above) and maturity of markets globally.

Land Availability—Because DER are typically located on site for electricity users, they have low land-use requirements compared to utility-scale infrastructure projects. Thus, a lack of land availability and/or the presence of dense urban environments with suitable rooftops may influence the decision to pursue the DER Revolution Pathway.

Key Economic Industries—Countries and jurisdictions may choose to place more emphasis on the DER Revolution Pathway to support other economic goals and opportunities such as manufacturing of DER technologies (e.g., batteries and PV panels). This can allow for coupling of power sector development goals with economic development goals. For an off-grid context, the DER Revolution Pathway can also play a critical role in supporting agriculture through the productive use of minigrids[31] and smaller-scale applications such as solar irrigation, which represents a key and growing market in many developing countries.

Market and Institutional Context—Decentralized power markets may lend themselves to the DER Revolution Pathway through providing more opportunities for diverse players and systems in the power market. Several other market factors such as utility insolvency (as in the case of Haiti), customer demand for DER, rising electricity/fuel prices (as seen in South Africa), opportunities for electricity subsidy reduction benefits (as observed in Mexico and Colombia), as well as opportunities for cross-sector electrification can also lead to an emphasis on the DER Revolution Pathway.

Grid Characteristics—The presence of a highly geographically dispersed distribution system exhibiting larger technical losses may influence decisions to pursue the DER Revolution Pathway. DERs can help to reduce technical losses and boost the reliability of weaker distribution networks, while also reducing the total amount of power delivered over transmission networks to more remote locations where DERs are located.

Power System Vulnerability—Certain power system vulnerabilities (especially those related to natural threats such as hurricanes) can also lead to an emphasis on the DER Revolution Pathway. For example, microgrids and storage are being used to support resilience during extreme weather events in several contexts globally.

[31] This paper uses the term microgrids as representative for both microgrids and minigrids. The terms minigrid and microgrid are often used interchangeably. A microgrid consists of DG and interconnected loads within a clearly defined electrical boundary that acts as a single controllable entity with respect to the grid. Microgrids can either be connected to the grid or apart from it. If connected to the grid, microgrids can disconnect to enable island-mode operation (Ton and Smith 2012). A subset of microgrids, minigrids are permanently islanded and are not designed to interconnect to the larger grid. Minigrids may also be referred to as rural energy power systems for islanded power systems. Minigrids are most applicable for the energy access context.

Table 3. Factors Aligning with the DER Revolution Pathway

	Pathways and level of alignment with factors			
	DER Revolution	***Bulk Power Transformation***	***Transmission and Distribution Interactivity***	***Distributed Transactional Future***
Area #1 - Local Power System Transformation Objectives				
Objective: Economic Development				
Objective: Energy Access				
Objective: Environmental Sustainability				
Objective: Resilience and Energy Security				
Objective: Energy Democratization + Responsiveness to Consumer Demand				
Area #2 - Renewable Energy Resource Availability				
Solar				
Wind				
Offshore Wind				
Geothermal				
Biomass				
Area #3 - Land Availability				
Significant Land Availability				
Minimal Land Availability				
Dense Urban Area with Suitable Rooftops				
Area # 4 - Key Economic Industries				
Established Distributed Energy Resource Installer Market				
Established Large-scale RE Manufacturing Sector (e.g., large wind turbines)				
Established DER Manufacturing Sector (e.g., batteries, PV panels)				
Significant Industrial Demand				
Significant Agricultural Demand				
Area # 5 - Market Factors				
Decentralized Power Market				
Centralized Power Market				
Utility Financial Insolvency				
Customer Demand for Distributed Energy Resources				
High Electricity and/or Fuel Prices				
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets				
Significant Cross-Border Trading Opportunities				
Significant Cross-sector Electrification Potential				
Area #6 - Grid Characteristics				
Robust Transmission & Distribution Networks				
Large Balancing Area				

	Pathways and level of alignment with factors			
	DER Revolution	***Bulk Power Transformation***	***Transmission and Distribution Interactivity***	***Distributed Transactional Future***
Strong Grid Management Capabilities				
Area #7 - Power System Vulnerability				
Dependence on Imported Fuels				
High Vulnerability to Natural Threats				
High Vulnerability to Physical or Cybersecurity Threats				

Pathway Alignment Color Legend

- Indicates a strong alignment of the factor with the pathway
- Indicates a moderate alignment of the factor with the pathway
- Indicates weak alignment of the factor with the pathway

5.1.4 DER Technology and Business Model Evolution Over Time

Technology and business model evolution and disruptions will have critical implications for how the DER Revolution Pathway may be pursued over time. A table comparing key DER technology cost projections to bulk power from an ultra-low-cost perspective out to 2050 is presented below and can further inform choice of pathways. Building on this information, there is a need to further assess technology costs over time at the country level based on localized data. While the information below can provide a starting point for considering this pathway, much more granular analysis is needed to inform country-specific pathways. For example, costs may be higher in areas with supply chain challenges and/or in rural and remote areas, especially with difficult landscapes.

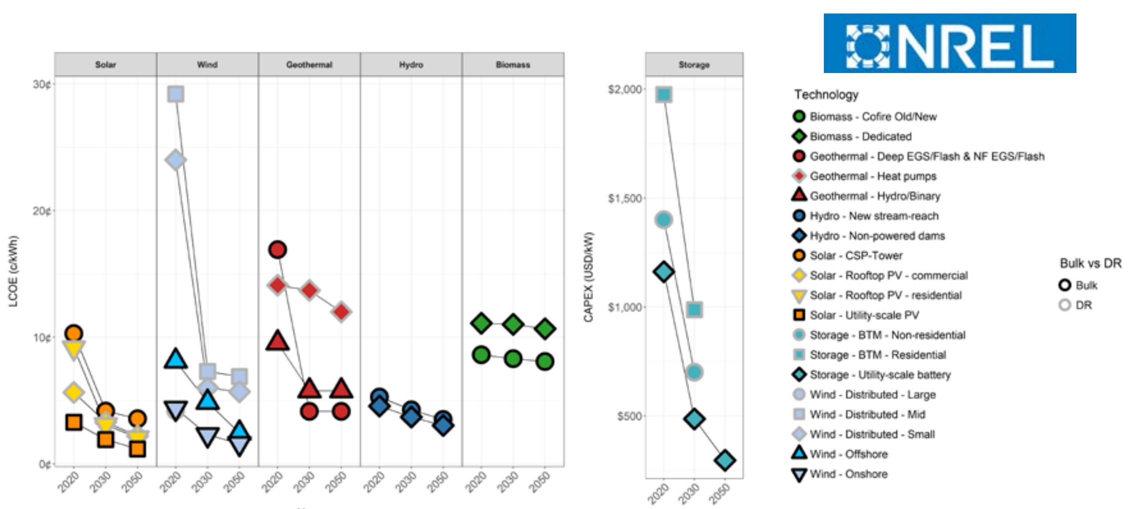

Figure 10. Comparison of DER vs. bulk power low cost technology projections to 2050

Source: U.S. Annual Technology Baseline data

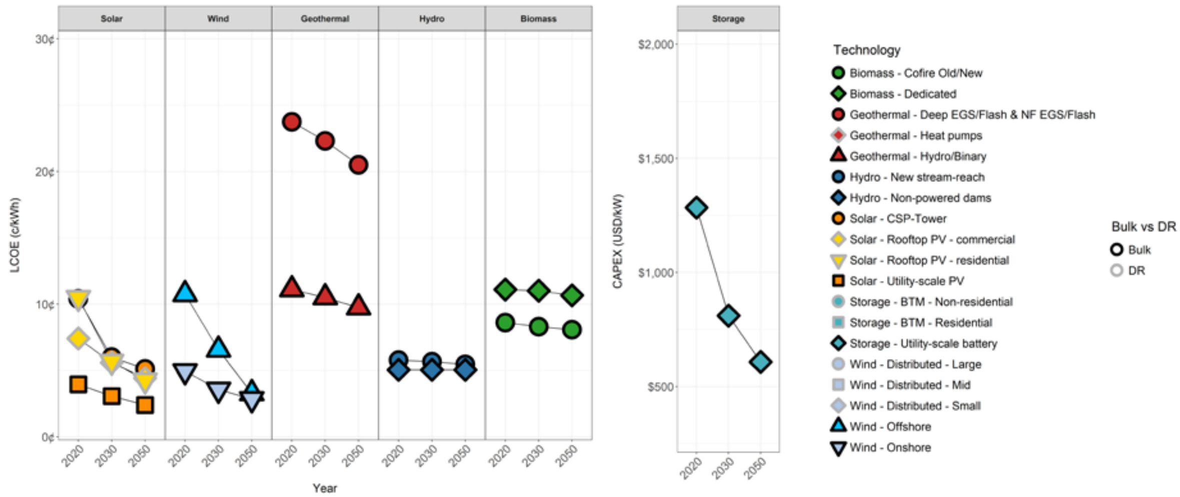

Figure 11. Comparison of DER vs. bulk power mid cost technology projections to 2050[32]

Source: U.S. Annual Technology Baseline data

The assumptions for the costs presented in Figure 11 are presented in Appendix A and could be enabled through the key policy, market, finance, and technology actions presented in Figure 7. Rapid cost reductions in distributed storage and solar, in particular, could provide a significant impetus for countries and municipalities to pursue an emphasis on the DER Revolution Pathway. Further, key technology disruptions and innovative business models, highlighted below, could also lead countries place a greater emphasis on the DER Revolution Pathway.

Building on the technology cost projections, many new and cutting-edge technologies and business models associated with these technologies are expected to significantly transform the DER sector over time. Figure 12 provides a snapshot of some of these technologies, as well as an indication of their potential impact and time required to reach market. As previously highlighted, these innovations and technologies would need to be considered in relation to unique circumstances in individual countries and jurisdictions. Nevertheless, these technologies could play an important role for decision-makers as they consider a possible emphasis on a DER Revolution Pathway. This graphic was developed based on expert opinion of the authors and can be considered illustrative based on many uncertainties regarding disruptive technologies.

[32] Additional technologies are included in the 'Low Cost' figure due to the availability of data.

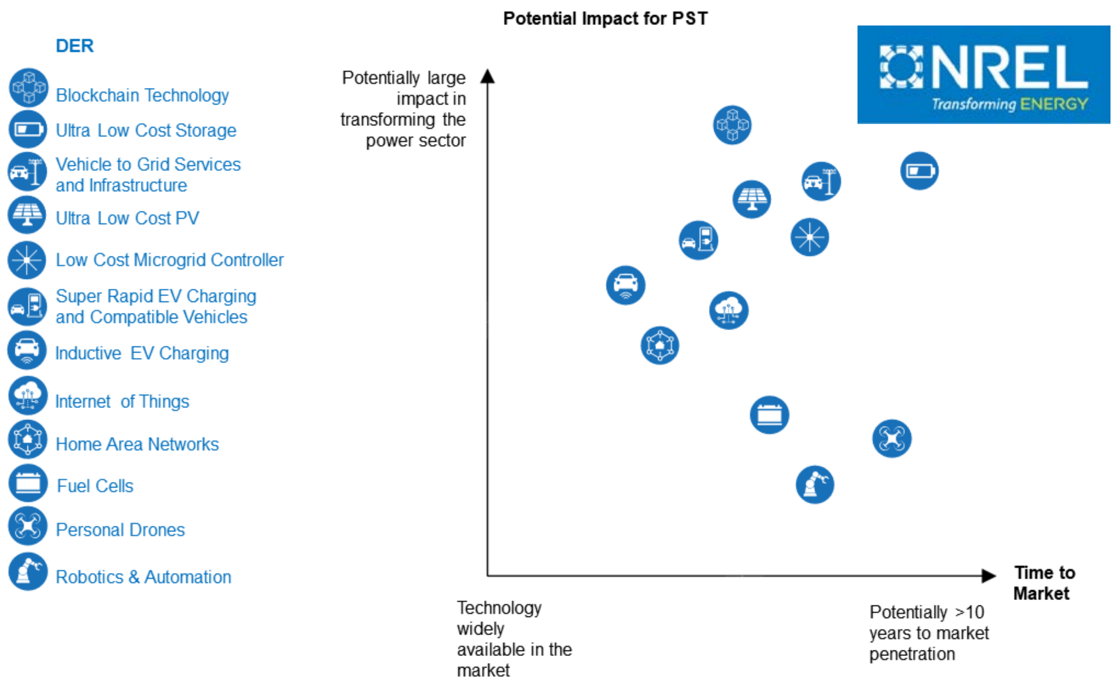

Figure 12. Potential impact and time to market for disruptive technologies

Innovative business models for these technologies are also expected to evolve over time, helping to unlock consumer financing while simultaneously moving these technologies closer to market readiness. Many innovative business models to support DER are already being tested around the globe. In particular, business models to enable distributed storage deployment are being implemented in several developed countries and can provide useful insights for scale-up in developing countries where residential storage markets are still largely nascent. Key DER business models are presented in Box 2. Importantly, many of these business models, and DER more broadly, is often enabled by utilities that are subject to a regulatory framework that includes revenue decoupling, further highlighted in Box 3.

Box 2. DER Revolution Pathway: Innovative Business Models

DER ownership structures, as well as business models and approaches, will play a key role in markets pursuing the DER Revolution pathway. Many of these structures and approaches have been implemented in developed countries and have significant potential for scale-up in developing country markets.[33]

DER Ownership Models[34]

Customer Ownership—In this model, customers directly purchase DER from installer companies and manage their use of resource—sometimes using energy management software—in response to the retail tariff they are subject to.

Third-Party Ownership—DER can also be financed by third-party entities and installed at commercial or residential buildings, with users being charged a "subscription" or "lease" fee for the unit. The fee is either fixed or calculated as some percent of energy savings. For DER systems with storage, the third party may be able to control the unit and dispatch it to yield further value from the distribution utility or system operator.

Utility Ownership—Utilities can potentially install, own, and operate DER systems on residential or commercial properties. This can allow the utility to exhibit more direct control these assets during peak hours and enable demand response. These programs tend to take place in regulated market segments where power sector regulators help to determine a fair level of compensation for retail customers who host DERs for the utility.

DER Business Models and Approaches

DER Aggregation Model—As DERs are smaller-scale, there is often a need for aggregation to enable investment and utilize the grid services they are capable of providing on a larger-scale. Importantly, aggregation does not necessarily rely on a single model for DER ownership and is often linked to the other business models discussed in this textbox. As one example, DER services can be aggregated by a third party and sold to utilities to help operate the power system, such as providing customer demand response by utilizing behind-the-meter storage systems. Similar aggregation schemes can also be conducted by utilities themselves in regulated programs.

Solar "Plus"—Some installation companies are coupling distributed PV systems with other systems, such as battery energy storage systems or energy efficient appliances. In the future, this Solar "Plus" model is likely to scale and include approaches such as solar + geothermal heat pumps and solar + electric vehicles, among others. Thus, this approach could be an important aspect of a DER Revolution pathway.

Microgrids for Energy Access—Microgrid business models have been evolving over the last decade as technology costs continue to decline, and there is an increasing understanding of the benefits of "anchor customers" or productive uses of microgrids to support effective business models and increase revenues. Effectively designed payment and tariff models are also critical for microgrids. In some cases, micro-grids are also being coupled with demand response to support successful outcomes.[35]

Storage-as-a-Service—An approach that has taken shape in developed countries is the leasing of behind-the-meter storage devices to customers, which similar to solar leasing models, helps to address financing barriers associated with high upfront capital costs.[36]

[33] (Eller and Gauntlett 2017)
[34] (Martin 2018)
[35] (Booth et al. 2018)
[36] (Maloney 2018)

Box 3. Utility Business Model Evolution to Enable DER

Currently, most utilities earn revenues through: (1) making approved capital expenditures; and (2) the volumetric sale of electricity under the applicable retail tariff. Regulators determine an acceptable rate of return on expenditures and adjust electricity tariffs accordingly based on expectations of sales. However, coupling electricity sales with revenue may lead to:

- an incentive for the utility to grow energy sales at the expense of energy efficiency and self-generation;
- a bias towards large capital expenditures (CAPEX) over seeking operational expenditure (OPEX) savings from DER deployment;
- a bias against risk and innovation at odds with the growing resources available to the utility; and
- a risk allocation in which ratepayers are often forced to pay for unsuccessful investments.[37]

There are a variety of regulatory strategies available to remove utility disincentives to support DER. First, through revenue decoupling schemes, regulators sever the connection between utility revenues and the volume of electricity sales. Rates for electricity are instead set to ensure the utility will earn enough to cover the costs of generation and maintaining the grid, removing the incentive to maximize energy sales and reducing the risk utilities face from fluctuating or decreasing energy demand.[38]

Regulators can also better align the interests of the utility with those of the broader public through performance-based regulation (PBR). PBR provides a framework to: (1) set utility goals and targets; (2) measure utility performance in achieving these goals and targets; and (3) link utility performance to utility compensation, including investor returns and executive compensation.[39] By setting predetermined metrics for performance, regulators can create financial incentives for activities that utilities might not normally be motivated to pursue, such as the streamlining DER interconnection processes or energy efficiency programs.[40]

Separating utility costs from utility revenue through Multiyear Rate Plans (MRP) is another way to align interests, by encouraging cost containment that benefits end consumers.[41] Using MRPs, utility compensation is fixed for a set period based on forecasted expenditures, rather than on a utility's historical cost of providing service. Under MRPs, utilities have a strong incentive to reduce costs, as they will see additional profits, as opposed to traditional, annual ratemaking, in which revenue and profit are directly tied to costs. If designed appropriately, these rate plans may create room for utilities to consider CAPEX and OPEX savings on even footing.

Finally, allowing the utility to profit from savings it generates through Shared Savings Mechanisms (SSMs) can help adjust utility behavior and offset lost revenues from innovative programs. Under SSM, utilities that reduce their costs compared to a baseline are allowed to keep a fraction of the windfall as profit, with the rest passed along to ratepayers.[42] In this way SSM can be used in incentivize investments in energy efficiency or DER programs, which may be otherwise passed over.[43]

As the electricity industry continues to experience the democratization and decentralization of energy resources, shifting away from traditional regulatory approaches through a combination of the above mechanisms, among many others, may allow utilities to reduce costs and emissions without sacrificing system reliability or their own revenue sufficiency.

5.1.5 Country/Jurisdiction Pathways and Insights

The following sections highlight three countries, Mexico, Haiti, and Puerto Rico, where key objectives and factors are leading to an emphasis on the DER Revolution Pathway within the power sector. Factors and objectives aligned with the DER Revolution Pathway in each country

[37] (Cross-Call et al. 2018; Moore 2018)
[38] (NREL 2009; Sullivan and DeCostanzo 2018)
[39] (Lowry and Woolf 2016)
[40] (Chang 2018)
[41] (Lowry et al. 2017)
[42] (Cross-Call et al. 2018)
[43] (Opalka 2017)

are described, as well as key insights on successes and good practices and needs for further support in these particular contexts.

Mexico

The Mexican Government has prioritized expansion of the distributed PV market to align with broader clean energy and climate goals. Overall, the country seeks to have 35% clean power by 2024 and 50% clean power by 2050. The liberalization of Mexico's power market under the Energy Transition Law opened up the power market to competition and "created a unique moment in Mexican history to set policy, regulations, and technical procedures to encourage the growth of the DG market in Mexico." [44] In addition, Mexico has built a solid policy framework to support DG, including establishing DG goals and objectives, codifying interconnection requirements, and defining compensation mechanisms. While Mexico is pursuing both bulk-power and DER-focused actions, several key objectives and factors highlighted in Table 4 have led to significant support for DER deployment.

Most notably, the key factors that have led Mexico to emphasize DER deployment are:

Renewable Energy Resource Availability—Mexico has significant solar resource potential, particularly in the northern part of the country, that can be utilized quickly (i.e., short development period) with DER technologies, particularly distributed solar.

Land Availability—Dense urban areas and industrial parks (with suitable rooftops) in Mexico also lend themselves to DER development.

Key Economic Industries—Within Mexico's large industrial and agricultural sectors, DER technologies are playing a growing role in supporting energy needs.

Market and Institutional Context—To address consumer demand for DER, a policy objective was put forth to improve energy democratization and consumer choice, as stated in the Energy Transition Law. This policy objective aligns closely with support for DER technologies and addresses a key market factor to meet consumer demand for DER. As an additional key market factor, analysis by the Mexican government found that scaled up DG deployment in Mexico in certain consumer market segments could lead to a significant reduction in electricity subsidy requirements, benefiting the country's overall national budget and providing further motivation to pursue the DER Revolution Pathway in particular areas of the country.[45]

[44] (Zinaman et al. 2018)
[45] (Secretaría de Energía 2017)

Table 4. Factors Contributing to DER Emphasis in Mexico

Factors for Mexico	Current relevance of factor	DER Revolution	Bulk Power Transformation	Transmission and Distribution Interactivity	Distributed Transactional Future
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-Scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-Sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

As indicated in the table above, in addition to being currently well-aligned with the DER Revolution Pathway, Mexico is also poised to become a leader in pursuing the Distributed Transactional Future Pathway (complementary to the DER Revolution) covered in Section 5.4.

Successes and Good Practices in Mexico Enabling DER Deployment:

Mexico is a leader in developing policy to enable a DER Revolution Pathway, particularly for DPV. The following successes and good practices can inform activities in other countries.

Promotion of Energy Democratization and Consumer Choice—Mexico's Energy Transition Law encourages greater energy democratization and consumer choice—policy priorities which naturally point to a large role for DER technologies that allow for customers to become "prosumers" of energy. Clearly stating policy objectives like these provides the justification for developing a comprehensive DER-enabling policy framework.

Effective Policy Design and Robust Stakeholder Engagement—Mexico has developed some of the key building blocks of DER deployment—establishing DG goals and objectives, codifying interconnection requirements, and defining compensation mechanisms. Moreover, Mexico has engaged stakeholders across other power sector institutions and the private sector through public and transparent processes to receive feedback that informs policy design.

Detailed Analysis of DPV Opportunities and Value to Inform Public Policy—Mexico's Energy Transition Law obligated the Ministry of Energy (SENER) to study the potential benefits of distributed generation and energy efficiency for the state, customers, and the environment. Together with other power sector institutions and universities, SENER led an analysis that ultimately determined distributed solar deployment could provide significant cost savings to the state, customers, and reduce CO2 and water use. The study revealed that public policy intervention would be necessary to better align the highest potential benefits for the state given the types of customers incentivized to deploy DG. Analyses like these bring data-driven analysis to inform public policy questions, build consensus about the value of DER among stakeholders, and shed light on potential public policy solutions to meet DER goals.[46]

Liberalization of the Power Market—The Energy Transition Law led to the unbundling of state-owned electricity company CFE into separate companies for retail, distribution, transmission, and generation segments. This effort to decentralize the Mexican power market and open it up to further competition—along with regulatory efforts to enhance DER interconnection processes and compensation structures—helped to enable a scaled-up level of DER deployment.

Key actions to further enable DER revolution in Mexico:

Improve Financing Availability—DG systems are a capital expense out of reach for most consumers in Mexico without access to financing. Most DG systems in Mexico to date have been cash-financed; loans and the few other financing programs that do exist often have higher interest rates and shorter terms. There is little public awareness that some financing programs even exist. Therefore, scaling up financing programs for DER and raising awareness of current programs could further facilitate the DER Revolution Pathway.

Develop Shared Solar Program and Virtual Net Energy Metering Regulations—Rooftop availability may limit the scale up of DPV, pointing to the importance of alternative shared solar models where multiple customers subscribe to a portion of a larger, off-site DG system and receive bill credits virtually (i.e., virtual net metering). Regulation for both shared solar and virtual net metering in Mexico are currently in nascent phases, but could be scaled up over time.

Develop Uniform National Installer Certification Standards and Equipment Standards—A strong DG market that attracts investors and maintains consumer confidence requires deployment of high-quality DG equipment by well-trained professionals. Several institutions in Mexico that offer financing have installer training and equipment requirements, but national, mandatory installer training programs or certification standards would further help safeguard against installation quality concerns. Uniform equipment standards would also have the additional benefit of ensuring cross-compatibility between the components of different manufacturers, potentially reducing both equipment and installation costs.

Further Consider Subsidized Retail Electricity Tariffs—Retail tariffs strongly influence the economics of deploying a DG system for customers. Currently, several customer classes in Mexico, including low-usage residential customers, agricultural customers, and some public service users, pay highly subsidized retail electricity rates. While these subsidies are in place as a matter of broader social policy, they do have the impact of muting economic incentives to deploy DG.

Haiti

A unique combination of power sector objectives and factors are leading the Government of Haiti to focus on a DER Revolution Pathway for power sector transformation. As a country where approximately 60% of the population is unelectrified, energy access serves as a key objective for the power sector. In addition, improving the reliability of power is seen as a key

[46] (Secretaría de Energía 2017)

need to support economic development through manufacturing and other opportunities. In rural areas, agriculture is an important industry, and connections across energy and agriculture are another area of emphasis. Finally, as an island nation, the modularity and geographic diversity of distributed generation may enable improved resilience to hurricanes and other natural disasters.

In addition to the principal objectives described above, key factors that are leading Haiti to emphasize a DER Revolution Pathway are:

Renewable Energy Resource Availability—Haiti is an island nation with abundant solar, helping to make the broader deployment of DPV a feasible and attractive option. This is well-aligned with the DER Revolution Pathway.

Land Availability—Haiti has low land availability, which also lends itself to the DER Revolution Pathway.

Market and Institutional Context—A notable factor influencing Haiti's emphasis on DER deployment, especially in rural areas, is the financial insolvency of the country's electric utility. Haiti's utility is currently unable to recover costs for electricity and, thus, cannot invest in grid expansion or improvements. Under this context, Haiti is pursuing an approach to energy sector development that focuses on significant deployment of microgrids and regional concessions for smaller-scale LNG and renewable energy power plants which are not connected (currently) to the central electricity network. As an island nation, costs of importing and transporting diesel is also a significant factor in pursuing hybrid solar minigrids.

Power System Vulnerability – Similar to other islands in the region, Haiti is extremely vulnerable to natural disasters. Diversified energy development (rather than reliance on a few central power plants) can allow for greater resilience during and following disasters.

Table 5. Factors Contributing to DER Emphasis in Haiti

Factors for Haiti	Current relevance of factor	DER Revolution	Bulk Power Transformation	Transmission and Distribution Interactivity	Distributed Transactional Future
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

	Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future
	Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future
	Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

	Indicates a strong alignment of the factor with the pathway
	Indicates a moderate alignment of the factor with the pathway
	Indicates weak or no alignment with the factor for the pathway

Pathway Score Legend

	Indicates a strong alignment of the country/jurisdiction's factors with the pathway
	Indicates a moderate alignment of the country/jurisdiction's factor with the pathway
	Indicates weak alignment of the country/jurisdiction's factor with the pathway

Successes and Good Practices in Haiti Enabling DER Deployment:

Political leadership for microgrid deployment—Haiti's regulator ANARSE and Energy Cell within the Ministry of Public Works, Transportation, and Communication are championing efforts to scale up microgrid deployment in the country through development of a Request for Proposals (RFP) for microgrids, with 54 total sites planned, and further work to develop a broader policy and regulatory framework.

Design of policies for microgrids– Building on the leadership noted above, ANARSE and Energy Cell included key elements within the RFP that lay the foundation for development of broader regulation and policies. The microgrid RFP and concession agreements with developers encompass key policy and regulatory pillars including clarity regarding licensing, tariff regulation, service standards, technical standards, and arrangements if the main grid arrives.

Development of data-driven tools to inform decisions – In collaboration with the World Bank, Energy Cell and ANARSE developed a detailed geospatial mapping of microgrid opportunities and use for critical facilities. Additionally, an RE Data Explorer (https://maps.nrel.gov/rede-haiti/) to support broader renewable energy development in Haiti was released in collaboration with the National Renewable Energy Laboratory.

Key actions to further enable DER Revolution Pathway in Haiti:

Develop a broader energy sector strategy – Haiti's energy sector strategy is currently out of date and a stakeholder-driven visioning and broader strategy development process that articulates potential aspects of the DER Revolution in Haiti could prove beneficial.

Create a robust policy framework and standalone policies for microgrid scale up – Building on the RFP and regulatory pillars within the RFP, standalone policies and regulations could be developed to create a more robust policy environment for microgrid deployment in Haiti.

Train microgrid developers – Further training of local microgrid developers couldo support successful microgrid outcomes in Haiti. Key topics for training could include: assessing demand, connecting with productive use, system design, monitoring and evaluation, etc.

Broader DG policy design – As Haiti scales up a more distributed energy future, PST could benefit from the design of a broader distributed generation law that defines DG and puts in place regulatory elements related to tariffs, etc. There could be opportunities for peer learning with the Dominican Republic based on the country's recently developed DG policy and scale up of rooftop PV in certain jurisdictions.

Puerto Rico

In September 2017, the island of Puerto Rico was struck by two consecutive hurricanes (Irma and Maria), leading to extended blackouts, which reached 9-10 months in duration in some regions. Hurricane Maria caused widespread damage to the island's transmission network, severing the connection between two of the most critical generating facilities in the south (Aguirre and Costa Sur, totaling over 2 GW) and the high demand centers in the northeast (which accounts for approximately 65% of the island's electricity demand).[47] In the aftermath of the devastation, the government of Puerto Rico has decided to rebuild with a focus on clean energy and resiliency. In March 2019 the legislature passed the Puerto Rico Energy Public Policy Act, which sets a Renewable Portfolio Standard, which requires 20% renewable penetration by 2025, 50% by 2040, and 100% by 2050, inclusive of distributed energy sources.[48] The bill also included several measures to promote the interconnection of renewable energy generators to both the transmission and distribution system. Furthermore, the government released guidelines on the development of microgrids ranging from single home to large-scale, which allowed microgrids to sell energy back to the grid and directed the utility (PREPA) to develop interconnection rules for microgrids.[49] While Puerto Rico's current factors are most aligned with an emphasis on the DER Revolution, several actions are also being pursued to support T&D Interactivity, which could lead to a greater emphasis on that pathway in the future.

The factors that have led Puerto Rico to emphasize the DER Revolution Pathway are:

Renewable Energy Resource Availability – Puerto Rico has excellent solar resources, which can make both centralized resources, such as utility-scale PV and wind, as well as distributed resources, such as rooftop solar and battery storage, more attractive. The presence of variable generation resources on both the distribution and transmission systems underscores the need for increased cooperation to make the most of these resources regardless of their position in the power system.

Market and Institutional Context – Puerto Rico has a remote, isolated grid that currently relies on expensive imported fuels, leading to higher electricity prices which can drive both centralized renewable assets and distributed renewable resource adoption. Puerto Rico's inability to rely on large balancing areas or on cross-border trade means that it will need to balance fluctuations in generation and consumption using only the resources on the island, further increasing the need to

[47] (New York Power Authority et al. 2017)
[48] (Ellsmoor 2019)
[49] (Puerto Rico Energy Commission 2018a)

engage resources both on the transmission and distribution level. Another element driving distributed resource adoption in Puerto Rico is the ubiquity of subsidized customers and its insolvent utility, PREPA. This combination makes on-site customer generation an attractive, more financially sustainable alternative to direct electricity subsidies.

Power System Vulnerability – Puerto Rico is highly susceptible to hurricanes and tropical storms. This is exacerbated by an overall weak grid infrastructure, a preponderance of isolated communities, and concentrated urban areas which are a significant distance away from centralized generation assets. This combination means that in Puerto Rico, customers are more likely to face prolonged outages in the aftermath of storms. Hurricane Maria has underscored the importance of developing resilient microgrids that can operate in isolation or in tandem with the larger power system. Current joint efforts between Puerto Rico and the mainland United States have discussed the benefit of dividing Puerto Rico's power system into a set of large microgrids, with smaller microgrids able to satisfy power needs for isolated communities. In addition to meeting local demand, these microgrids will be able to integrate and coordinate distributed resources that can provide services to the larger power system.[50]

[50] (New York Power Authority et al. 2017)

Table 6. Factors Contributing to DER Revolution Emphasis in Puerto Rico

Factors for Puerto Rico	Current relevance of factor	DER Revolution	Bulk Power Transformation	Transmission and Distribution Interactivity	Distributed Transactional Future
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-Scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

Successes and Good Practices in Puerto Rico Enabling DER Revolution Pathway:

Market Liberalization – In response to PREPA's outstanding debts, the government announced plans to restructure the debt and open the generation market segment to private developers in an attempt to improve PREPA's financial solvency[51];

Private Authorization for Microgrids– As part of its "Regulation on Microgrid Development," the Puerto Rico Energy Commission granted official recognition and authorization for private enterprises or citizens to build and operate microgrids and authorization to sell excess distributed energy back to the bulk power system;[52]

T&D Hardening Plan – As part of a large coalition of stakeholders, including utilities from New York, the government of Puerto Rico and PREPA outlined a plan to overhaul and harden the transmission and distribution system to ensure effective and reliant energy delivery throughout the island[53];

Maximum Interconnection Times – A new renewable energy mandate, signed into law in April 2019, includes provisions to ensure the timely interconnection of distributed resources, including a maximum deadline for medium sized PV-systems and an automatic interconnection process for smaller solar PV systems.

Key actions to further enable DER Revolution Pathway in Puerto Rico:

Ancillary Services from DER – In order to maximize the benefit of the growing number of resources on the distribution system, as well as to improve the reliability of the entire power system, Puerto Rico regulators could provide technical assistance and guidelines to allow

[51] (Caribbean Business 2018; Dzierzak and Greenemeier 2018)
[52] (Puerto Rico Energy Commission 2018b)
[53] (New York Power Authority et al. 2017)

distributed resources to provide ancillary services to the transmission system operator (TSO) or distribution system operator (DSO);

Coordinated T&D Actions – To improve the efficiency of all of the assets on the power system and prevent conflicting operation of the T&D system, utilities and regulators could initiate and encourage discussion on how to coordinate the actions between the private entities which may operate generation assets in the future and regulated entities which operate T&D assets separately;

Harmonized planning and operation – Regulators could help maximize the benefits of new assets on the power system and help harden the power system by formulating joint planning, communication and operation procedures between the new TSOs and DSOs and encourage stronger grid management capabilities through funding for smart infrastructure and trainings;

Low-income assistance – Regulators and other government officials could ensure equitable investments in and deployment of DERS by providing financial assistance to lower-income Puerto Ricans, which could simultaneously reduce subsidy payment requirements.

5.1.6 Possible Interventions to Enable Significant Scale Up of the DER Revolution

Building on information in the previous sections, five key interventions that could support the DER Revolution Pathway are presented below.

Collection and public dissemination of local data on DER deployment, technology cost and performance trends, and other relevant aspects to inform data-driven decision-making and regularly updated planning exercises for the energy sector;

Accounting of DER in integrated resource plans (IRP) and other types of power sector planning processes, development of metrics to track DER deployment, and continual iteration on power sector plans to include disruptive technologies and business models that may arise;

Piloting and scale-up of DER aggregation schemes, particularly in more developed renewable energy markets;

Designing the next generation of DER policy and regulatory frameworks, which provide fair compensation and investment certainty for DER customers and enable broader participation of DER in the power system; and

Support for robust policy frameworks, investment models and effective project development for off-grid DER solutions, in particular minigrids.

5.2 Bulk Power Transformation Pathway

The Bulk Power Transformation Pathway is characterized by scaled-up integration of utility-scale renewable energy resources, improvements to the transmission grid to more effectively utilize existing (and overbuilt in some cases) equipment on the system, and improved power system flexibility.[54] Finance availability can support large-scale infrastructure development plans under this pathway. This pathway can also be enabled by bulk power market reforms that encourage valuation of carbon, power system flexibility services, and transmission efficiency, as well as interactivity with DERs. As in all pathways described in this report, energy efficiency can play role in helping to reduce both overall electricity demand growth as well as peak demand growth. Several emerging elements could enable this pathway out to 2050, including:

Bulk power technology cost and performance improvements and innovations

Improved operational capabilities to support management of power system flexibility resources

Increased interconnection with neighboring power systems

Faster (e.g., sub-hourly) power system operational dispatch

Reduced capital uncertainty for bulk clean generation and storage

Augmentation of power markets to better value grid services from a range of resources

Introduction of additional competition in various power market segments (e.g., unbundling of vertically integrated utilities)

Implementation of performance-based regulatory constructs to unlock utility business model innovation

Deployment of advanced power system operational data collection systems that can remotely identify issues (in lieu of sending utility staff) and, in some circumstances, become “self-healing”

Development of relevant cybersecurity standards to prevent cyber and physical disruptions.

Under the Bulk Power Transformation Pathway, conducting energy planning exercises that examine the impact of infrastructure investment decisions over longer periods of time than is conventionally done today may increase the likelihood of both reducing emissions and avoiding technology "lock-in." A future scenario with significant technology lock-in may result in the stranding of a substantial amount of assets that could impact the future financial health of utilities and slow economic growth. In practice, examining infrastructure decisions over a 20–30-year period may be inadequate to support power system transformation efforts, particularly if most large capital investments being considered have economic lifetimes of 40-60 years. It can be a good practice to utilize power sector planning exercises to track and analyze impacts across horizons of at least 50 years, in order to fully consider impacts over the longer term. As the Bulk Power Transformation Pathway focuses on larger-scale investments, conducting planning exercises with longer timeframes can be an important strategy.

[54] Power system flexibility can be defined as ”the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply” (IEA 2019).

Based on vast country experience, Figure 13 presents supportive actions that could enable the Bulk Power Transformation Pathway out to 2050.

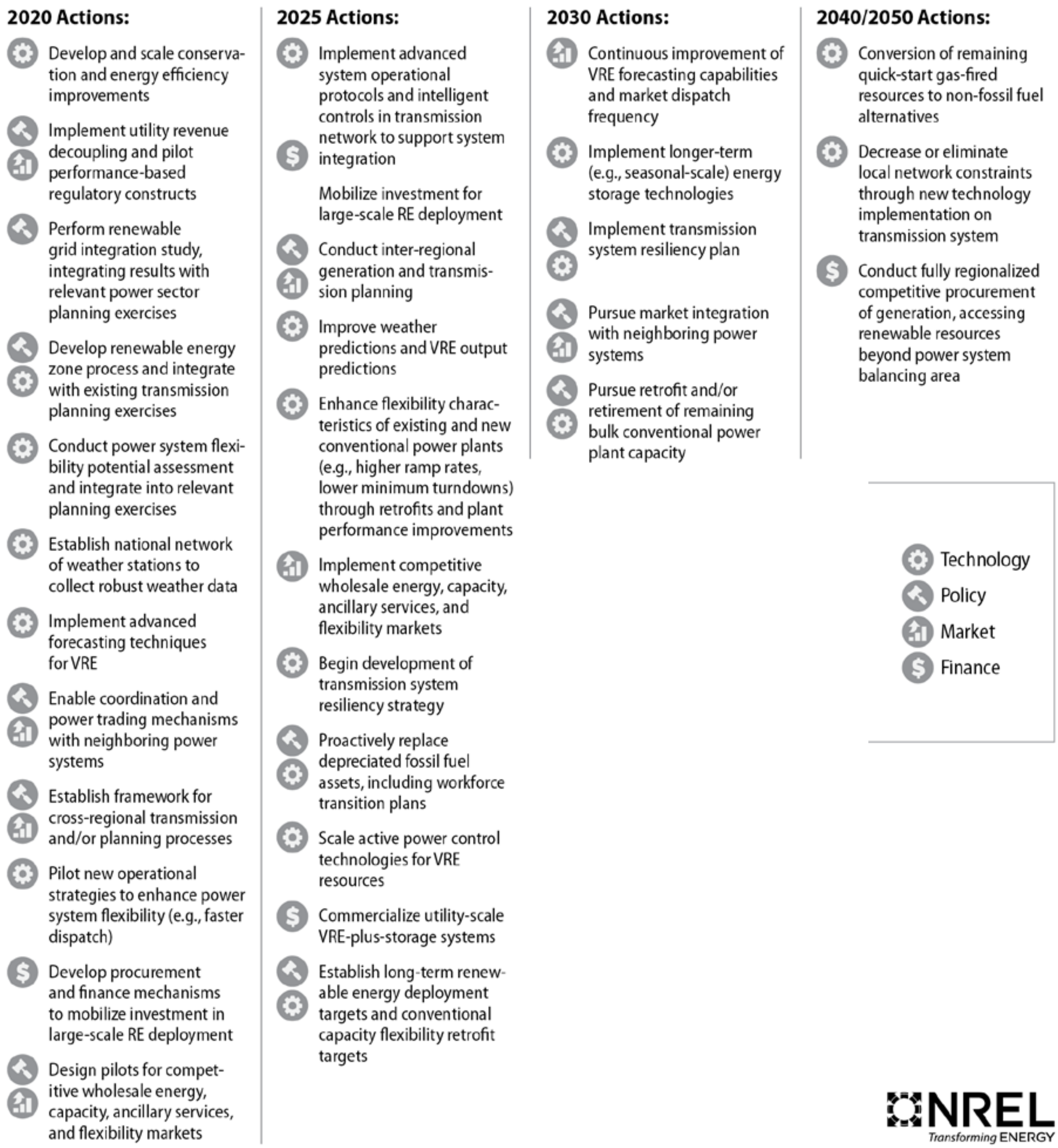

Figure 13. Bulk Power Transformation Pathway out to 2050 – Supportive Actions

5.2.1 Issues for Consideration - Bulk Power Transformation Pathway

Variability and Uncertainty – Increasing utility-scale variable renewable energy, such as wind and solar, introduces additional variability and uncertainty into the supply-side of the bulk power system. For instance, a sudden change in weather can reduce solar energy outputs dramatically. Therefore, unlike system planning with traditional energy resources, which relied primarily on dispatchable or baseload technologies, a new approach including variable renewable energy

(VRE) generation forecasting and flexibility analysis is critical to making the system operate reliably and economically.[55]

Power System Flexibility – Power system flexibility[56] is becoming a global priority to support power system transformation. The type, amount, and location of VRE resources present on a power system are key drivers of power system flexibility requirements. System flexibility can originate from power plants (both existing and new), electricity networks, energy storage, and distributed energy resources. It can also be enhanced through changes to operational practices by system operators (e.g., faster dispatch, improved VRE forecasting). Periodically identifying system flexibility requirements, as well as formulating system flexibility potential estimates, is a good practice to support power system transformation efforts. Based on these activities, it is also critical to design effective regulations, policies and market mechanisms to incentivize long-term investments in flexibility and short-term provision of flexibility.

Grid Integration Studies – In order to accommodate significant VRE, conducting grid integration studies can be an important undertaking to enhance understanding of the impact VRE on the grid. A complete analysis could include a suite of scenarios that are designed to inform power sector stakeholders on the capability and needs of a power system to accommodate significant VRE, as well as any need to increase system flexibility and/or stability.[57] Aligning modeling scenarios with various established and aspirational renewable energy deployment targets can help to elucidate the costs, benefits, obstacles, and opportunities associated with large-scale VRE deployment.

Cutting-Edge and Complementary Technologies – In cases where higher GHG-emitting power plants are retired, VRE itself can help to manage the increased variability and uncertainty on the bulk power system. For instance, utility-scale wind generators equipped with automatic generation control (AGC) can provide active power ancillary services to provide frequency regulation services.[58] Additionally, utility-scale energy storage can be used to mitigate transmission congestion by storing excess electricity and releasing the power at peak transmission congestion times.[59] New technologies can either help RE resources themselves contribute to the stability of the power system or can help mitigate the sometimes inherent variability associated with RE, thereby maintaining or even improving power system reliability

Increasing Importance of Transmission Infrastructure – Unlike conventional power system resources, the output of variable renewable energy resources is weather-dependent. Locations with strong and/or high-value renewable resources may not be co-located or in close proximity to load centers –thus, transmission infrastructure must help bridge this gap. Country or jurisdictions pursuing the Bulk Power Transformation Pathway can evaluate the capability of the existing transmission system to integrate VRE and identify new requirements to incorporate more large-scale VRE resources in different combinations. This could include building more transmission lines, increasing balancing area coordination, boosting the trade of electricity across borders, and

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[55] (Milligan and Katz 2016)
[56] Defined as "the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant time scales" (IEA 2019).
[57] (Katz and Cochran 2015)
[58] (Aho et al. 2015)
[59] (Hewett et al. 2016)

improving system operator performance, among other actions. For more information on actions to support transmission planning and renewable energy integration, please visit: https://greeningthegrid.org/Renewable-Energy-Zones-Toolkit.

Table 7. PST Objectives and Alignment with Bulk Power Transformation Pathway

Objectives	Pathway Alignment	Country and Jurisdiction Examples
Economic Development	Development of bulk renewable power can enable economic development through powering key industrial loads (e.g., manufacturing) and load centers, enabling job creation (e.g., wind turbine and solar panel technicians, construction of new transmission and VRE infrastructure), and opening opportunities for power trade across borders with potential balance of trade benefits. In addition, the Bulk Power Transformation Pathway may align more closely with manufacturing opportunities for larger-scale RE technologies (e.g., utility-scale wind turbines), and countries may wish to align their RE manufacturing objectives with a bulk power emphasis.	Social development and job creation impacts of Menengai geothermal development project in Kenya[60] Economic benefit assessment exercise for Nepal-India Electricity Trade, indicating that increased power trading can increase GDP growth of Nepal and reduce India's electricity system costs.[61]
Energy Access	To support energy access, policymakers and planners can choose to extend current transmission infrastructure to unelectrified areas. This decision is highly specific to the particular circumstances and related costs of such an approach. Historically, motivating the financing for this approach has in some circumstances been difficult, particularly when prospective unelectrified customers are remote and/or have a low capacity to pay. However, in other circumstances, bulk transmission-based electrification can be a highly successful approach.	China's RE resources are located far from the load centers. To support increased energy access, high voltage DC/AC (HVDC/AC) lines were used for inter-regional and inter-provincial transmission[62].
Environmental Sustainability	Integrating large-scale RE with the bulk power system can support environmental objectives such as significant decreases in GHG emissions (e.g., through replacing coal-fired power plants). Water and air quality improvements can also occur near areas where coal or natural gas production is decreased. Scaling up bulk power RE may also lead to more significant GHG emission reductions in the near term, as compared to other pathways which may have emission reductions over a longer timeframe due to the smaller scale of technologies.	The Energy Imbalance Market in the western United States enables better balancing area coordination, reduces renewable curtailments, and results in carbon emission reductions.[63]
Resilience and Energy Security	Power systems focused heavily on centralized bulk power can be more vulnerable to impacts of extreme weather events. Further, certain RE bulk power resources, such as hydropower, may face	Lao Resilience Action Plan with a focus on hydropower vulnerability and resilience actions

[60] (Bah et al. 2011)
[61] (Integrated Research and Action for Development 2016)
[62] (Hurlbut et al. 2017)
[63] (Rothleder 2019)

	challenges related to seasonal changes in precipitation and water shed impacts over time.	

5.2.2 Factors to Consider for the Bulk Power Transformation Pathway

In addition to the PST objectives above, specific factors within a country or jurisdiction may lead decision-makers to place a greater relative emphasis on the Bulk Power Transformation Pathway. Table 8 presents factors, summarized below, that may lead countries to place greater emphasis on this pathway.

Renewable Energy Resource and Land Availability – This pathway requires significant suitable land be available with abundant renewable resources, allowing for large and highly interconnected balancing areas. Geothermal, land-based and off-shore wind, and utility-scale solar resources can play a significant role in the Bulk Power Transformation Pathway.

Key Economic Industries – Countries or jurisdictions with large-scale manufacturing and large industrial loads may choose to emphasize the Bulk Power Transformation Pathway, especially in countries focused on the development of large-scale RE technologies (e.g., large wind turbines). Some industrial processes may have significant electricity demand requirements that could necessitate bulk power development to reliably and cost-effectively serve.

Market and Institutional Context – Countries with an already-centralized power market may place greater emphasis on the Bulk Power Transformation Pathway. Second, countries with large-scale legacy generation and transmission assets may also focus on the Bulk Power Transformation in order to improve efficiency and increase utilization rates of these assets. Lastly, opportunities for cross-border trade may also lead to a greater emphasis being placed on the Bulk Power Transformation Pathway, as large-scale transmission could be scaled up to reach bulk power resources that may improve power reliability, resilience and affordability across borders.

Grid Characteristics – Countries with large balancing areas may also emphasize the Bulk Power Transformation Pathway, as such systems can integrate resources across larger geographic areas with transmission infrastructure, leading to lower aggregate power system flexibility requirements. Balancing area expansion and coordination can mitigate the variability and uncertainty associated with higher penetrations of VRE resources (see Box 4). Strong grid management capabilities can also lend themselves to a Bulk Power Transformation Pathway, as such capabilities are required to ensure energy system stability as utility-scale renewable deployment increases.

Table 8. Factors Aligning with the Bulk Power Transformation Pathway

	Pathways and level of alignment with factors			
	DER Revolution	***Bulk Power Transformation***	***Transmission and Distribution Interactivity***	***Distributed Transactional Future***
Area #1 - Local Power System Transformation Objectives				
Objective: Economic Development				
Objective: Energy Access				
Objective: Environmental Sustainability				
Objective: Resilience and Energy Security				
Objective: Energy Democratization + Responsiveness to Consumer Demand				
Area #2 - Renewable Energy Resource Availability				
Solar				
Wind				
Offshore Wind				
Geothermal				
Biomass				
Area #3 - Land Availability				
Significant Land Availability				
Minimal Land Availability				
Dense Urban Area with Suitable Rooftops				
Area # 4 - Key Economic Industries				
Established Distributed Energy Resource Installer Market				
Established Large-scale RE Manufacturing Sector (e.g., large wind turbines)				
Established DER Manufacturing Sector (e.g., batteries, PV panels)				
Significant Industrial Demand				
Significant Agricultural Demand				
Area # 5 - Market Factors				
Decentralized Power Market				
Centralized Power Market				
Utility Financial Insolvency				
Customer Demand for Distributed Energy Resources				
High Electricity and/or Fuel Prices				
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets				
Significant Cross-Border Trading Opportunities				
Significant Cross-sector Electrification Potential				
Area #6 - Grid Characteristics				
Robust Transmission & Distribution Networks				
Large Balancing Area				
Strong Grid Management Capabilities				

Area #7 - Power System Vulnerability				
Dependence on Imported Fuels				
High Vulnerability to Natural Threats				
High Vulnerability to Physical or Cybersecurity Threats				

Pathway Alignment Color Legend

- Indicates a strong alignment of the factor with the pathway
- Indicates a moderate alignment of the factor with the pathway
- Indicates weak alignment of the factor for the pathway

5.2.3 Bulk Power Technology and Business Model Evolution Over Time

Technology and business model evolution and disruptions will have critical implications for how the Bulk Power Transformation Pathway may be pursued over time. Figures presenting key bulk power technology cost projections out to 2050, for mid and low cost assumptions are presented below and can further inform choice of pathways.[64] Building on this information, stakeholders can further assess technology costs over time at the country level based on localized data to better inform long-term system planning. While the information below can provide a starting point for considering this pathway, much more granular analysis is needed.

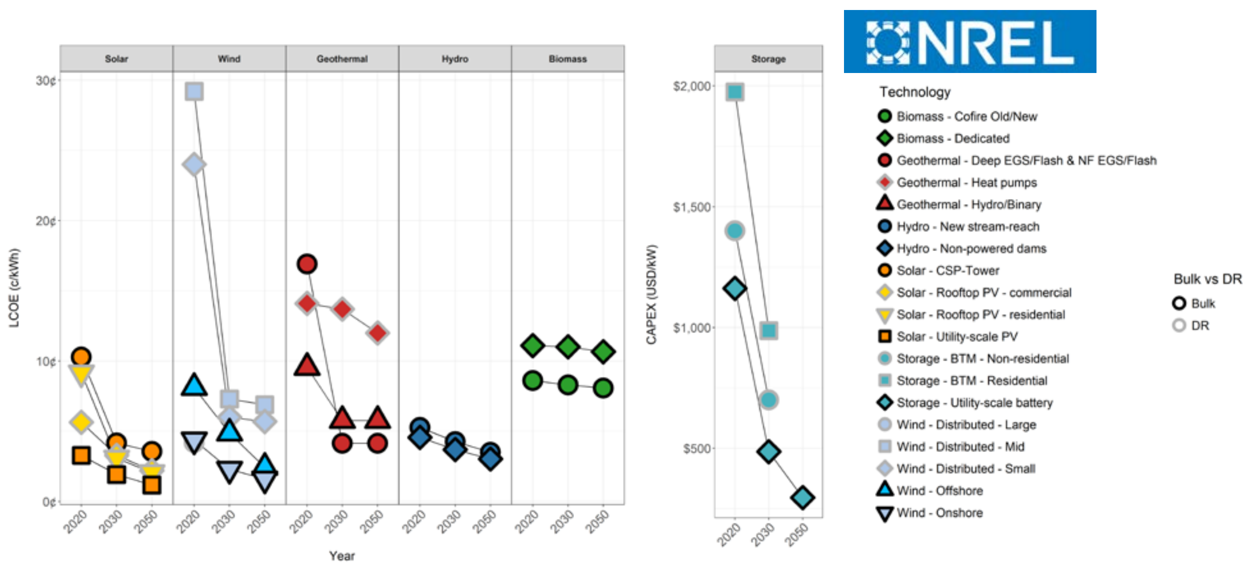

Figure 14. Comparison of Bulk Power vs. DER low-cost technology projections to 2050[65]

Based on U.S. Annual Technology Baseline data

[64] (NREL 2018)

[65] Additional technologies are included in the 'Low Cost' figure due to the availability of data.

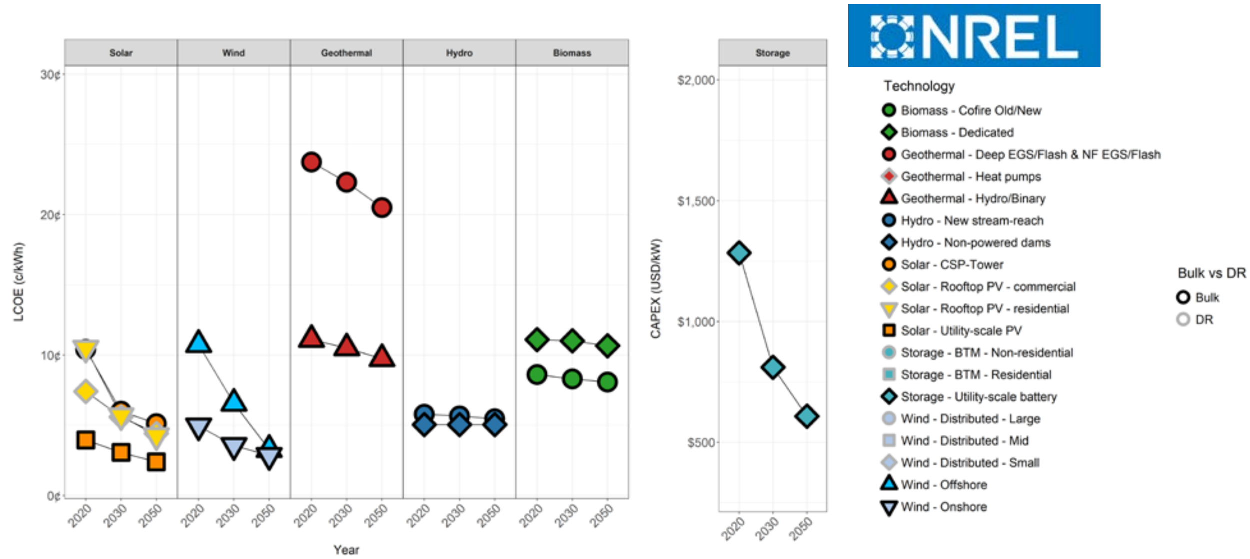

Figure 15. Comparison of Bulk Power vs. DER mid-cost technology projections to 2050

Based on U.S. Annual Technology Baseline data

In addition to price declines for existing technologies, there are many new technologies that have the potential to accelerate the Bulk Power Transformation Pathway moving forward. Figure 15 highlights some of these technologies and indicates their potential impact and approximate timeline for market-readiness. This graphic was developed based on expert opinion of the authors and can be considered illustrative based on many uncertainties regarding disruptive technologies.

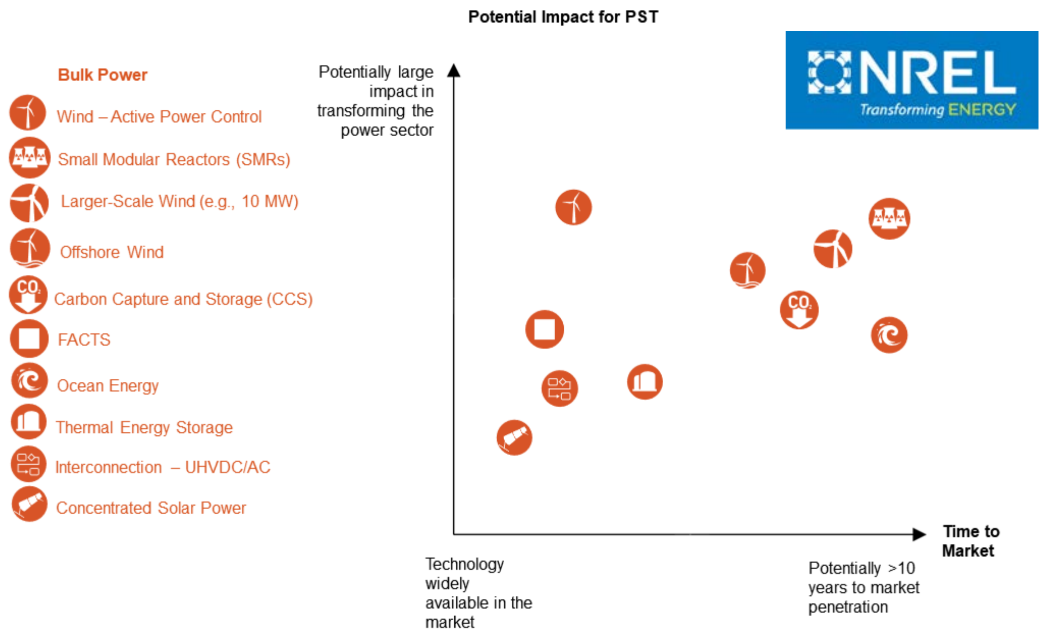

Figure 16. Potential impact and time to market for disruptive bulk power technologies

As deployment of technologies like wind and solar PV increases, it will become increasingly important to manage their variable generation patterns to ensure that demand and supply are continuously balanced. Technologies will also be needed to supply power during periods of poor solar and wind resources. Enhanced geothermal systems (EGS), ocean energy, and combined concentrated solar power (CSP) and thermal energy storage (TES) all offer the ability to continue producing power after wind has stopped blowing and the sun has stopped shining. These clean, non-intermittent and, in some cases, dispatchable generators have already seen some deployment today, but as costs continue to decline, they may begin playing a more prevalent role in the power system of the future.

Despite their promise, these technologies are marked by a limited geographic range in which they are economically or technically feasible to employ. For instance, CSP has a high threshold for direct solar irradiance before becoming functional, EGS requires specific geologic formations, and ocean energy requires particularly strong tidal patterns. While these regions may overlap with demand centers, in many cases they will not. This will necessitate advanced transmission systems capable of transferring power from areas of high generation potential to areas of high demand.[66] Ultra-high-voltage AC/DC (UHV AC/DC) lines offer the ability to transfer power over large distances with relatively low efficiency losses. These will be crucial not only for connecting generation with load centers, but also for connecting balancing areas with one another to improve system wide efficiency, reduce costs, and more reliably integrate VRE (see Text Box below). Transmission systems, which are already enablers of power system flexibility, may themselves need to become more flexible resources to support the reliable

[66] As an example, see the proposed DESERTEC project which aims to connect high load centers in Europe with areas of high solar potential in Northern Africa through the use of high voltage DC lines: https://www.desertec.org/.

integration of VRE resources. This can be achieved through the use of power electronics to provide rapid, highly controllable reactive power to the system, also known as Flexible AC Transmission Systems (FACTS). FACTS devices can improve voltage quality and increase the stability and line transfer capability of transmission lines[67].

As variable renewable energy resources continue to deploy, they will need to begin playing a larger role in directly contributing to the reliable operation of the power system through the provision of ancillary services. These services, currently provided by conventional generators, include balancing unexpected fluctuations in demand or generation and helping the system recover from contingency events. Despite their variable nature, generators such as wind and solar are still capable of providing a wide range of ancillary services given the proper infrastructure and, in many jurisdictions, are already required to do so in order to interconnect to the system (see Box 4).

Finally, utility-scale storage is also expected to play a significant role in the Bulk Power Transformation Pathway. Storage can provide a broad range of ancillary services and turn variable renewable generation into clean dispatchable power. As storage prices continue to decline, power systems are likely to experience increased deployment of this emerging technology. However, in order to maximize the value of storage to both the system and the developers, jurisdictions can ensure storage has the ability to provide all the services of which it is capable by removing economic, technical, and regulatory restrictions (see Box 4). Long-duration storage, or seasonal storage, can also play an enormous role in the Bulk Power Transformation Pathway, as well as potentially across other pathways. As variable renewable energy resources experience significant seasonal variations (in addition to intra-hour, -day, and -weekly variations)(e.g., there is less solar resource in the winter due to shorter days and generally less consistent wind in the summer due to increased turbulence) the ability to store energy during seasons of high resource availability to use during seasons of low availability will be crucial.

[67] (Csanyi 2011)

Box 4. Bulk Power Transformation Pathway – Market and Operational Actions to Support Bulk Power Technology Deployment

Balancing area expansion and coordination - One way to enable increased integration of utility-scale variable renewable energy is through increasing the size of balancing areas (BA), which represent the geographic boundaries within which system operators must balance the supply and demand of electricity. Larger BAs are more likely to contain geographically diverse renewable energy resources, which tend to have less correlated weather patterns. In practice, this means that fluctuations in the generation patterns of individual resources are more likely to be smoothed over by other resources elsewhere in the BA, lowering overall system variability and uncertainty and potentially reducing the need for curtailment.[68] Larger BAs also allow system operators access to a larger pool of reserve resources, which are used to respond to unexpected variations in energy supply. As reserve requirements typically do not increase proportionally with the system size, larger BAs can encourage a more efficient use of reserves and can lower the overall need for reserves, which in turn lowers overall power system operational costs and associated renewable energy integration costs.[69]

System operators can increase the size of BAs through a variety of methods.[70] One such method is coordinated scheduling, which involves the frequent exchange of energy through a mechanism such as an Energy Imbalance Market (EIM).[71] In an EIM, each system operator submits its projected load and available capacity, and the market operator dispatches generating resources from across the BA to help meet real-time energy imbalances. The use of EIM can reduce curtailment, lead to the more efficient dispatch of generating resources, lead to more efficient clearing of imbalances between supply and demand, and reduce the need for flexibility reserves.[72] For instance, in the Western EIM operated by CAISO, the collective system operators have seen over $650 million in gross benefits since 2014 and over 22,000 metric tons of CO_2 avoided through reduced curtailment in just the first quarter of 2019.[73]

Ancillary services - Another method for supporting the system integration of VRE is by requiring and encouraging renewable energy resources to contribute to system reliability by providing ancillary services. Despite their variable nature, renewable resources such as wind and PV generators are capable of providing ancillary services such as reactive and active power control and frequency regulation.[74] Frequency regulation, or automatic generation control (AGC), can be procured from generators which have the proper system controls in place to respond to signals from the system operator. This AGC is used by system operators to bring the system back to its normal operating frequency when the system experiences an imbalance between load and generation, either during normal operating conditions or contingency events.[75]

Although renewable energy generators are technically capable of supplying economically competitive frequency regulation, wind may not be required to install the system controls necessary to provide the response. Furthermore, insofar as generators are not adequately compensated for AGC, providing such a response represents lost revenue as they produce less than their maximum output.[76] Regulators and system operators can encourage the provision of ancillary services from VRE by ensuring adequate compensation and access to markets for

[68] (Bird and Milligan 2012)
[69] (Denholm and Cochran 2015)
[70] ibid.
[71] For balancing areas without a centralized market, bilateral exchanges, facilitated through a centralized system can also be employed to more efficiently coordinate dispatching of resources across balancing areas (ibid.).
[72] (Milligan 2012)
[73] (CAISO 2019c)
[74] (NREL 2019)
[75] (Ela et al. 2014)
[76] ibid.

renewable energy that can meet the technical requirements for the ancillary services.[77] Regulators can also ensure that generators are technically capable of responding to signals from the system operator by requiring a level of embedded communication and control architecture in the resources' interconnection or compensation agreements.[78] Requiring VRE to provide ancillary services helps ensure that these resources' presence on the grid contributes to system reliability, and ensures a larger and more diverse pool of resources from which to procure reliability services.

Utility-scale storage – Utility-scale storage systems are increasingly being deployed around the world for a range of purposes. As costs continue to decline and storage developers are able to seek remuneration for a wider set of system services, utility-scale storage deployment is expected to increase. One way of maximizing storage's contributions to the grid and increasing their economic viability is through what is known as "value-stacking." Value-stacking refers to the process of designing and allowing a storage system to provide multiple services in order to maximize its utilization and revenues. This is possible as the timescales and frequency of many services a battery can provide are often quite different.[79] For some services, however, value-stacking will not be possible, as they require mutually exclusive battery designs.

Aside from technical considerations, it is important to remove regulatory or market barriers to value-stacking to achieve the maximum benefit with energy storage.[80] These barriers can include: not recognizing the quality of the service the battery is able to provide (e.g., batteries can typically respond much more quickly than other generators, but may not be compensated for doing so)[81]; not allowing fair access to the market or ensuring batteries are considered by system operators[82]; or not setting clear regulation regarding the role of batteries in the grid or clarifying if existing regulations apply.

In California, the public utilities commission developed an explicit set of rules to facilitate the ability of energy storage to value-stack.[83] These rules classified services as either being 'reliability' or 'non-reliability' in nature, with the former having precedence. Furthermore, they ensured that providing additional services did not interfere with a battery's obligation to provide reliability services. These rules will ensure market actors can select the most optimal and cost-effective combinations of services to provide for their specific systems without interfering with the reliable operation of the grid. Allowing batteries to provide every service of which they are technically capable of providing, and ensuring they receive fair compensation for doing so, can help maximize both battery deployment and system benefits.

5.2.4 Country/Jurisdiction Pathways and Insights

The following section highlights the region of Southeast Asia and the nation of Kenya as cases where the Bulk Power Transformation Pathway is being emphasized in the power sector.[84] Each section presents key objectives and factors that have led to an emphasis on this pathway. For each case, this section also investigates the current status, as well as gaps, success, and good practices related to each jurisdiction's pursuit of this pathway.

Southeast Asia

The countries of the Association of Southeast Asian Nations (ASEAN) have joined together to pursue power sector transformation that places a relative emphasis on the Bulk Power

[77] FERC Order 755, which required U.S. wholesale market operators to implement performance-based compensation for the provision of frequency regulation services, is one example of such an effort (Chernyakhovskiy et al. 2019).
78 In Colorado, for example, the utility Xcel's standard power purchase agreement (PPA) for wind generators requires that the generator have the appropriate technology to be able to provide AGC (NREL 2019).
[79] (Denholm 2019)
[80] (Bhatnagar et al. 2013)
[81] This was addressed in the U.S. through FERC Order 755; see footnote 71.
[82] This was addressed in the U.S. through FERC Order 841 (FERC 2018).
[83] (CPUC 2018)
[84] In this paper, only the members of the Association of Southeast Asian Nations (ASEAN) are discussed

Transformation Pathway.[85] In 2015, these countries jointly developed the ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025, which aimed to increase the share of renewable energy to 23% of total ASEAN energy consumption by 2025.[86] Some ASEAN members have more ambitious targets. For example, Laos and Thailand aim to achieve 30% and 25% of total energy consumption from renewables by 2025.[87]

The unevenly distributed load centers and renewable resource potential are the key drivers of power market integration at the regional and sub-regional level of Southeast Asia.[88] In order to utilize bulk renewable resources such as hydropower, wind and solar, the ASEAN Power Grid (APG)[89] has proposed three sub-regional markets and eventually aims to implement cross-border power trade in large balancing areas. Three proposed clusters are presented in Figure 17.[90]

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85 ASEAN includes Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam (https://asean.org/asean/asean-member-states/).

86(Yanfel Li and Kimura 2016)

87 (Wu 2016)

88 (Matsuo and Tsunoda 2016)

89 The APG is an initiative to construct a regional power interconnection to connect the region. More detailed information can be accessed via: http://www.aseanenergy.org/programme-area/apg/.

90 (Hermawanto 2016)

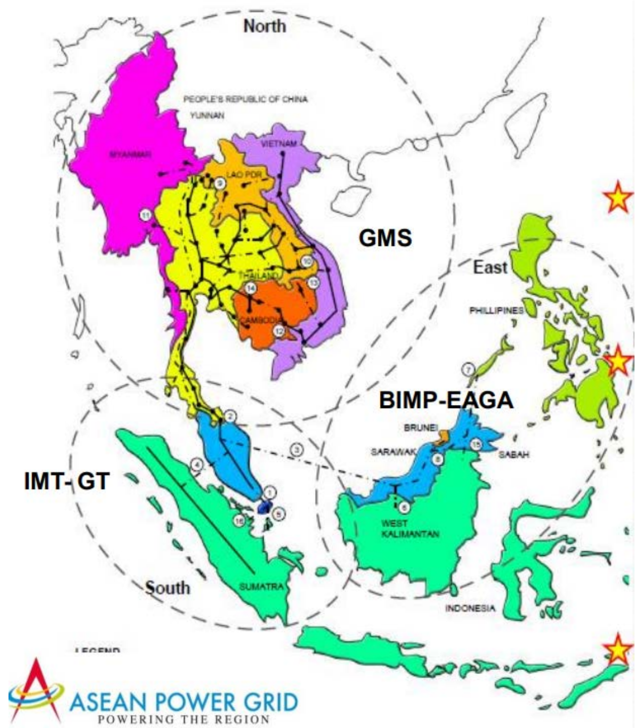

Figure 17. Three Proposed Sub-Reginal Electricity Market in ASEAN[91]

Building on the information above, three key objectives and several factors have led the ASEAN region to place an emphasis on the Bulk Power Transformation Pathway at the regional level over the longer term. The principal objectives for the region include: (1) enabling improved reliability; (2) supporting economic development; and (3) enabling sustainable environmental outcomes. Building on these objectives, the following factors outlined below and presented in Table 9 have led to an emphasis on the Bulk Power Transformation Pathway in Southeast Asia. The list below outlines the factors having the greatest influence on this pathway (dark blue in the table) and the full list of all factors is included in the table.

Renewable Energy Resource and Land Availability – Across the ASEAN region as a whole, there are several geographic regions suitable for utility-scale renewable energy development including hydropower, land-based wind, solar, and potentially offshore wind energy resources. This geographically diverse endowment of RE resources is well-aligned with the objective to pursue increased cross-border power trading, which could help to reduce system flexibility requirements, promote renewable energy integration, and improve affordability.

Key Economic Industries – Certain countries in the ASEAN region are manufacturing large-scale renewable energy technologies, which allows for complementarities with the Bulk Power Transformation Pathway. In addition, the region has many large industrial loads, particularly

[91] The North sub-regional market is located in the Greater Mekong Sub-Region (GMS), the South sub-regional market includes the Indonesia-Malaysia-Thailand Growth Tringle (IMT0GT), and the East ASEAN Growth Area (BIMP-EAGA) represents the East sub-regional market.

manufacturing in Indonesia, Thailand, and Vietnam, that may be influencing the region's emphasis on a Bulk Power Transformation Pathway[92] to be enabled by regional power trade.

Market and Institutional Context – Several market factors are leading to a greater emphasis on bulk power transformation in the ASEAN region. These factors include: highly centralized power markets in many countries, significant large-scale legacy assets (and opportunities to use those more efficiently), and significant opportunities for cross-border power trading (as highlighted above).

Grid Characteristics – Grid characteristics in the Southeast Asia region also lend themselves to bulk power transformation regionally. These include a large balancing area (across countries) and strong grid management capabilities in many of the participating countries.

[92] (Arbulu et al. 2018)

Table 9. Factors Contributing to Bulk Power Emphasis Across Borders in Southeast Asia

Factors for ASEAN Countries	Current relevance of factor	DER Revolution	Bulk Power Transformation	Transmission and Distribution Interactivity	Distributed Transactional Future
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

Successes and good practices in the ASEAN region enabling Bulk Power Transformation Pathway:

Analysis-informed incremental roadmap development – To achieve cross-border trading and integrate increasing penetrations of utility-scale renewables, a roadmap document was developed for the Brunei-Indonesia-Malaysia-Philippines East ASEAN Growth Area (BIMP-EAGA),[93] and the insights from this roadmap have been used to inform the ASEAN Power Grid efforts.[94] The roadmap also supports an incremental approach to developing power trading in the region, critical for supporting this type of complex regional integration. The key steps in this process are described below.

Stage 1. Incremental development of regional transmission backbone infrastructure. The APG has proposed a series of interconnection projects enabling power transformation in Southeast Asia.[95]

Stage 2. Incremental intra-regional power trade. This incremental power trade is initially focused on Borneo island, Brunei, Indonesia, and Malaysia as key participants. This stage started with unidirectional trade and is moving toward bidirectional power transactions.

Stage 3. Incremental inter-regional trade arrangements. This stage refers to inter-Borneo trade to fully utilize energy resources such as hydropower to address the demand and supply challenges across a larger balancing area.

Stage 4. Establishment of multi-buyer and multi-seller market. This stage refers to the development of a multilateral market system to facilitate trading across countries with different power market industry structures.

[93] Among the three clusters illustrated in the proposed sub-regional electricity market in ASEAN, the BIMP-EAGA is the least advanced region in terms of built-out power system infrastructure.
[94] (Yanfel Li and Kimura 2016)
[95] (Toh 2016)

Key actions to further enable Bulk Power Transformation in the ASEAN region:

Further analyze development of competitive electricity markets throughout the region – The current lack of a competitive electricity market is a notable challenge to enabling cross-border power trade in the region. Support in this area could focus on further analysis of the opportunity and feasibility and peer learning from countries in the region undertaking efforts to introduce additional competition into various power market segments. In particular, Vietnam is establishing a competitive wholesale electricity market[96] and Singapore and the Philippines have already established competitive electricity markets.

Enable development of interconnection infrastructure – Unevenly distributed resource and load centers are a challenge for system integration in the region. To enhance energy transformation capabilities, the APG has planned a series of interconnection projects. For example, the Sarawak- West Kalimantan (existing), Sarawak-Brunei (2018), and Philippines-Sabah (2020) are designed to support bidirectional power transactions.[97]

Coordinated planning of generation and transmission development – ASEAN countries have different power industry structures which presents a challenge for balancing area coordination, especially when implementing inter-regional power exchanges. ASEAN is expected to establish a multi-buyer and multi-seller market on a multilateral market system. Further support is needed to improve both the national and international coordination of generation and transmission planning exercises.

Policy mapping and support for improved policies for renewable integration at the country level - Energy challenges for each AESAN country varies, and policies to address these challenges are also diverse and, in some cases, require further design support for development. For example, two barriers to renewable deployment in Vietnam are low compensation for wind and restrictions on international investors for solar PPAs. Indonesia, on the other hand, faces challenges related to oversupply and curtailment.[98] It is important to work individually with the countries on RE policy development to address unique challenges. This individualized support can then enable positive outcomes as the region's power is further integrated.

Kenya

To support power system reliability, economic development, industrialization and low carbon objectives, Kenya has placed a greater relative emphasis on the Bulk Power Transformation Pathway. While the northern regions of the country have seen off-grid innovation and distributed power development,[99] this case focuses on utility-scale power transformation in Kenya, with an emphasis on geothermal development.

In 2008, Kenya launched the Kenya Vision 2030 to transform Kenya into a middle-income country in a clean and secure environment.[100] In 2013, the Ministry of Energy and Petroleum of Kenya developed the Power Generation and Transmission Master Plan, with a medium-term plan

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[96] (Yanfei Li et al. 2016)
[97] (Yanfel Li and Kimura 2016)
[98] (Naimoli and Nakano 2018)
[99] (Gordon 2018)
[100] For more information on the Kenya Vision 2030 initiative, see: https://vision2030.go.ke/.

(2015-2020) and master plan (2015-2035) published in 2016.[101] Several international partners also engaged closely to support power sector development in Kenya including Power Africa.[102]

Kenya has a rich renewable resource potential suited for bulk power including geothermal, hydropower and minimal fossil fuels. By 2016, 65% of the population in Kenya was electrified, the highest level in East Africa; and renewables accounted for 72% of total final energy consumption.[103] As presented in the Master Plan 2015-2035, Kenya put forward a target for geothermal to meet 56% of annual electricity demand by 2035, combined with 16% from hydropower, 11% from wind, 2% from biomass cogeneration, and 2% from PV. Energy imports and coal power generation were expected to supplement 7% and 6% of the remaining power demand required, respectively.

To improve bulk power interconnections and achieve the Kenya Vision 2030 goals, the Kenya Electricity Transmission Company Limited (KETRACO) is in the process of constructing over 8,000 km of high-voltage transmission lines.[104] These transmission lines will improve intra-regional power transmission, integrate additional renewables including geothermal, hydropower, and wind, and facilitate regional power trade with neighboring countries. Figure 18 illustrates Kenya's current transmission network and planned lines and highlights geothermal resource areas.

[101] (Energy & Petroleum Regulatory Authority 2019)
[102] (USAID Kenya and East Africa 2016)
[103] (United Nations 2018b)
[104] (USAID Kenya and East Africa 2016)

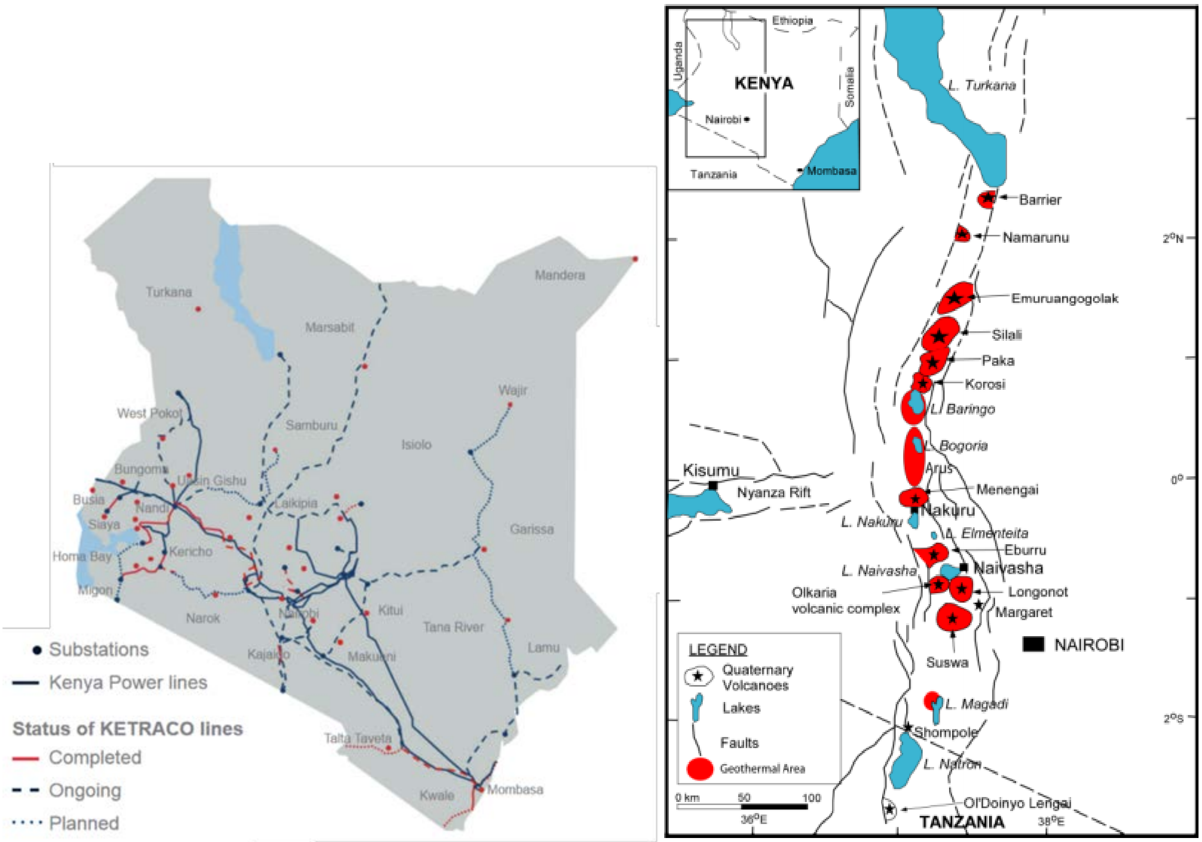

Figure 18. Kenya map of KETRACO transmission network (left)[105] and geothermal centers (right)[106]

Building on the information above, several factors have led Kenya to emphasize the Bulk Power Transformation Pathway. Similar to Southeast Asia, improving system reliability, supporting economic development, and enabling a clean and secure environment are principal objectives for Kenya's power system transformation. With these objectives as the foundation for Bulk Power Transformation, several factors, highlighted below and in Table 10, are also influencing decision-makers to place emphasis on this pathway.

Renewable Energy Resource and Land Availability – Geothermal, hydropower, and wind resources are the key renewables driving bulk power transformation in Kenya. In addition, the country has significant land available to support large-scale wind development.

Key Economic Industries – The Kenya Vision 2030 aims to create a robust, diversified, and competitive manufacturing sector. Large-scale manufacturing and industrial loads can be reliably supported under a Bulk Power Transformation Pathway.

Market and Institutional Context – Two market factors are particularly significant for influencing Kenya's emphasis on the Bulk Power Transformation Pathway. First, opportunities exist for cross-border trade and development of regional interconnection with Ethiopia, Uganda,

[105] ibid.
[106] (Omenda and Simiyu 2015)

and Tanzania. Second, with significant large-scale legacy assets, there is a need to use these bulk resources more efficiently.

Grid Characteristics –Kenya is also building strong grid management capabilities to support planned increases in geothermal and wind resources.

Table 10. Factors Contributing to Bulk Power Transformation Emphasis in Kenya

Factors for Kenya	*Current relevance of factor*	*DER Revolution*	*Bulk Power Transformation*	*Transmission and Distribution Interactivity*	*Distributed Transactional Future*
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-Scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-Sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

Successes and good practices in Kenya enabling Bulk Power Transformation Pathway:

Long-term planning – Kenya has developed a mid-term (2015-2020) and long-term (2015-2035) Power Generation and Transmission Master Plan, which provides a robust foundation for bulk renewable power scale up. The plan puts forth ambitious goals for increasing renewable penetration, especially for geothermal energy to support large-scale manufacturing investments.

High-level partnership with developed countries – Kenya has several international partnerships that provide opportunities to leverage best practices and lessons learned from power sector transformation in developed countries.

Key actions to further enable Bulk Power Transformation in Kenya:

Ensure reliability with increasing renewable penetration – As the power network expands in Kenya and with increasing penetration of VRE resources, the implementation of state-of-the-art grid integration measures, operational protocol improvements and capacity-building can support stronger grid management.

Scale up investment and finance – Power Africa indicated that Kenya has a gap of 14-18 billion USD in financing to achieve the targets in the power sector by 2020.[107] To address this challenge, Power Africa has put forth three solution areas: catalyze private investments, strengthen public utilities, and attract impact investors.

5.2.5 Possible Interventions to Enable Significant Scale Up

Building on information in the sections above, five key interventions that could be supportive of the Bulk Power Transformation Pathway are outlined below.

Perform large-scale analysis across broader regions to inform planning. This could include development of grid integration analyses and detailed power sector planning studies, as well as

[107] (USAID Kenya and East Africa 2016)

identification of infrastructure and services needed to support large-scale renewable integration at a regional level;

Improve weather predictions and VRE output predictions using state-of-the-art forecasting techniques;

Identify and implement key complementary technologies (e.g., utility-scale storage), that, when paired with utility-scale VRE, provide essential grid services;

Design and execute wholesale, capacity, ancillary services, flexibility markets, and other innovative approaches to support energy system reliability and cost efficiency; and

Identify sources of capital and design improved finance mechanisms for large-scale VRE and transmission development.

5.3 Transmission and Distribution Interactivity Pathway

The Transmission and Distribution (T&D) Interactivity Pathway sits somewhat between the Bulk Power Transformation and the DER Revolution Pathways and can be understood as a potential middle ground between the two future pathways, with respect to the role of centralized versus decentralized energy resources. In this pathway, a more efficient use of existing resources on both the transmission and distribution system, combined with a more streamlined integration of new resources on the distribution system may yield an affordable and low-carbon power system with high reliability characteristics. This pathway is characterized by:

Continuous acceleration of DER adoption

Integrated planning between transmission and distribution system operators

Co-optimized operation of the entire grid, which respects operational constraints and resource availability on both the transmission and distribution systems

Improved, publicly available data on real-time and forecasted system needs

Increasing prominence of microgrids

Improved investment opportunities for microgrids and DER as access to new revenue streams, such as wholesale energy markets, grows.

Under the T&D Interactivity Pathway, as the role and technical capabilities of DER expands on the distribution network, transmission system operators (TSOs) and distribution system operators (DSOs) will begin to holistically consider how DER may impact system operations. The growing role of DER leads to new requirements for increased observability of the system, and the ability for system operators to communicate in real-time with DER to address distribution or transmission system needs. Due to the increasingly noticeable impacts of distribution-located DER on the transmission system, TSOs and DSOs will be required to communicate more frequently and effectively about their real-time system operations and forecasted needs. This, in turn, will lead to increased data sharing and interlocking operational models to converge on a more holistic view of the entire power system, rather than the current planning and operation of transmission and distribution systems in relative isolation.

In areas with low energy availability and/or an increased need for reliability, microgrids may become a more prevalent approach, with initial capital costs being ultimately offset by compensation from TSOs and DSOs for the services they provide to these systems. Even outside of microgrids, providing services to the TSO, DSO, or both, may provide DER owners and aggregators with new revenue streams. This, combined with increased system awareness, may allow private individuals and developers to maximize the value of their investments and align their investment decisions with the current and forecasted needs of the grid. Thus, an increased ability to sell services, a growing pool of resources on the distribution system, increased awareness of the network, coordinated operations and planning, and a steady stream of high-frequency operational data sharing, can allow both the TSO and the DSO to find the most efficient, reliable, and affordable use of their combined resources.

Although much of the transition in the T&D Interactivity Pathway will be focused on the incorporation of new distributed assets, centralized generators will also need improved flexibility to address the increased variations in net load caused by the proliferation of utility-scale VRE and distributed generation (DG). Increasing penetrations of DG may have dramatic impacts on the residual load which must be met with centralized generators. These generators will need to ramp up and down more quickly to meet changes in demand as customers' own resources power up and down. The additional cycling, or changes in the output, of these centralized assets can cause additional wear and tear in these plants, particularly for baseload plants which were not designed to change output frequently. Although some of this cycling can be avoided through the more effective use and coordination of distributed assets, improving the inherent flexibility of the centralized fleet may also prove beneficial. This can be done through retrofitting baseload plants such as nuclear and hydropower, strategic curtailment of centralized variable renewable energy resources such as utility-scale wind and solar or large-scale battery storage.

Building on country experience related to this pathway, Figure 19 presents supportive actions that could enable the T&D Interactivity Pathway out to 2050. The key actions are meant to be illustrative and are not covered in detail, as literature elsewhere covers these topics extensively.[108] The key actions can be approximately grouped into actions on:

enabling and accelerating the deployment of microgrids, with an emphasis on ensuring their interactivity with the broader power system to contribute to system reliability;

improving data sharing between relevant TSO and DSO entities, as well as third-party developers, to align their actions to maximize system benefits and minimize unnecessary and/or duplicative costs;

coordinating the planning and operation of the transmission and distribution system to improve visibility and controllability and enhance system efficiency and reliability;

[108] The author recommends in particular: (ENTSO-E 2015a; 2015b; 2016; Ebrill 2016; SmartNet 2019; Gerard et al. 2016; Stadler et al. 2016)

ensuring that DER are allowed to participate in the power system to provide a range of system services and seek fair remuneration for doing so;

clarifying jurisdictional roles to prevent confusion or unnecessary regulatory hurdles for participation, given the new roles of the TSO and particularly the DSO; and

improving the flexibility of centralized assets.

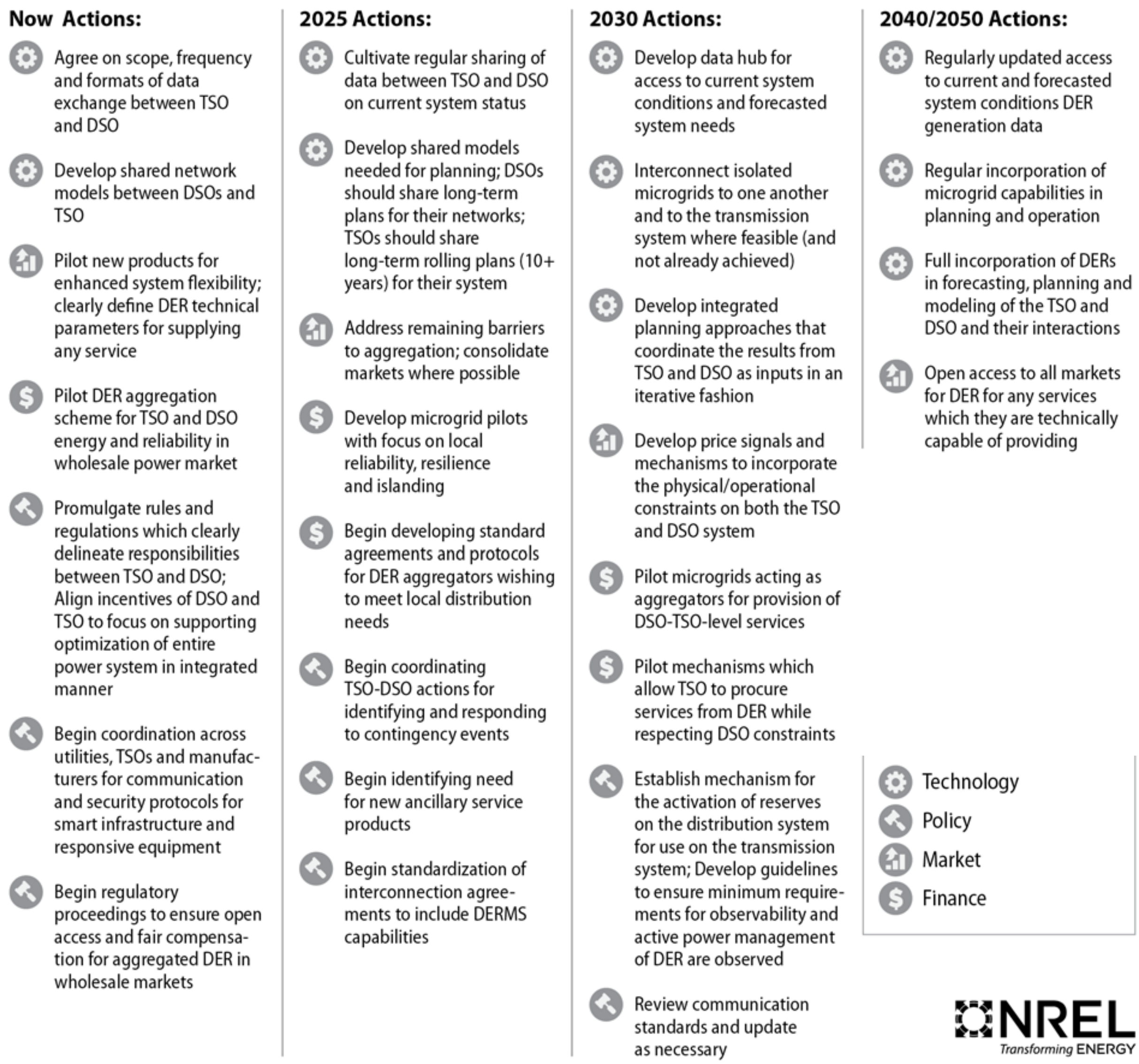

Figure 19. T&D Interactivity Pathway out to 2050 – Supportive Actions

5.3.1 Issues for Consideration - Transmission & Distribution Interactivity Pathway

In pursuing the T&D Interactivity Pathway, specific areas can enable the reliable and efficient coordination of TSO and DSO actions. These areas are described below.

Coordinated planning and operation of the T&D system - As resources on the distribution level begin to play a larger role on the transmission level, T&D system operators will need the ability to communicate effectively about both the current and forecasted conditions of their respective systems to one another. In terms of real-time operation, this means that both TSOs and DSOs will need to know how much DER is available to meet both systems' needs and how much each system operator has already procured. Furthermore, distribution-level constraints such as localized congestion will need to be factored in by the TSO when attempting to procure resources on the distribution system, in order to prevent exacerbating local reliability issues. In terms of future planning, TSOs and DSOs will need to begin sharing the forecasted growth and needs of their respective systems. For instance, the more TSOs procure distribution-level assets, the more relevant a DSO's forecasted adoption of resources like storage and distributed solar PV may become to their system planning. Good planning procedures for both system operators can involve sharing quantitative planning models and assumptions for the growth of demand and distributed asset adoption, eventually leading to a set of synchronized models which feed into one another to converge on a more holistic view of the grid's growth. At some point, full integration into a single planning modeling framework may even become technically feasible. In any case, for both the current operation of the power system and for future planning, a mutually agreed upon standard for sharing data and assumptions will be key, and this data could eventually be shared with third-party developers in order to align their actions with the system's needs.[109]

Expanded end-use customer roles - As with the DER Revolution, the growth of DERs in this pathway will enable consumers to begin to take a more active role in both their own energy needs and the system's needs. In order to make the most of these assets, TSOs and DSOs could encourage these consumers' active participation in providing services and energy. This can be done by removing legal barriers to such assets' aggregation and participation in the wholesale market[110] and, where there are no markets, through directly procuring such services from aggregators or individual customers. Ensuring that a value-based compensation for the services these resources provide to the grid can also encourage their adoption while balancing disparate stakeholder interests. In particular, compensation which considers their location-specific value to and impact on the system can incentivize adoption in places it is most needed.[111] The presence of unique resources such as energy storage, distributed solar PV and demand response may further require the creation of new categories of market products to ensure their participation.[112] As these resources begin playing a larger role, the creation and enforcement of adequate standards for communication, security, and technical performance ensure these resources can be consistently relied upon.

Harmonized regulation to prevent jurisdictional issues – Traditionally, TSOs are governed by central government institutions while DSOs have been subject to more local regulations and controls. However, as the roles and actions of both system operators and resources begin to affect the operation of both systems, relevant regulations may need to be reviewed in order to ensure adequate and harmonized oversight. Furthermore, regulatory frameworks governing the role of the DSO may need to be modified to allow and encourage the transition of traditional vertically integrated utilities to new DSO roles. Guidance on evolving business models for these DSOs may also aid in their transition (see below).

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[109] (Gerard et al. 2016; 2018)
[110] See, for instance, FERC's Order 841 on storage's participation in wholesale markets (FERC 2018).
[111] See, for instance, New York's Reforming the Energy Vision (REV) initiative which seeks to replace the standard net energy metering incentive for DER with a more granular incentive structure which considers distributional impacts (Lowder et al. 2017). The REV initiative also included a Locational System Relief Value (LSRV) which provided extra compensation for resources in areas with needs that could be addressed by DER (NYPSC 2018).
[112] See for instance CAISO's Proxy Demand Resource, Distributed Energy Resource Provider and Non-Generating Resource models (CAISO 2019a).

5.3.2 PST Objectives and Alignment With T&D Interactivity Pathway

The T&D Interactivity Pathway can support various PST objectives. Table 11 provides an overview of how this pathway is aligned with particular objectives and examples of this alignment from particular countries and jurisdictions.

Table 11. PST Objectives and Alignment with T&D Interactivity Pathway

Objectives	Pathway Alignment	Country and Jurisdiction Examples
Economic Development	As the transmission and distribution systems begin to interact more, there are more opportunities for DER to extract revenues from both systems and there may also be certain distribution-level services that the bulk system can provide. Aggregated DER or larger DER installations can potentially bid into wholesale markets at the TSO level to provide ancillary services, capacity, and energy, and/or respond to local reliability needs from the DSO. Both of these actions could provide additional revenue for DER owners and help maximize the value of their investments. As the economics of these systems improve, deployment of DER will grow, potentially leading to more jobs in fields related to the installation, operation, and manufacturing of these distributed assets. Furthermore, coordinated transmission and distribution planning, modeling, and system operations may lead to a more efficient use of all grid resources across both systems, relative to the current scenario of each system operator attempting to only minimize costs within their own system. These improvements to efficiency may lead to lower electricity prices. For large customers, lower electricity prices can reduce the cost of manufacturing and other industries, driving economic development. For residential customers, lower energy prices can enable increased household spending that in turn can spur economic growth.	See DER Revolution section for examples of DER deployment driving economic development. PNNL in coordination with ARPA-E has begun developing a pilot to create a "hierarchical control framework for coordinating the flexibility of a full range of DERs".[113] This framework relies on a 'distribution reliability coordinator' (such as a DSO) to act as the interface between the bulk power system and the individual DER on the distribution system. This pilot, in combination with the larger NODES program[114] is expected to replace roughly 4.5 GW of spinning reserves currently needed to meet imbalances between supply and demand, which represents approximately $3.3 billion in savings per year. By reducing the costs of maintaining system reliability, such efficiency increases can lead to lower power bills for customers, stimulating economic growth.
Energy Access	The T&D Interactivity Pathway can indirectly drive improved energy access and quality by improving the economics of developing and interconnecting microgrids and other distributed resources.[115] The improved coordination between the transmission and distribution system in this pathway creates additional value streams available to distributed assets, such as selling bulk power system services in the wholesale market. These additional value streams can encourage the deployment of distributed assets.	Husk Power currently builds hybrid power systems (biomass + solar PV) for rural communities without energy access in Bihar, India and Tanzania. Additionally, they monitor and manage the system through the use of advanced metering infrastructure, helping ensure 24/7 energy access. Although these systems currently remain off-grid, such

[113] (PNNL 2015)
[114] (DOE 2015)
[115] (Stadler et al. 2016)

	Unlike in the DER Revolution Pathway, the economics of these systems are dependent on their integration into the larger power system, which are the primary markets for the services these distributed assets can provide. This means that this T&D Interactivity Pathway is not well-suited to providing power to systems that are currently isolated or will remain isolated from the larger bulk power system.	microgrids could one day interconnect to the larger DSO territory to improve economics and reliability for both the microgrid and distribution system.[116]
Environmental Sustainability	Increased flexibility in the system due to coordinated TSO-DSO actions and aggregated demand response and storage can help increase the amount of DER that the system can install without reducing reliability, which may help to reduce reliance on carbon-intensive power generation. Additionally, more efficient dispatch of conventional generation, due to coordinated operations between the TSO and DSO, may reduce the amount of thermal generation cycling or capacity that is left operating at less than optimal output, which can further reduce emissions. Moving forward, as DER continues to meet an increasing amount of system needs, there may be a decreased need for new centralized conventional generation assets, reducing future emissions of this resource class.	The company Sunrun was recently awarded a contract in ISO-NE's capacity market to provide 20 MW of capacity needs in 2022. The use of local clean energy sources to provide capacity for peak periods will reduce ISO-NE's reliance on more emissions-intensive generation assets such as gas power plants, and can help reduce cycling of other thermal generation assets and even potentially obviate the need for new thermal generation by meeting demand during the most constrained hours of the year.[117]
Resilience and Energy Security	Additional deployment of DER, enabled by increased revenue streams and improved operations, has the potential to improve system wide resilience by offering system operators a wider set of geographically dispersed resources with which to recover from contingency events. These resources, combined with a decreasing reliance on centralized generation, may also improve individual DSO territory resilience by increasing the generating resources and dispatch capabilities available to DSOs independent of assets located on the transmission system. This decreased reliance on centralized resources can also reduce the chances of a natural disaster destroying or disabling key infrastructure (such as large transmission lines) and causing a system-wide power outage. As with the DER Revolution Pathway, the ability for smaller sections of the power system to function independently can help prevent a single reliability event from completely paralyzing each DSO territory within the same larger TSO territory. Once	In the aftermath of Hurricane Maria, Puerto Rico's utility PREPA filed its integrated resource plan which called for the rapid deployment of solar and storage and a system of eight large distribution level microgrids which could operate independently of the larger transmission system during severe weather events. Additionally, the plan called for more microgrids in areas difficult to repair and a separate initiative was initiated in March 2019 to help accelerate the development of microgrids in rural areas to improve energy resilience.[118]

[116] For more information on Husk Power's operations and locations, see: http://www.huskpowersystems.com/.
[117] (Sunrun Inc. 2019)
[118] (New York Power Authority et al. 2017)

	the fault is isolated, power can be redirected around the fault through resources on the distribution system and transmission level to minimize outages and bring portions of the power system back online more quickly, a process known as "self-healing."	
Energy Democratization and Responsiveness to Consumer Demand	As in the DER Revolution Pathway, increasing penetrations of DER, DR, storage, and home area networks enabled by more efficient operations, better planning, clearer legislation, and more open markets may translate into shorter interconnection times and lower upfront capital costs (or none under third-party ownership) for consumers.	Currently the blockchain trading platform LO3 and the European Power Exchange Spot market have begun developing pilot projects in Allgäu and Landau in Germany to allow private consumers located in microgrids to sell their surplus energy to the German wholesale energy market.[119] Being able to sell energy on the wholesale market brings additional revenue to DER owners and can potentially incentivize the creation of novel tariff structures to align DER dispatch with broader system needs, empowering consumers to maximize the benefits of their DER assets.

5.3.3 Factors to Consider for the T&D Interactivity Pathway

Building on the PST objectives, specific factors within a country or jurisdiction may provide even further impetus to pursue the T&D Interactivity Pathway. Factors that may lead countries to place greater emphasis on this pathway are outlined below and presented in Table 12.

Renewable Energy Resource Availability - The availability of specific renewable resources is not necessarily a driving factor for the T&D Interactivity Pathway. Although certain resources such as solar lend themselves better to interconnection at the distribution level, even jurisdictions with poor solar resource could choose this pathway to improve efficiency and reliability by utilizing non-generation resources such as demand response and distributed storage. More important than resource availability is geographic diversity of the resources, the location on the grid of the generators which use the resources (either centralized or distributed) as well as the ability of utilities and system operators to coordinate the generators using the resources.

Land Availability - As with resource availability, land availability is not a driving factor for the T&D Interactivity Pathway. While large expanses of available land might lead to a more centralized option and dense urban areas may lead to a more decentralized approach, this pathway is compatible with all land types and indeed benefits from a balance of large centralized resources and smaller decentralized resources. However, as it is the distributed resources that ultimately trigger the need for TSO-DSO increased cooperation, this pathway may arise more organically for countries with less available land area.

[119] (Karlsruher Institut für Technologie 2018; Andrew Burger 2017)

Key Economic Industries - Countries interested in bolstering DER manufacturing industries could consider pursuing the T&D Interactivity Pathway, as it both incentivizes and facilitates an increasing penetration of DER by reducing barriers to DERs' deployment and providing new sources of revenue for DER. The improved coordination of resources fostered by this pathway furthermore may allow increasing penetrations of DER without reductions in system reliability.

Countries with large industrial loads may benefit from this pathway, as these customers provide 'low-hanging fruit' for effective demand response programs, which can lower customer bills and provide system reliability without the need for aggregating resources. Countries with agricultural loads, which can often be subsidized or are far away from system feeders, can also benefit from this pathway. DER at the site of agricultural loads can reduce the cost of subsidies and reduce the stress these faraway loads place on the system. When not meeting local needs, these DER can sell their energy and services back to the larger system, helping offset the overall costs of such resources which can be a barrier to their deployment.

Market and Institutional Context - The presence of centralized markets could play a large role in emphasizing this pathway as such a market could provide both important revenues for decentralized assets, as well as a means of most efficiently selecting and dispatching such resources. Furthermore, effectively dispatching decentralized assets into centralized markets would require improved communication and cooperation between TSOs and DSOs. Jurisdictions with insolvent utilities may also pursue this pathway in order to make more efficient use of existing resources, as well as reduce subsidies to certain customer classes by empowering them to meet their own (and the system's) energy needs.

Both customer demand for DER and high electricity or fuel prices, which could be an important factor driving customer demand for DER, will drive the T&D Interactivity Pathway. As DER deployments increase, the system will need to become more flexible in order to accommodate them and will look to utilize these resources to reduce system costs while increasing system reliability. The presence of cross-sector electrification efforts may also provide an increasing source of distributed energy resources (e.g., grid-interactive electric vehicle charging stations), which could be used to meet system needs.

Grid Characteristics - A robust, reliable transmission and distribution system is fundamental to the T&D Interactivity Pathway. Without it, there is no feasible way to efficiently and reliably incorporate resources across both systems. Similarly, strong grid management capabilities are key to handling the proliferation of numerous, small distributed resources, which will require complex tools and protocols to observe and control.

Power System Vulnerability - Countries with vulnerable power systems, whether due to infrastructure or natural disasters, may be more drawn to the T&D Interactivity Pathway as it facilitates the deployment of microgrids which can operate in isolation should power from the transmission system be unavailable. These microgrids and DER can not only meet local reliability needs during or after a disaster, they can also help the system recover from the loss of centralized assets, whether transmission lines or large generators.

Table 12. Factors Aligning With the T&D Interactivity Pathway

	Pathways and level of alignment with factors			
	DER Revolution	***Bulk Power Transformation***	***Transmission and Distribution Interactivity***	***Distributed Transactional Future***
Area #1 - Local Power System Transformation Objectives				
Objective: Economic Development				
Objective: Energy Access				
Objective: Environmental Sustainability				
Objective: Resilience and Energy Security				
Objective: Energy Democratization + Responsiveness to Consumer Demand				
Area #2 - Renewable Energy Resource Availability				
Solar				
Wind				
Offshore Wind				
Geothermal				
Biomass				
Area #3 - Land Availability				
Significant Land Availability				
Minimal Land Availability				
Dense Urban Area with Suitable Rooftops				
Area # 4 - Key Economic Industries				
Established Distributed Energy Resource Installer Market				
Established Large-scale RE Manufacturing Sector (e.g., large wind turbines)				
Established DER Manufacturing Sector (e.g., batteries, PV panels)				
Significant Industrial Demand				
Significant Agricultural Demand				
Area # 5 - Market Factors				
Decentralized Power Market				
Centralized Power Market				
Utility Financial Insolvency				
Customer Demand for Distributed Energy Resources				
High Electricity and/or Fuel Prices				
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets				
Significant Cross-Border Trading Opportunities				
Significant Cross-sector Electrification Potential				
Area #6 - Grid Characteristics				
Robust Transmission & Distribution Networks				
Large Balancing Area				
Strong Grid Management Capabilities				

Area #7 - Power System Vulnerability				
Dependence on Imported Fuels				
High Vulnerability to Natural Threats				
High Vulnerability to Physical or Cybersecurity Threats				

Pathway Alignment Color Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak alignment of the factor with the pathway

5.3.4 T&D Interactivity Technology and Business Model Evolution Over Time

As mentioned previously, the T&D Interactivity Pathway brings together elements from both the DER and Bulk Power Pathways, and as new technologies are developed and existing technologies see continued price declines, this pathway will become more achievable and impactful.

On the bulk power side, decreasing costs may lead to increased deployments of variable generation such as on- and off-shore wind and solar photovoltaics (see Figure 4), which will drive the need for increasing levels of system flexibility requirements. As system operators seek to balance demand with a more variable set of supply-side resources, they may turn to resources on the distribution system and enlist demand itself to meet imbalances through demand response programs. On the DER side, price declines for technologies such as DPV, wind, and storage will present both challenges and opportunities for system operators (see Figure 4). Without changes to business models (see Box 5) and planning and operation, customers supplying more of their own energy needs may pose a financial risk to utilities. However, given changes to operational practices (see Box 6) and new business models, resources on the distribution level can help system operators more efficiently balance load and generation, provide new services, and integrate more clean energy.

At present, there are a number of new technologies that may come to market in the next decade which have the potential to transform the power system and enable the T&D Interactivity Pathway (Figure 5). On the bulk power side, aside from utility-scale generation technologies, more robust and efficient transmission interconnections and more flexible transmission system operation will help integrate more resources on both the distribution level and transmission level. Ultra-High Voltage DC/AC (UHV DC/AC) interconnections will allow access to more remote resources and better integration of neighboring power systems. The use of power electronics to improve the flexibility of the transmission system (FACTS) may enable the T&D Interactivity Pathway by increasing the number of resources TSOs can reliably incorporate into their operations both at the transmission and distribution system.

On the distribution side, price declines for distributed generation and storage technologies may further spur their deployment, driving the need for T&D interactivity by increasing both system flexibility requirements and the resources to provide such flexibility. New technologies will also accelerate the adoption of EVs (super rapid charging, inductive charging) and enable their active participation in the system as distributed storage resources (i.e., via a Vehicle-to-Grid approach). This represents an enormous resource potential from which to procure ancillary services and help balance generation and load both at the distribution and transmission level,[120] but it will require enhanced cooperation in order to realize. Similarly, technologies which allow smaller customers to coordinate and control their own consumption and generation (e.g., Home Area Networks), will provide system operators with increased sources of generation and demand response, but will again require increased communication and cooperation to access. Finally, as costs for microgrid controllers decline, microgrids may become more prevalent, leading to an environment of smaller systems which can both provide services to the larger grid, and function independently of the grid during contingency events and natural disasters.

Two keys areas will play an integral role in business model evolution to support the T&D Interactivity Pathway. The first business model area relates to development of a distribution system operator and the second area focuses on coordination between transmission and distribution system operators. These business model topics are highlighted in Box 5 and Box 6, respectively.

Box 5. T&D Interactivity Pathway – Business Model for Distribution System Operators

Currently, much of the electricity around the world is delivered by vertically integrated utilities which are tasked with the planning and operation of the distribution system, as well as the transmission and generation market segments. These utilities invest in and own assets such as distribution lines and distributed power plants, which they finance through regulated retail electricity tariffs from consumers. These tariffs in turn are overseen by regulators and cover the cost of providing electricity plus a level of profit determined by the relevant regulatory agency. Utilities have typically only needed to consider operational scenarios with one-way power flow and have therefore only needed to communicate with the TSO and large, centralized generation assets. The rise of DER on the distribution system has begun to fundamentally change the role of the utility as customers begin to both meet their own energy needs (undermining the utility's monopoly status) and begin sending excess power back to the grid (leading to two-way power flows). DER can also offer many benefits, but these may be out of reach for traditional utilities. In order to take advantage of these resources, regulators and policymakers may need to intervene to define the technical and financial relationship between DER customers, distribution operators, and transmission operators, while also ensuring that that there is streamlined communication (and in some cases, operational control rights granted) among these parties. Furthermore, utilities would need to begin taking DERs into consideration when operating and planning for the buildout of the distribution system. In this way, distribution operators may come more to resemble today's TSOs, owning and operating distribution lines and related infrastructure but not necessarily the resources that interconnect with the distribution system. The distribution system's analog to the TSO would be the DSO. The DSO's new role could involve the coordination of these distributed resources, either directly or through aggregators to ensure adequate energy supply and ancillary services. When these resources provided energy in excess of local system needs, the DSO could ensure the reliable delivery of energy and services from such resources to the transmission system. When these resources could not meet the distribution system's needs, the DSO would procure generation from the TSO.

[120] (Arias et al. 2019)

Box 6. T&D Interactivity Pathway –Conceptual Models for Coordination Between Transmission and Distribution System Operators[121]

Under the T&D Interactivity Pathway, the role of the distribution utility may continue as an extension of its current role or could evolve to become a distribution analog to ISOs in wholesale markets. The interaction between the DSO and the TSO could vary dramatically depending on the priorities and concerns of the relevant regulators (e.g., energy access, competition, market power) and the local system characteristics (e.g., number of DSOs, prevalence of DER, communication capabilities of TSOs and DSOs).

On one end of the spectrum, closest to the current status of DER-DSO-TSO interactions in many systems, the TSO could directly contract DER from the DER owners for ancillary service procurement through a centralized market. In this arrangement, the DSO could also procure DER for local system services, but through an alternative mechanism than the market (i.e., through bilateral contracts, or through direct ownership and operation of the DER). In this arrangement, local constraints on the DSO may or may not be taken into consideration by the TSO during procurement, if they are, it would need to be through a 'pre-qualification' process that ensures such DER procurement does not lead to issues such as congestion on the distribution system. If they are not taken into consideration, it is possible that under certain operational conditions, utilization of DER to meet the TSO's real-time system requirements could negatively impact the DSO's operations. (See 'Centralized AS Market' in figure below).

On the other end of the spectrum both the TSO and the DSO are jointly responsible for the operation of an integrated marketplace where both the TSO and DSOs can procure DER for energy or ancillary services. In this arrangement, distribution and transmission level constraints (such as congestion) are factored into the market bids to prevent the procurement from either entity from interfering with the reliable operation of the other's system (See 'Common TSO-DSO AS Market' in figure below). This marketplace could also allow non-regulated, commercial parties to privately procure energy or system services independent of the TSO or DSO. In this case, the market could be overseen by an impartial third-party to prevent conflicts of interest (See 'Integrated Flexibility Market' in figure below).

Depending on the arrangement chosen, the 'DSO' role could act as it does in its current capacity, as another procurer of energy and services from the market much as the TSO does today, or as the interface between distributed energy resources and the TSO. In this latter capacity, the DSO's responsibilities could include organizing and monitoring the aggregation of DER, consolidating multiple aggregations into single bids to the TSO at each shared transmission-distribution interface. The DSO could optimize local DER in its territory to provide transmission level grid services as requested by the TSO. It could also seek to manage supply and demand locally within its territory and minimize the impacts of DER variability at the transmission-distribution interface. When local distributed resources would not suffice to meet local needs, the DSO could coordinate additional resource dispatch from the TSO.

In any of these arrangements, regulators may seek to transition the distribution utility away from its historical 'volumetric- and capital-based ratemaking' (wherein utilities were incentivized to sell more electricity and invest in more capital projects to increase their return-on-equity) to 'performance-based ratemaking' in which a DSO earns its regulated rate of return based on its ability to meet certain metrics such as increasing penetration of DG, improved reliability, or lower interconnection application processing times.

[121] (Gerard et al. 2018; 2016)

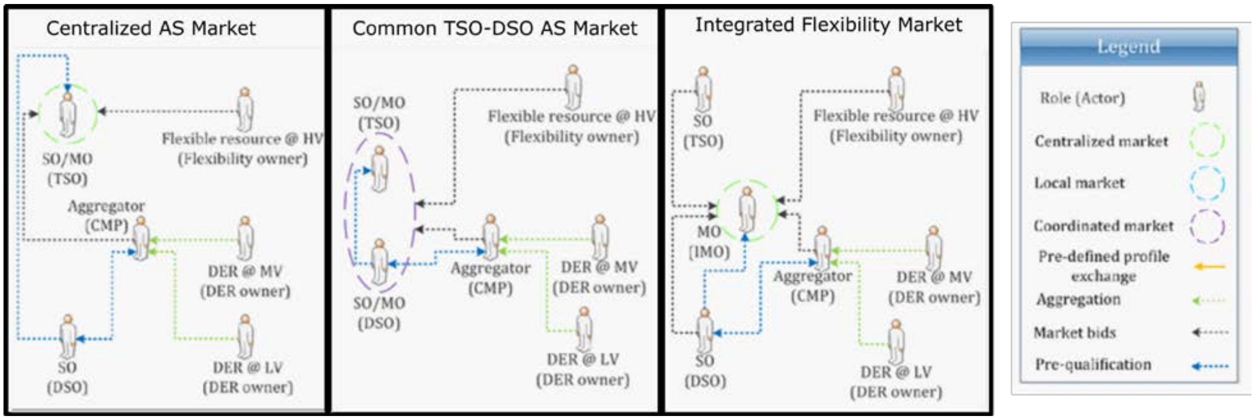

Figure 20. Conceptual Models for Coordination between TSOs and DSOs

Source: (Gerard et al. 2016)

5.3.5 Country/Jurisdiction Pathways and Insights

The following section highlights the jurisdiction of the European Union where the T&D Interactivity Pathway is being pursued. It should be noted that in the E.U., the Transmission and Distribution Interactivity Pathway is being pursued alongside other pathways described in this paper. However, the European Network of Transmission System Operators (ENTSO-E) territory has been identified as a case where a greater relative emphasis is being placed on this pathway, based on key factors and objectives highlighted below. In the subsequent section, the T&D Interactivity Pathway in the E.U. is detailed, as well as key insights, successes, good practices, and gaps in this particular context.

European Union (ENTSO-E Territory)

The European Network of Transmission System Operators for Electricity (ENTSO-E) represents 43 transmission system operators all across Europe. ENTSO-E was established in 2009 in order to promote European energy and climate policy with a specific focus on renewable energy integration and the completion of an Internal Energy Market (IEM). Beginning in 2015, ENTSO-E, in collaboration with DSO associations, began developing a 'DSO-TSO Cooperation Platform' in order to identify and address potential issues in increasing the coordination between the Transmission and Distribution System.[122] The platform initiative sought to address challenges related to uncoordinated access to resources, regulatory uncertainty and lack of grid 'visibility,' and led to a series of workshops focused on data management, reactive and active power management and network planning. The platform initiative also led to a series of papers which sought to provide key recommendations to policymakers and system operators to ensure successful cooperation between the TSO and DSO.[123] Separate initiatives funded by the European Commission have also begun piloting projects to improve coordination and data exchange between entities on the grid in order to improve the integration of renewable energy resources. One such project, Smart Net, plans on developing three pilots in Italy, Denmark, and Spain and will focus on:

[122] (Gimeno 2015)
[123] (ENTSO-E 2015a; 2015b; 2016; Ebrill 2016)

TSO-DSO coordination for accommodating ancillary services from the distribution system

Market architectures for integrating ancillary services from DER

Communication and Information and Communication Technology (ICT) requirements.[124]

Most notably, the factors that have led ENTSO-E to emphasize the Distribution and Transmission Interactivity Pathway are:

Renewable Energy Resource Availability – The territories within the ENTSO-E jurisdiction have a diverse set of both wind and solar resources, which when interconnected through transmission and available to a broad array of system operators can help reduce the aggregate variability on the system.

Land Availability – Much of the ENTSO-E demand centers are dense cities without large expanses of open area for renewable energy development, making distributed resources more attractive.

Market and Institutional Context – The European Union has a policy goal and mandate for the development of a large, centralized energy market that spans several European countries, increasing the need for cooperation and the number of resources available for all system operators. Furthermore, there is very high customer demand for distributed energy resources, notably distributed solar PV and home battery systems as well as 'smart-homes,' partly inspired in some countries by relatively high energy prices.[125] There is also a large opportunity and desire for cross-sector electrification of transportation and heating, which will create more opportunities for demand response resources at the distribution level. However, there is also significant large-scale generation assets (both clean and traditional) which might otherwise be stranded in a DER Revolution Pathway.

Grid Characteristics – ENTSO-E has well-developed transmission systems which create ample cross-border trade opportunities, which in turn allow for higher penetrations of DER. Furthermore, ENTSO-E operators have significant experience with variable renewable energy resources, strong grid management capabilities, and large balancing areas, which enable increased TSO-DSO cooperation and renewable energy penetration.

[124] (SmartNet 2018)
[125] (Hockenos 2019).

Table 13. Factors Contributing to T&D Interactivity Emphasis in the European Union

Factors for ENTSO-E	*Current relevance of factor*	*DER Revolution*	*Bulk Power Transformation*	*Transmission and Distribution Interactivity*	*Distributed Transactional Future*
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-Scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-Sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

Successes and good practices in Europe enabling T&D Interactivity Pathway:

Harmonized Wholesale Market – As part of a larger policy package from the European Union ENTSO-E has developed a harmonized wholesale electricity market across multiple countries with a variety of ancillary services which are sold in addition to energy and capacity;

DSO Research – ENTSO-E and other European institutes have begun significant investigation into the future role of DSOs as traditional distribution utilities begin transitioning;[126]

Data-sharing procedures – ENTSO-E has begun development of harmonized data-sharing between TSOs and DSOs to facilitate more harmonized operation and planning across the distribution and transmission system;[127]

Pilot projects – The E.U.-funded SMARTNET project has analyzed potential DSO-TSO coordination schemes and begun developing pilots to address procuring ancillary services from the distribution network;[128]

Regulatory guidelines for T&D cooperation – The Council of European Energy Regulators (CEER) has put forward principles that should set the trajectory of the future DSO-TSO relationship and related regulatory arrangements in the areas of governance, network planning, and system operation.[129]

[126] (ENTSO-E 2015a)
[127] (ENTSO-E 2016)
[128] (Gerard et al. 2018; 2016; SmartNet 2019)
[129] (Ebrill 2016)

Key actions to further enable T&D Interactivity Pathway in Europe:

Aggregated DER – To ensure the optimal use of distributed resources, particularly in wholesale markets, regulators can continue deepen support and research of aggregated DER participation in energy market;

Real-time status sharing – To help ensure that market participant or system operator actions do not exacerbate issues on the distribution system, operators can better reflect the current status of the distribution system to TSO and to other market participants;

Third-party data sharing – To help coordinate market participants' investments with forecasted demand and system needs system operators and utility could improve data sharing with third-party providers (e.g., through the use of a centralized, public data-sharing hub);

Additional Pilots – European regulators could continue to develop pilots for TSO-DSO coordination to help further analyze how to implement real-world joint operation and planning between the TSO and DSO.

5.3.6 Possible Interventions to Enable Significant Scale Up

Based on information in the sections above and the jurisdiction example, four key interventions that could support the T&D Interactivity Pathway are presented below.

Encourage the joint planning and operation of the DSO and TSO systems, including the development of hybridized models for the transmission and distribution system that consider each's impact on the other;

Create a regular, mutually agreed upon data sharing protocol for both real-time data on network operation and DER generation and forecasted data for network growth and DER adoption. This agreement should include the format, frequency and depth of information shared. This data should be made publicly available for commercial developers to help align their projects with system needs;

Investigate the impacts that providing energy and ancillary services to the transmission system may have on the distribution system and develop a systematic approach to identify and mitigate negative impacts such as congestion; and

Encourage the growth of microgrids and DER aggregation through legislation and incentives and ensure their ability to supply energy and ancillary services; furthermore, ensure their fair and accurate compensation for the full value they provide the distribution and transmission system.

5.4 Distributed Transactional Future

Technical innovations in distributed energy resources (DER)—including distributed photovoltaics (DPV), behind-the-meter energy storage, and automated energy management and controls systems—continue to deliver new capabilities that can save money for consumers, support grid resilience and reliability, and drive progress toward clean energy goals. However, limited market opportunities for these technologies may threaten to constrain their utilization, deployment, and ability to operate in a coordinated and operationally-optimized manner within the broader power system. A key factor to support the deployment of these technologies will be the adoption of enabling technologies and systems that support seamless, flexible coordination of both centralized and decentralized power system elements, and such transformation is unlikely to occur if the various value streams of DER cannot be monetized in novel, creative ways.[130]

Furthermore, increased digitization and automation across the electricity value chain (from production, transmission, distribution, and consumption) together with the growth of DER are changing the fundamental nature of power systems in myriad ways. Traditionally, system operators have had perhaps only a couple of dozen control points to manage on the supply side, coupled with hundreds or thousands of—what have until recently been passive—nodes on the demand side. Now, this is shifting in two critical ways:

<u>More nodes and control points</u> – Systems are moving from having dozens of nodes to control power injection into the grid and related grid services, to now having potentially hundreds or thousands of control points—each one linked to a new DER resource;

<u>Changing nature of control points</u> – What had formerly been strictly passive load nodes interacting in a unidirectional way with the grid will now double as supply nodes needing to interact bidirectionally with the grid.

In order to unlock technical advances made in the primary pathways (namely the DER Revolution and T&D Interactivity Pathways, with the Bulk Power Transformation Pathway to a lesser extent), the way energy services are characterized, valued, priced, procured, and transacted may need to change. Thus, the Distributed Transactional Future Pathway can be understood as a complementary pathway to the three primary PST pathways. The undertakings entailed under this pathway focus on a transformation of the electricity services market and system operations paradigm intended to enable innovative DER technologies and approaches to operate at their maximum value. Importantly, the pursuit of the Distributed Transactional Future Pathway in isolation may not help to accelerate PST efforts. However, a simultaneous move toward this pathway could help promote more rapid change and uptake in the other pathways by creating a clear market mechanism for early technology adopters to realize the full value of their DER investments.

For example, a homeowner with a combined storage-plus-DPV system may be able to reduce their electricity bill, yet otherwise may be limited in their capability to contribute to the flexibility or stability of the power system and seek compensation for providing those services. This is largely due to the lack of a market mechanism to dynamically interact with the utility and/or other market participants. Markets that would allow such customers to sell excess generation to neighbors, charge for access to a home electric vehicle charging station, provide grid support services, and/or act on a number of other profitable uses do not yet exist. More generally, operational and financial optimization of distribution networks through retail electricity markets is often inhibited by a lack of incentives that entice customers to respond in real-time to fluctuations in overall energy demand and capacity requirements. This lack of an

[130] Cutler et al. (forthcoming white paper).

effective interface results in fewer potential value streams for customers, underutilized assets for utilities, and fewer growth opportunities for vendors and manufacturers.

An automated, secure, and real-time distributed energy market utilizing emerging distributed network protocols, such as blockchain, presents a transformative opportunity to enable distributed energy markets and scale DER. Just as companies such as Uber and AirBnB have created new platforms for accessing latent value by maximizing utilization of traditionally underutilized assets (e.g., a car sitting in a driveway or an unoccupied bedroom, respectively), a similar (albeit far more complex) shift to a distributed energy transaction environment could enable underutilized DER capacity and related grid services to be marketed through real-time markets hosted on integrated platforms that enable utility sales, peer-to-peer energy transactions, broadscale enrollment of demand response (DR) resources, and the provision of a range of grid services from retail customers.

Finally, there are many similarities between the T&D Interactivity Pathway and the Distributed Transactional Future Pathway as both discuss enhanced digitization, coordination and communication to a great extent. However, a distinction can effectively be drawn between interactions that occur upstream of the distribution system and those that occur downstream of the distribution system. Thus, while the T&D Interactivity Pathway focuses upstream on interactivity between bulk transmission systems and distribution system operators, the distributed transaction section focuses further downstream on enhanced coordination, communication and real-time control between distribution system operators and customers.

Based on jurisdictional experience, Figure 21 provides supportive actions that could enable the Distributed Transactional Future pathway out to 2050.

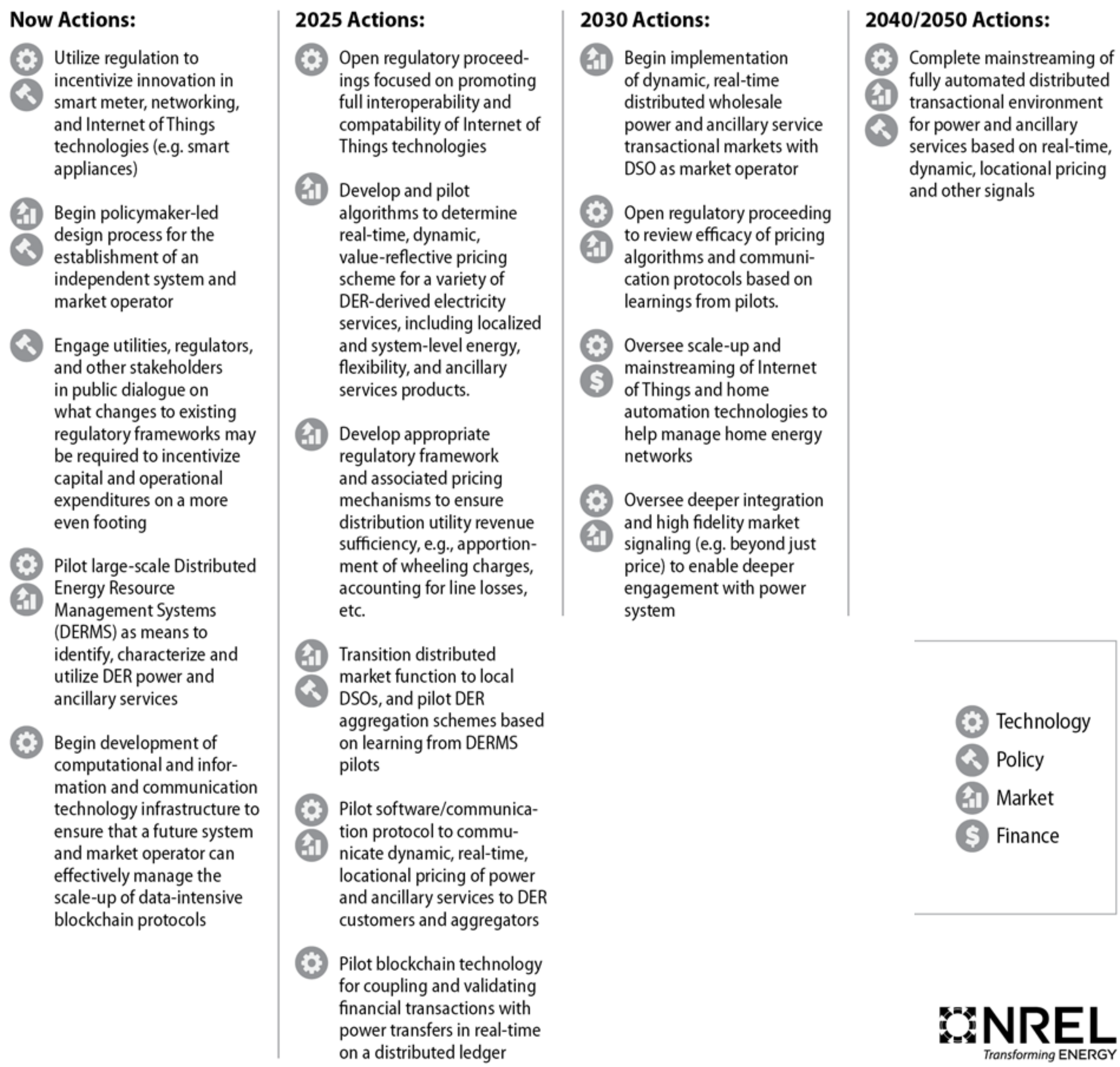

Figure 21. Transactional Future Pathway out to 2050 – Supportive Actions

*The key actions listed here have been distilled from a much larger series of actions required to enable a truly Distributed Transactional Future, with the goal of presenting an easily digestible summary of the highest priority areas where progress is required. For a more detailed description and in-depth treatment of the prerequisites to transition to a Distributed Transactional Future, the authors suggest the Transactive Energy Systems Research, Development and Deployment Roadmap prepared by the GridWise Architecture Council for the U.S. Department of Energy. [131]

5.4.1 Issues for Consideration - Distributed Transactional Future Pathway

Energy Services Value Structure – A Distributed Transactional Future is rooted in the premise that decentralized energy resources and energy consumption hold nascent value that is currently under-realized by power system participants (e.g., consumers, producers, and system operators).

[131] (Gridwise Architecture Council 2018)

For this transformation to occur, a fair, transparent, and dynamic mechanism for pricing all energy services—including energy production, demand response, and ancillary services—must be established. Clearly communicated value propositions and pricing signals and real-time response from an active group of market participants would serve as the underlying mechanism to balance supply and demand across the entire network, in real-time and at the lowest possible cost to all participants. This represents a major shift away from the current paradigm in which energy service values are typically assigned by utilities and/or system operators in less than real time.

Transaction Protocol and Market Operation – The shift toward a dynamic, distributed transactional environment for how power services are procured and traded is poised to unlock a whole new suite of services and previously untapped value from DER in the next decade. However, this will require a fundamental change in the way electricity services markets operate—namely a secure means to establish seamless, real-time interaction of DER control points with and across the network. Digital ledger protocols (e.g., Blockchain) are one possible example and offer a mechanism for establishing consensus among participants in a decentralized virtual network—or, in the case of a power system, every other DER prosumer connected to the power distribution network. Such a decentralized and secure architecture may not need to rely on central authorities or trust between individual participants and makes possible platforms and services that significantly reduce the cost, settlement time, and risk associated with digital transactions. This would shift the responsibilities of a traditional market operator (e.g., price formulation, communication and transaction settlement) away from utilities and ISO's and instead toward a real-time, dynamic, automated system.

Digitization, Automation and Interoperability – In order for decentralized resources to dynamically interact with the distribution network and effectively balance supply and demand across the entire power system on a real-time, value-based premise, digitization and automation of energy consuming and energy producing appliances and infrastructure are prerequisite. This transition is already beginning to occur (e.g., rise of Internet-of-Things or "IoT" technology) but will be necessary at scale for market participants to access the full value of their investments in DER and IoT technology. Appliances and distributed power sources would need to be able to communicate to one another and to the distribution network in order to make real-time, value-based decisions about how and when to operate. Furthermore, the communication protocols underlying digitized and automated building appliances and energy systems would need to be seamlessly interoperable with one another.

5.4.2 PST Objectives and Alignment With Distributed Transactional Future Pathway

Table 14. PST Objectives and Alignment with Distributed Transactional Future Pathway

Objectives	Pathway Alignment	Pilot Project Examples
Economic Development	The Distributed Transactional Future Pathway can enable economic development in several ways, chief among them by providing a means for prosumers of the future to realize the true monetary benefits for their investments in distributed generation, EVs, and IoT technologies such as smart appliances and home energy management systems. Furthermore, by shifting to a paradigm in which power system operators are incentivized to reduce overall total system costs rather than maximize revenue from kWh sales, capital resources for power sector infrastructure could be put to work in a much smarter and more productive way—for example by investing in intelligent demand response infrastructure instead of building a brand new power plant that may only be used a few hours per year to meet peak demand. Additional revenue streams for prosumers and more efficient allocation of corporate capital can both help spur economic activity across the economy. Furthermore, improvements to energy efficiency and its associated cost savings for consumers—especially large businesses—may help spur reinvestment into more economically productive activities than electricity purchasing which might contribute more to economic growth. Finally, the distributed transactional future would serve to maximize demand for DERs which, as noted above, are more job-intensive on a per-kW-basis than utility-scale projects of the same magnitude.	No robust examples as of the time of this writing. However, ABB and Enbala have partnered to launch a DERMS pilot in Switzerland that uses more top-down control to manage responsive loads on behalf of its customers to achieve cost savings. At this time, there is no clear linkage to increased economic development.
Energy Access	DER, particularly in the case of the isolated microgrid systems, are proving an effective means to enable energy access in locations where grid extension may be cost prohibitive, or, in some instances, in cases in which the grid is simply unreliable and undesirable as an option. To this end, the Distributed Transactional Future Pathway may be a key facilitator in driving adoption of DER in underserved areas and aid system operation of microgrids for energy access. Just as many emerging economies have effectively "leap-frogged" old technology in the telecommunications space by skipping landlines in lieu of cellular technology, a similar phenomenon is already starting to occur in the power sector in which microgrids and solar-home-systems are taking root as a viable and cost-effective means to achieve electrify unserved communities. As microgrid operators seek means to improve the operational efficiency of their systems – which often rely on a mix of solar, battery and diesel technology – distributed control and transaction technologies are beginning to be discussed as a potentially viable option. These microgrids effectively serve as test beds and could serve as a valuable proving ground for distributed transaction technologies.	No robust, proven examples as of the time of this writing. However, more efficient operation of microgrids relying on local RE resources could enable cheaper, more effective solutions for remote energy access applications.
Environmental Sustainability	By helping realize the maximum value from technological advances in the other pathways, the Distributed Transactional Future Pathway can ensure that DER, VRE, and demand	No robust examples as of the time of this

	response resources are fully utilized, maximizing the positive environmental impacts of those technologies. Furthermore, this pathway may help to drive more rapid adoption and scale-up of DER and EE technologies by future prosumers, by presenting a clear and trusted mechanism by which technology adopters will realize the full monetary benefits of investments in RE and EE technologies.	writing. However, distributed transactions could offer a mechanism to enable seamless tracking of RECs and/or other sustainability attributes
Resilience and Energy Security	Closely aligned with the reliability objective, the Distributed Transactional Future Pathway can help improve system resilience by enabling more rapid scale-up and maximum utilization of DER, EE, and advanced energy management technologies. Modularity of these systems and greater geographic diversity the location of generation and control nodes can, if managed properly, create significant advantages versus a paradigm of centralized power generation and control in the case of natural or man-made disasters. Automated home energy management can allow homes and business to better cope with the impacts of natural or man-made disasters on an individual scale, and real-time automation based on dynamic pricing signals or direct control from emergency system operators will allow the system at large to curtail demand or divert energy to critical loads in areas affected by disasters or extreme weather events.	Brooklyn Microgrid Pilot in New York (see case study below).
Energy Democratization and Responsiveness to Consumer Demand	The Distributed Transactional Future Pathway is likely to be the most effective and meaningful way to engage consumers as active participants in the power system and empower them with greater agency and control over how they choose to interact with the other system participants as well as the system at large. Real-time, dynamic pricing for a full range of energy services—enabled by a trusted distributed transactional infrastructure—can provide a wider range of value streams to prosumers who choose to invest in DG, EE, EVs, IoT, and related technology and create new revenue streams for those consumers. Conversely, automated home energy managements enabled by IoT technology may allow consumers to choose exactly how they respond to dynamic prices based on their preferences (e.g., whether they choose simply to minimize costs to operate their home system through minor time-of-use adjustments, maximize on-site clean energy utilization to reduce their personal GHG footprint, or maximize incoming revenue by providing available grid services when needed by the system, among other options).	The Brooklyn Microgrid (BMG) in New York and the Distributed Energy Exchange (deX) in Australia both represent good examples of this – BMG is responding to demand for clean, local energy purchasing options while deX is responding to increased adoption of “smart” devices and DER systems. (See case studies

		below for more detail).

5.4.3 Factors to Consider for the Transactional Future Pathway

Building on the PST objectives, specific factors within a jurisdiction may lead decision-makers to place a greater relative emphasis on the Distributed Transactional Future Pathway. Factors that may lead jurisdictions to place greater emphasis on this pathway are outlined below and presented in Table 15.

Renewable Energy Resource Availability - The availability of specific renewable resources is not a major driving factor for this pathway, though certain resources, such as solar, do tend to drive more distribution-level generation and thus lend themselves better to a Distributed Transactional Future Pathway. However, resource availability is not a mandatory prerequisite for the Distributed Transactional Future Pathway, which also serves to integrated and compensate other DERs such as demand response, distributed storage, and EVs, among others.

Land Availability – Similar to the resource availability, land availability is also not a major factor, though denser urban areas do tend to drive uptake in DER and hence may play a role in helping drive the realization of a Distributed Transactional Future. However, as illustrated by the two case studies presented below, distributed transaction pilot programs have been explored both in highly dense urban areas such as Brooklyn, New York, as well as in relatively dispersed rural areas such as parts of Australia.

Key Economic Industries – The Distributed Transactional Future Pathway can help countries more effectively adopt and integrate DERs such as rooftop PV, distributed storage, EVs, smart appliances, and other DER technologies, grounded in a strong foundation on IoT technology. Hence countries that have or are interested in growing these industries may benefit from a Distributed Transactional Future that can facilitate deployment of these technologies and create new value streams to spur consumer investment. Furthermore, countries with large industrial loads may benefit as these loads are often early targets for DER uptake—especially price-based demand response programs.[132]

Market Factors – Market factors are a significant driver of the Distributed Transactional Future Pathway. Jurisdictions with decentralized markets are prime targets for adoption of distributed transactional framework as the presence of an unbundled power market can help to remove barriers to implementation and help to increase the value and impact of this pathway for distribution system operators and customers. However, centralized markets can benefit from the Distributed Transactional Future Pathway as well, by improving the ability of market operators to coordinate, balance, dispatch, and compensate distributed resources (e.g., as illustrated by the deX Australia case study below). On the customer side, both demand for DER and high electricity or fuel prices can be an important factor driving customer demand for DER, which in turn may drive a Distributed Transactional Future Pathway (e.g., as illustrated by the Brooklyn

[132] A price-based demand response program, typically administered by a distribution system operator, is a demand response program that uses real-time price signals—which consumers can choose to respond to or not—as a mechanism to curb or shift consumer demand. This is different from other demand response programs in which a utility may have direct control and ability to curb a consumer's demand in accordance with a standing agreement between the utility and the consumer.

Microgrid case study). Existing cross-sector electrification efforts and goals may also benefit from this pathway, as each new source of power sector demand can potentially serve as an resource node on the system with unique spatial and temporal load patterns, and these prosumers will need to be effectively integrated, dispatched, and valued on distribution networks to meet system needs.

Grid Characteristics - A robust, reliable transmission and distribution system with strong grid management capabilities will be indispensable for the Distributed Transactional Future Pathway. Without these prerequisites, effective integration, coordination, and dispatch of DER on the distribution network will not be possible. Improved grid management is perhaps the single biggest driver of the Distributed Transactional Future Pathway, which aims to provide a paradigm shift that will enable cost-effective, market-based operation of an increasingly complex and spatially disaggregated set of power system participants.

Power System Vulnerability – Transitioning towards a Distributed Transactional Future Pathway can be one of the most effective and proactive means to mitigate threats to the power system and increase reliability, security, and resilience. The Brooklyn Microgrid was developed explicitly with this in mind, designed to be able to fully decouple from the power system and operate as a self-contained microgrid in the event of a power system disruption. By enabling increased uptake of DERs and facilitating direct transactions without the need for a middleman (i.e., a distribution system operator or utility), this pathway can significantly improve system resilience in the face of natural or man-made disasters that cause electricity service interruptions. In the face of ever-increasing cybersecurity threats, the secure nature of distributed transactional ledgers such as blockchain can further enhance cybersecurity. However, this transition is also not without risks, as the shift towards increased utilization of IoT technology and automation may also create additional targets that may be susceptible to cyberattacks.

Table 15. Factors Aligning With the Distributed Transactional Future Pathway

	Pathways and level of alignment with factors			
	DER Revolution	*Bulk Power Transformation*	*Transmission and Distribution Interactivity*	*Distributed Transactional Future*
Area #1 - Local Power System Transformation Objectives				
Objective: Economic Development				
Objective: Energy Access				
Objective: Environmental Sustainability				
Objective: Resilience and Energy Security				
Objective: Energy Democratization + Responsiveness to Consumer Demand				
Area #2 - Renewable Energy Resource Availability				
Solar				
Wind				
Offshore Wind				
Geothermal				
Biomass				
Area #3 - Land Availability				
Significant Land Availability				
Minimal Land Availability				
Dense Urban Area with Suitable Rooftops				
Area # 4 - Key Economic Industries				
Established Distributed Energy Resource Installer Market				
Established Large-scale RE Manufacturing Sector (e.g., large wind turbines)				
Established DER Manufacturing Sector (e.g., batteries, PV panels)				
Significant Industrial Demand				
Significant Agricultural Demand				
Area # 5 - Market Factors				
Decentralized Power Market				
Centralized Power Market				
Utility Financial Insolvency				
Customer Demand for Distributed Energy Resources				
High Electricity and/or Fuel Prices				
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets				
Significant Cross-Border Trading Opportunities				
Significant Cross-sector Electrification Potential				
Area #6 - Grid Characteristics				
Robust Transmission & Distribution Networks				
Large Balancing Area				
Strong Grid Management Capabilities				

Area #7 - Power System Vulnerability				
Dependence on Imported Fuels				
High Vulnerability to Natural Threats				
High Vulnerability to Physical or Cybersecurity Threats				

Pathway Alignment Color Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak alignment of the factor for the pathway

5.4.4 Distributed Transactional Future Technology and Business Model Evolution Over Time

As the Distributed Transactional Future Pathway is still a nascent concept, examples of concrete business models are still lacking. However, this pathway has the potential to unleash an entirely new ecosystem of power system services and value chains upon which new business models may evolve.

Innovation is already well underway for DG, DSM, EVs, and IoT technology, which are key technologies that support the Distributed Transactional Future Pathway. While some of the benefits of these new technologies can and are being realized today, the full potential for innovation will likely only be met once these technologies are fully untethered and enabled to interact with the power system on a truly dynamic and multi-directional basis—responding in real-time to price and others signals indicated by the grid. As consumers gradually realize value from these innovative technologies it could spur further demand for new technology and innovation.

Several of these services and models are summarized in Box 7 below.

Box 7. Distributed Transaction Pathway – Blockchain as an Enabler of Innovative Business Models

Based on the discussion paper by David Livingston et al. 2018, "Applying Blockchain Technology to Electric Power Systems"

The Council on Foreign Relations recently conducted a survey looking at innovative applications of blockchain as a digital distributed transaction ledger to enable new business models in the electricity sector (Livingston et al. 2018).The survey yielded interesting insights into the potential applications of blockchain—not only as an enabler of energy services trading—but also as a way to transactions in areas peripherally related to the power sector. While electricity services trading (both peer-to-peer transactions and grid transactions) represent the majority of applications, innovative applications are also emerging, such as using blockchain to enable microfinance investors to fund clean energy projects, or to track the trading of sustainability attributes of electricity (e.g., RECs) to make clean energy projects more viable. The relative prevalence of various innovative applications of blockchain is summarized in Figure 22 below. Generally, these applications can be split into the following categories:

Peer-to-peer (P2P) energy trading. This is generally the most commonly discussed and easy to conceptualize application of blockchain in the power sector. P2P trading networks would essentially allow individuals to trade virtual energy surpluses (e.g., kWhs) from distributed resources with one another. This would allow customers with distributed generation resources to access value from those resources at market rates. Importantly, such P2P trading networks would still rely on a common grid and do not actually affect the physical flow of electricity—rather it can be likened to more of a real-time commodity trading market. The benefit is that a digital distributed transaction ledger can enable tracking of trades in a range of locations and at smaller scales where traditional centralized means of tracking and clearing transactions may have been untenable.

Grid services transactions. While P2P energy trading may be the most popularly discussed potential application, blockchain also stands to benefit more traditional wholesale power markets and distribution systems. Traditional power markets are still largely operated by a centralized clearing authority with inherent limits on the speed or volume of transactions they are able to process. Increased speed and transparency enabled by blockchain can allow these markets to operate much more efficiently while also opening the market to new participants for whom traditional transaction costs may have been prohibitively high. Furthermore, as discussed at length in this section, such applications can also open new ancillary services markets for prosumers and enable more effective, value-driven balancing within.

Energy financing. Rather than facilitating trading of power services directly, blockchain technology can also be used as a tool to help raise capital for energy projects. While utility-scale energy projects require significant investment, which has typically come from large, institutional investors, blockchain can potentially enable a multitude of small or individual investors to contribute to projects—for example clean energy projects. While perhaps similar to traditional online crowdfunding services, integration with blockchain may enable individual investors to be rewarded—say with a credit or cryptocurrency token that can be redeemed for reduced-rate electricity—which otherwise may not be possible on the same scale or volume with traditional crowdfunding platforms.

Sustainability attribute trading. Blockchain may also be used to facilitate trading of sustainability attributes of energy projects. While markets for Renewable Energy Certificates (RECs) are fairly mature, they are still operated by a centralized authority responsible for awarding, validating, and tracking REC transactions. Blockchain could be used to increase the transparency and accuracy of the REC trading process to reduce transaction costs and increase the flow of financial value to sustainable energy projects.

Electric vehicle interactions. One of the biggest barriers to uptake of electric vehicles is the availability of public charging stations and the ease of tracking charging transactions. Blockchain can help reduce this barrier by enabling the creation of a platform that facilitates the participation of unused charging stations (both public and private) to easily enter into transactions with EV owners to sell electricity. While one-way charging transactions may be viable with current credit card technology (i.e., similar to how existing gas stations work), blockchain has the potential to enable smarter charging that allows EVs plugged into a station that isn't their "home" charging station to respond to changing needs and prices on the distribution network they may be connected to, according to preferences of the vehicle owner.

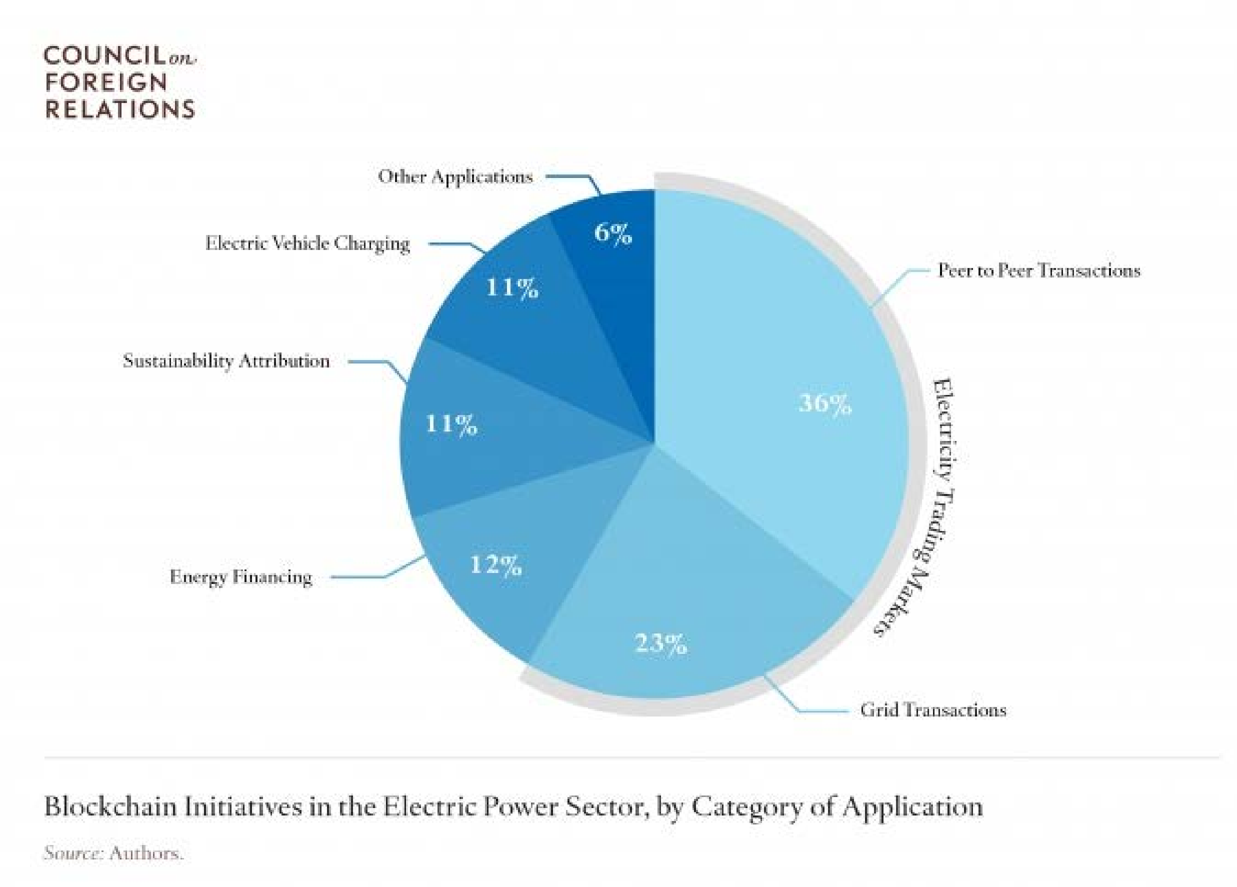

Figure 22. Innovative applications of blockchain to the electric power sector[133]

5.4.5 Pilot Project Pathways and Insights

As an emerging new approach to electricity services markets still in the conceptual phase and not yet well-understood, the Distributed Transactional Future Pathway has yet to be successfully piloted at the national level or considered as a centerpiece of any jurisdictional government's approach to power system transformation. However, several early pilots are underway with limited scope and a multitude of technology start-up companies are entering the space with the goal of creating an effective distributed transactional platform, and these pilots can lend helpful insights into this nascent field. Two such pilots are highlighted below, each with a slightly different business model (see Box 7 above). One of these—the Brooklyn Microgrid—represents a direct peer-to-peer energy trading application while the other—the Distributed Energy Exchange—represents more of a grid services transaction application.

LO3 Energy and the Brooklyn Microgrid (New York, United States)

The BMG represents one of the first ever successful pilots of a decentralized, albeit limited, transactional system enabling peer-to-peer trading of energy among neighbors. Launched in 2016 by LO3 Energy, a New York-based technology start-up company, the project aims to connect neighbors through both a virtual and physical microgrid to allow them to trade surplus generation

[133] (Livingston et al. 2018)

from rooftop photovoltaic systems with one another.[134] Currently the BMG contains around 60 prosumers who are able to automatically sell surplus power in near real-time to a larger number of local consumers using LO3's blockchain-based trading platform.[135] The BMG was conceived to work in tandem with the conventional grid, as part of New York State's Reforming the Energy Vision effort underway to make the state's power system more flexible, resilient and economically efficient while reducing GHG emissions.[136]

The BMG project was designed with resilience and energy security in mind, hence has developed not only the virtual microgrid for local energy transactions, but also a physical microgrid connecting participating prosumers that operates in parallel to the existing local distribution grid.[137] This setup allows the physical microgrid to decouple from the local distribution network to act as a true backup in the event of power outages and other emergencies, such as 2012's Hurricane Sandy.[138]

The BMG has shown that blockchain-based decentralized transactions can enable peer-to-peer trading that creates local value and establishes clear price signals to drive adoption of local rooftop PV and other distributed energy resources. However, it still faces regulatory hurdles limiting its ability to seamlessly integrate with the local distribution utility (Con Edison) to serve as broker of electricity sales or offer simplified combined billing to help expand its customer base.[139]

Notably, the major factors that spurred the launch of the BMG pilot include:

Land Availability – In the dense urban landscape of Brooklyn, scarce availability of land limits the ability of communities to invest in local energy sources, driving them instead toward rooftop photovoltaics.

Market Factors – Customer demand for DER and high electricity prices are two explicit drivers behind the BMG pilot and are also driving customer participation in the program.

Power System Vulnerability – The BMG was designed first and foremost with system resilience and security in mind (even specifically calling out the impact of 2012's Hurricane Sandy). The system is designed to increase reliance on local resources to improve resilience and to be able to decouple from the larger distribution network to operate as a self-sustaining microgrid in the event of power system disruptions.

[134] (Tormen 2018)
[135] (Livingston et al. 2018)
[136] (Cardwell 2017)
[137] (Mengelkamp et al. 2018)
[138] (DSX Team 2018)
[139] (Livingston et al. 2018)

Table 16. Factors Contributing to Distributed Transactional Future Emphasis in Brooklyn

Factors for the Brooklyn Microgrid Pilot	*Current relevance of factor*	*DER Revolution*	*Bulk Power Transformation*	*Transmission and Distribution Interactivity*	*Distributed Transactional Future*
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-Scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-Sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

Successes and good practices enabling Distributed Transactional Future for the BMG pilot:

High level of community engagement in their energy future

Clear project goals and objectives rooted in state-wide goals with political backing (i.e., New York's Reforming the Energy Vision effort)

Implementation of a sound technical platform and market system that enables direct peer-to-peer trading of credits, successfully implemented using blockchain

Both virtual software and physical hardware deployed in tandem to enable both streamlined virtual transactions, as well as physical grid decoupling in the event of disasters.

Gaps and challenges for the BMG pilot:

Effective collaboration with utility and regulators remains a challenge (e.g., initially consumers could not legally sell electricity directly so they sold virtual RE credits instead, LO3 Energy still lacks ability to collaborate with ConEd to present a combined customer bill including P2P transactions and grid-purchased electricity).

Currently piloted in a very wealthy neighborhood where homeowners are more likely to be able and willing to install rooftop PV and pay premiums for locally produced renewable energy.

Limited trading of market products. Initially, only renewable energy certificates were sold. The pilot did not feature a market for storage, EVs, demand response or ancillary services; however, an expansion of market products is planned.

Installed separate physical microgrid on top of existing network to ensure reliability/resiliency goals were met. This is duplicative but necessary because of lack of ability to coordinate with existing utility—in future, better coordination with existing infrastructure can eliminate this requirement.

The Decentralized Energy Exchange (deX)

The Government of Australia put forward an *Independent Review into the Future Security of the National Electricity Market: Blueprint for the Future* in 2017 that lays out a vision and plan for Australia's power system centered around four objectives: increased security, future reliability, rewarding consumers, and lower emissions.[140] Guided by this national vision, the Australia Renewable Energy Agency (ARENA) has recently announced support to pilot a new distributed transactional platform known as the Decentralized Energy Exchange (deX).

Led by tech startup GreenSync, deX is a digital marketplace that allows connected customers with rooftop PV systems and/or battery storage to sell excess power into the wholesale market and thus create additional value from their distributed assets.[141] The platform is designed to offer power systems operators a means for improved coordination and control over distributed energy resources, while also allowing consumers to access additional value from their energy assets by rewarding them for providing ancillary and grid services, in addition to energy.[142]

The deX platform relies on traditional Application Programming Interfaces (APIs) to serve as an intermediary between DER and network and market operators. The interface allows technology providers to seamlessly connect "smart" energy producing and consuming hardware with the deX platform. Once registered on deX, consumer devices are then visible to network and market operators and can be contracted and called upon to provide grid services such as supplying energy during peak demand, managing frequency or grid voltage, and reducing network constraints.[143]

Notably, and in contrast to the BMG, the deX platform is not based on blockchain or designed to enable direct peer-to-peer energy trading (though it may facilitate that in the future). Rather, it is intended to offer a mechanism to enable distributed energy resources to bid into wholesale energy and grid services markets, allowing traditional network operators to directly contract and compensate DER where they previously were unable to do so efficiently or cost-effectively. This may not represent a truly decentralized transactive future since the network/market operator still plays a central role, but it signifies an important step toward more effective integration and management of distributed energy resources on the grid to maximize value based on dynamic, real-time market principles for a range of services they are capable of providing.

Notably, the major factors that spurred the launch of the deX pilot include:

Market Factors – Customer demand for DER was a major driver behind the launch of the deX pilot. As customers adopt increasing amounts of DER, the deX will allow power system and market operators to more effectively coordinate and dispatch these distributed resources, while adequately compensating customers for their services.

Grid Characteristics – Similar to the above, the deX system allows market and system operators to further improve grid management practices by more effectively coordinating,

[140] (Finkel et al. 2017)
[141] (Townsend 2017)
[142] (Australian Renewable Energy Agency 2019)
[143] ibid.

procuring, and compensating ancillary and grid services from DERs. Previously, they had been unable to do so.

Power System Vulnerability – The Australian government's *Blueprint for the Future* explicitly calls out security and reliability as the first and second objectives for the power system. deX was piloted with the goal of meeting these objectives by creating a regional energy management system that more effectively incentivizes distributed energy resources, while allowing grid operators to coordinate and dispatch ancillary services from those distributed resources, which can improve the resilience, reliability, and security of the system.

Table 17. Factors Contributing to Distributed Transactional Future Emphasis in Australia

Factors for Decentralized Energy Exchange	Current relevance of factor	DER Revolution	Bulk Power Transformation	Transmission and Distribution Interactivity	Distributed Transactional Future
Area #2 - Renewable Energy Resource Availability					
Solar					
Wind					
Offshore Wind					
Geothermal					
Biomass					
Area #3 - Land Availability					
Significant Land Availability					
Minimal Land Availability					
Dense Urban Area with Suitable Rooftops					
Area # 4 - Key Economic Industries					
Established Distributed Energy Resource Installer Market					
Established Large-Scale RE Manufacturing Sector (e.g., large wind turbines)					
Established DER Manufacturing Sector (e.g., batteries, PV panels)					
Significant Industrial Demand					
Significant Agricultural Demand					
Area # 5 - Market Factors					
Decentralized Power Market					
Centralized Power Market					
Utility Financial Insolvency					
Customer Demand for Distributed Energy Resources					
High Electricity and/or Fuel Prices					
Large Fleet of Legacy Utility-Scale Thermal Power Plants and Transmission Assets					
Significant Cross-Border Trading Opportunities					
Significant Cross-sector Electrification Potential					
Area #6 - Grid Characteristics					
Robust Transmission & Distribution Networks					
Large Balancing Area					
Strong Grid Management Capabilities					
Area #7 - Power System Vulnerability					
Dependence on Imported Fuels					
High Vulnerability to Natural Threats					
High Vulnerability to Physical or Cybersecurity Threats					
GRAND TOTAL					
Pathway Score Based on Current Factors:					

Relevance of Factors and Objectives for Country/Jurisdiction Legend

Indicates the factor is highly relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is somewhat relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Indicates the factor is not relevant for the country/jurisdiction or the country/jurisdiction's aspirational or anticipated future

Pathway and Level of Alignment with Factors Legend

Indicates a strong alignment of the factor with the pathway

Indicates a moderate alignment of the factor with the pathway

Indicates weak or no alignment of the factor with the pathway

Pathway Score Legend

Indicates a strong alignment of the country/jurisdiction's factors with the pathway

Indicates a moderate alignment of the country/jurisdiction's factor with the pathway

Indicates weak alignment of the country/jurisdiction's factor with the pathway

Successes and good practices enabling the Distribution Transactional Future for the deX pilot:

Clear project goals and objectives rooted in national goals with political backing (i.e., the *Blueprint for the Future*)

Interoperable software platform enabling seamless integration of device and hardware across technology providers

Market and compensation system in place for a range of grid and ancillary services.

Gaps and challenges for the deX pilot:

Still progress to be made to achieve truly distributed transactive future. For example, in the deX case, the network operator still plays the central role in determining price and procuring services. Challenge remains to determine if and how to minimize the role of the operator as a middleman in order to reduce risks of bottlenecks.

Currently designed to apply exclusively to wholesale markets (i.e., no direct peer-to-peer trading, though this is not inherently a problem, depending on how the Distributed Transactional Future Pathway evolves)

Lack of transparency about market and pricing rules for non-power injection services, resulting in uncertainty to customers about how, when, and why the ancillary and grid services provided by their DER may be valued and procured by the network operator.

Pilot still represents a unidirectional control environment (i.e., DERs bid into market to provide services to the grid at the operator's discretion) – no converse mechanism enabling "smart" home energy management systems to respond to network signals regarding when and how to operate (e.g., appliances only operate when electricity prices are below a threshold or only operate when RE is available)

5.4.6 Possible Interventions to Enable Significant Scale Up

Based on information in the sections above, four key interventions that could support the Distributed Transactional Future Pathway are presented below.

Support a paradigm shift in how power systems are regulated, moving away from traditional revenue-motivated models to reward improved efficiency and minimization in total system cost;

Continue development, cost-reduction, and adoption of network infrastructure (e.g., smart meters, broadband, charging stations, automated home energy management systems, IoT technology, smart appliances and devices);

Pilot innovative approaches to market design and price determination to show how a truly decentralized, real-time market covering a range of services (e.g., power injection, demand response, grid services) could work; and

Establish clear roles and responsibilities—including how and by whom both the virtual market and the physical network will be maintained and operated.

6 Conclusion

There are various pathways countries can consider as they move toward power system transformation. This paper presents four possible pathways as well as various objectives and factors that countries can explore as they consider pathway decisions. The paper also sheds light on potential key actions to support each pathway as well as good practices and gaps in supporting pathways from a country perspective. Table 18 summarizes identified potential needs for intervention to support each pathway, based on the country examples.

Table 18. Potential Interventions for Each Pathway Based on Country Examples

Pathway	Possible Interventions/Needs
Distributed Energy Resource Revolution	1. Collection and public dissemination of local data on DER deployment, technology cost and performance trends, and other relevant aspects to inform data-driven decision-making and regularly updated planning exercises for the energy sector; 2. Accounting of DER in integrated resource plans (IRP) and other types of power sector planning processes, development of metrics to track DER deployment, and continual iteration on power sector plans to include disruptive technologies and business models that may arise; 3. Piloting and scale up of DER aggregation schemes, particularly in more developed renewable energy markets; 4. Designing the next generation of DER policy and regulatory frameworks which provide fair compensation and investment certainty for DER customers and enable broader participation of DER in the power system; 5. Support for robust policy frameworks, investment models and effective project development for off-grid DER solutions, in particular minigrids.
Bulk Power Transformation	1. Perform large-scale analysis across broader regions to inform planning. This could include development of grid integration analyses and detailed power sector planning studies, as well as identification of infrastructure and services needed to support large-scale renewable integration at a regional level. 2. Improve weather predictions and VRE output predictions using state-of-the-art forecasting techniques. 3. Identify and implement key complementary technologies (e.g., utility-scale storage), that, when paired with utility-scale VRE, provide essential grid services. 4. Design and execute wholesale, capacity, ancillary services, flexibility markets and other innovative approaches to support energy system reliability and cost efficiency.

	5. Identify sources of capital and design improved finance mechanisms for large-scale VRE and transmission development.
Transmission & Distribution Interactivity	1. Encourage the joint planning and operation of the DSO and TSO systems, including the development of hybridized models for the transmission and distribution system that consider each's impact on the other. 2. Create a regular, mutually agreed-upon data sharing protocol for both real-time data on network operation and DER generation and forecasted data for network growth and DER adoption. This agreement should include the format, frequency and depth of information shared. This date could be made publicly available for commercial developers to help align their projects with system needs. 3. Investigate the impacts that providing energy and ancillary services to the transmission system may have on the distribution system and develop a systematic approach to identify and mitigate negative impacts such as congestion. 4. Encourage the growth of microgrids and DER aggregation through legislation and incentives and ensure their ability to supply energy and ancillary services; furthermore, ensure their fair and accurate compensation for the full value they provide the distribution and transmission system.
Distributed Transactional Future	1. Support a paradigm shift in how power systems are regulated, moving away from traditional revenue-motivated models to reward improved efficiency and minimization in total system cost. 2. Continue development, cost reduction, and adoption of network infrastructure (e.g., smart meters, broadband, charging stations, automated home energy management systems, IoT technology, smart appliances, and devices). 3. Pilot innovative approaches to market design and price determination to show how a truly decentralized, real-time market covering a range of services (e.g., power injection, demand response, grid services) could work. 4. Establish clear roles and responsibilities—including how and by whom both the virtual market and the physical network will be maintained and operated.

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Appendix A. DER and Bulk Power Pathways Technology Cost Information

Table A- 1. DER and Bulk Power Technology Cost Projections

Low Cost Assumptions are displayed on top, Mid Cost Assumptions are displayed on bottom where available. Where multiple cost projections for a technology were available (e.g., for Rooftop PV in multiple cities throughout the United States), the average for the technology, cost assumption and year is provided.

Technology	Unit	Current Cost	Projected Cost in 2030	Projected Cost in 2050	Note
Rooftop PV – Residential	LCOE c/kWh	Low: 9.2 Mid: 10.5	Low: 3.1 Mid: 5.7	Low: 2.1 Mid: 4.3	NREL ATB 2019; R&D Finance
Rooftop PV – Commercial	LCOE c/kWh	Low: 5.6 Mid: 7.4	Low: 3.3 Mid: 5.6	Low: 2.2 Mid: 4.4	NREL ATB 2019; R&D Finance
Distributed Wind – Small	LCOE c/kWh	Average: 24[144] Median: 20.9	Average: 6 Median: 5.2	Average: 5.7 Median: 5.0	Current cost refers to Y2017 Turbine size: ≤ 100 kW 2030, 2050 costs are based on NREL's LCOE trajectory study[145]
Distributed Wind – Mid	LCOE c/kWh	Average: 29.2 Median: 32.3	Average: 7.3 Median: 8.1	Average: 6.9 Median:7.7	Current cost refers to Y2017 Turbine size: 101 kW - 1 MW Current cost: Only 4 samples were included. The minimum cost is 6.3 c/kWh. 2030, 2050 costs are based on NREL's LCOE trajectory study[146]
Distributed Wind – Large	LCOE c/kWh	Average: 4.2 Median: 3.1	NA	NA	Current cost refers to Y2017 Turbine size: > 1 MW
Geothermal Heat Pumps	LCOE c/kWh	14.1[147]	13.7[148]	12 (Levelized costs of heating)[149]	Current cost refers to Y2010
Behind-the-Meter Storage - Residential	CAPEX $/kW	1975	987[150]	NA	lithium-ion batteries 2-hour storage[151]
Behind-the-Meter Storage – Non - Residential	CAPEX $/kW	1400	700[152]	NA	lithium-ion batteries 2-hour storage[153]
Onshore Wind	LCOE c/kWh	Low: 4.4 Mid: 5.0	Low: 2.3 Mid: 3.6	Low: 1.6 Mid: 2.9	NREL ATB 2019; R&D Finance
Offshore Wind	LCOE c/kWh	Low: 8.1 Mid: 10.8	Low: 4.9 Mid: 6.6	Low: 2.4 Mid: 3.3	NREL ATB 201; R&D Finance
Utility-Scale PV	LCOE	Low: 3.3	Low: 1.9	Low: 1.2	NREL ATB 2019; R&D Finance

144 Current cost for small, mid and large size distributed wind are accessed via (Orrell et al. 2018)
145 (Lantz et al. 2016)
146 (Lantz et al. 2016)
147 (Connolly et al. 2015)
148 (Frontier Economics and Element Energy 2013)
149 (Knobloch et al. 2018)
150 IRENA projected 54-61% price reductions for Li-ion batteries from 2016 to 2030. Assuming a 50% reduction from 2019 to 2030 (IRENA 2017).
151 (WoodMackenzie and Energy Storage Association 2019)
152 IRENA projected 54-61% price reductions for Li-ion batteries from 2016 to 2030. Assuming a 50% reduction from 2019 to 2030 (IRENA 2017).
153 (WoodMackenzie and Energy Storage Association 2019)

	c/kWh	Mid: 4.0	Mid: 3.1	Mid: 2.4	
Concentrated Solar Power –Tower	LCOE c/kWh	Low: 10.3 Mid: 10.4	Low: 4.2 Mid: 6.0	Low: 3.6 Mid: 5.1	NREL ATB 2019; R&D Finance 10-hour Thermal Energy Storage
Geothermal – Hydro/Binary	LCOE c/kWh	Low: 9.6 Mid: 11.1	Low: 5.8 Mid: 10.5	Low: 5.8 Mid: 9.7	NREL ATB 2019; R&D Finance
Geothermal – NF EGS/Flash	LCOE c/kWh	Low: 16.9 Mid: 23.7	Low: 4.2 Mid: 22.3	Low: 4.2 Mid: 20.5	NREL ATB 2019; R&D Finance
Geothermal – Deep EGS/Flash	LCOE c/kWh	Low: 16.9 Mid: 23.7	Low: 4.2 Mid: 22.3	Low: 4.2 Mid: 20.5	NREL ATB 2019; R&D Finance
Hydro – Non-Powered Dams	LCOE c/kWh	Low: 4.6 Mid: 5.1	Low: 3.7 Mid: 5.1	Low: 3.0 Mid: 5.1	NREL ATB 2019; R&D Finance
Hydro – New Stream-Reach Development	LCOE c/kWh	Low: 5.3 Mid: 5.8	Low: 4.3 Mid: 5.7	Low: 3.5 Mid: 5.5	NREL ATB 2019; R&D Finance
Biomass – Dedicated	LCOE c/kWh	Low: 11.1 Mid: 11.1	Low: 11.0 Mid: 11.0	Low: 10.7 Mid: 10.7	NREL ATB 2019; R&D Finance
Biomass – Cofire Old/New	LCOE c/kWh	Low: 8.6 Mid: 8.6	Low: 8.3 Mid: 8.3	Low: 8.1 Mid: 8.3	NREL ATB 2019; R&D Finance
Utility-scale Battery Storage	CAPEX ($/kW)	Low: 1161.8 Mid: 1284.1	Low: 485.9 Mid: 810.3	Low: 295.7 Mid: 607.8	Current cost refers to Y2020 NREL ATB 2019;

Note: Unless specified, Current Cost refers to the Year 2019. LCOE refers to Levelized Cost of Energy. Monetary values are converted to $2019 based on inflation rates.

Distributed Resources: For distributed PV, the approach, methodology, cost and performance assumptions, and reference capacity are defined by NREL ATB 2018. Costs refers to ultra-low values. For distributed wind, due to the limited sampling data in this study, average and median values are used to represent the costs.

Bulk Power Resource: The approach, methodology, cost and performance assumptions, and reference capacity are defined by NREL ATB 2018 Unless specified at the Note column, costs refer to ultra-low values.

Appendix B. Technology Innovation and Costs to Date Background Information

Technology Drivers

Technological innovations driving power sector transformation include improvements in renewable energy (RE) technologies, such as solar photovoltaics and wind, that are raising capacity factors (IRENA 2018); improvements in battery storage technologies that when paired with RE can provide dispatchable energy and demand response; and the advent of smart energy technologies, such as advanced inverters, that allow for interoperability of the grid. The extent to which these emerging technologies are deployed to allow existing power plants to operate more flexibly to accommodate increasing amounts of distributed energy resources (DER) on the grid is also a driver of PST (IEA and NREL 2018).

Ongoing innovations in wind and solar technologies have an important role to play in power sector transformation by making it more technologically feasible and cost-effective to deploy them at scale. Solar panels are increasingly efficient and cost-effective, driven by technological developments including in the areas of high-efficiency crystalline and polycrystalline thin film PV and other advanced materials (NREL, n.d.-b). A U.S. Department of Energy synopsis of technological advancements in wind energy describes increased efficiency of both land-based and offshore installations as well. For land-based utility-scale wind plants, bigger turbines with longer blades are improving performance, with capacity factors increased by 79% in recent years compared with projects installed from 1998-2001. Similarly, "new offshore wind turbines are being developed with 10–12 megawatts [MW] of capacity… compared to an average capacity of 5.3 MW for offshore wind turbines installed in 2017" (DOE 2018).

The combination of energy storage systems with wind and solar at both utility and residential scales makes energy from variable sources available on demand, further driving PST. At the utility scale, advancements in lithium-ion batteries are, "enabling utilities to transition large-scale renewables from intermittent to dispatchable energy resources," as evidenced by recent investments in large-scale solar-plus-storage projects by both Florida Power & Light and Hawaiian Electric (Mai 2019). At the distributed scale, solar plus battery storage can be integrated with appliances such as smart hot water heaters, air conditioners, and EVs that provide services during off-peak times (see Figure B- 1). In this way, customers can maximize the use of self-generated power by shifting their loads to times of peak PV output, which is especially beneficial in situations where customers are not paid by the utility for excess electricity supplied to the grid by interconnected PV systems (net metering), or are charged higher rates for electricity during times of peak demand (time-of-use pricing) (O'Shaughnessy et al. 2017).

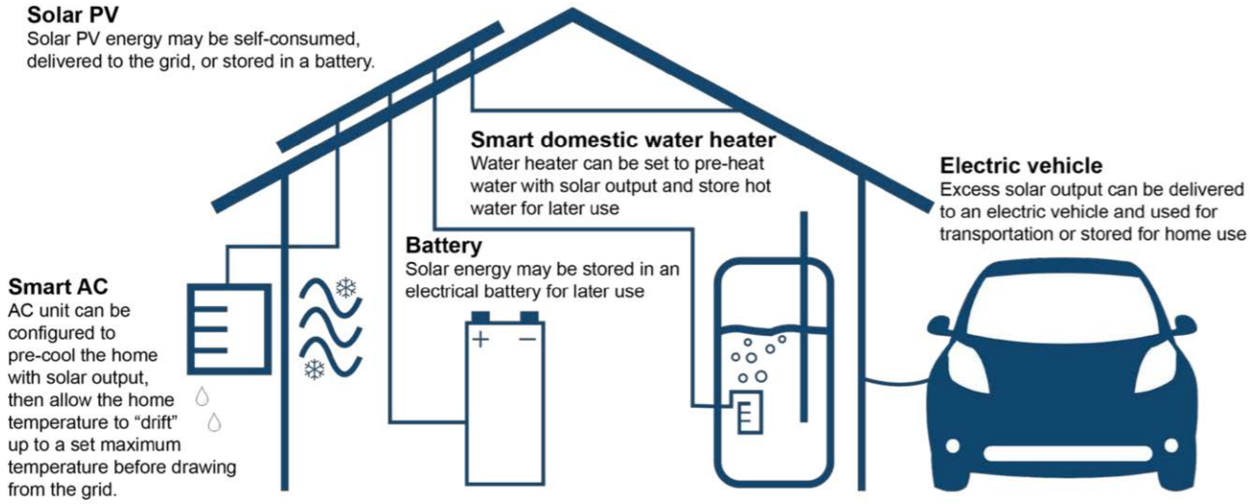

Figure B- 1. Solar plus technologies have a role to play in PST

Source: O'Shaughnessy et al. 2017

Technological innovation in the form smart grid technologies such as advanced inverters is also driving PST by enabling integration of distributed energy resources into the distribution system and enhanced interoperability. As a whole, the smart grid is, "a power production and distribution system that allows for two-way flow of electricity and communication," and, "utilizes a range of advanced information, communication, and energy technologies working together to respond digitally to variable electricity demand across the grid" (Mow 2017). Advanced inverters contribute to this system through their ability to "ride through" minor disturbances to frequency or voltage; help maintain system stability by feeding in or taking electricity from the grid as needed; and the ability to have a "soft start" after an outage by staggering reconnection of DERs to avoid spikes in power being fed into the grid and prevent another disturbance (Mow 2017).

The report *Status of Power System Transformation 2018: Advanced Power Plant Flexibility* describes how these technological developments together allow power plants to operate more flexibly to accommodate increasing amounts of DERs on the grid. The authors define power system flexibility as, "all relevant characteristics of a power system that facilitates the reliable and cost-effective management of variability and uncertainty in both supply and demand" (IEA and NREL 2018, p. 7). Examples provided of technological advancements that drive PST through increased power plant flexibility are: dispatchable generators that ramp up or start up quickly, "to cover periods of low VRE availability or rapid increases in demand" (p.23); wind and solar PV that connect to the grid using software-controlled power electronics such as advanced inverters to provide services, "ranging from fast frequency response to up/down ramping and operating reserves," (p. 23); and advancements in electricity storage technologies for bulk energy storage, among other services (IEA and NREL 2018). Technological advancements in concert with policy and market forces are making possible transformations in the power sector on a global scale.

Cost Drivers

Shifting costs associated with technological evolution are also driving PST. Bloomberg New Energy Finance (BNEF) made notable changes to its *Climatescope* methodology in 2018 to respond to,“the transformation of the energy sector brought about by a renewables revolution,” exemplified by “the 70% drop in the cost of Chinese-made PV modules” since 2011 (BNEF 2018, p. 19). Similarly, the International Renewable Energy Agency (IRENA) reports that, “the global weighted-average LCOE [levelized cost of energy] of utility-scale solar PV projects commissioned in 2017 was 73% lower than those commissioned in 2010… driven by an 81% reduction in module prices since the end of 2009” (IRENA 2018, p. 34). The global LCOE of concentrating solar power (CHP), offshore, and onshore wind all declined in the same period, with geothermal, hydro, solar PV, offshore, and onshore wind power prices all within the fossil fuel cost range (see Figure B- 2).

Source: IRENA Renewable Cost Database.

Note: The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE value for plants commissioned in each year. Real weighted average cost of capital is 7.5% for OECD countries and China and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

Figure B- 2. Global levelized cost of electricity (LCOE) from utility-scale renewable power generation technologies, 2010-2017

Source: IRENA 2018

Additional drivers identified by IRENA include increasing economies of scale in the manufacturing of renewable energy technologies and process improvements that reduce cost; more competitive global supply chains; standardization of processes by experienced RE project developers; and the use of real-time data to improve operations and maintenance (O&M) practices and reduce the loss of generation from unplanned outages (2018, p. 33). Indeed, IRENA reports that in many regions of the world RE technologies are often the lowest-cost source of new power generation (2018, p. 37). This may account in part for why, in 2017, "the majority of the world's new zero-carbon power capacity was built in developing countries. A total of 114 GW (including nuclear and hydro as well as 'new renewables') was added in these nations, compared with approximately 63 GW added in wealthier nations" (BNEF 2018).

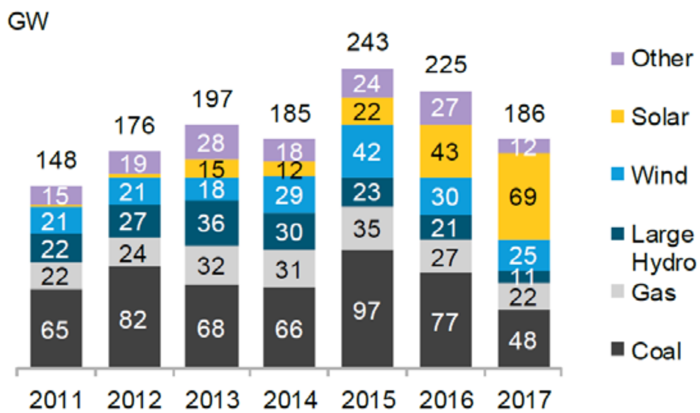

Figure B- 3. Total annual capacity additions by technology in emerging markets. (Includes data from 100 non-OECD countries plus Chile, Mexico, and Turkey. Other includes biomass and waste, geothermal, nuclear, small hydro, oil, and other fossil fuels.)

Source: BNEF 2018

According to BNEF, low- and middle-income countries undergoing rapid electrification are driving down renewable energy costs, making these technologies more competitive with fossil fuel-based generation. One procurement mechanism that drives down project cost are reverse auctions. "Over 35 emerging markets have held reverse auctions for clean power delivery contracts to date, including Mexico ($21/MWh for PV) and India ($41/MWh; wind), procuring 140 GW vs. 41 GW in OECD countries." The effect is an estimated LCOE for wind and solar below $50 for many emerging markets (BNEF 2018, p. 1).

A shadow side of VRE can appear in the form of curtailment in locations where the policy environment may not be as favorable to renewable generation. Due to renewables' potential to deliver, "large volumes of intermittent clean generation into existing power markets… at effectively zero marginal cost," when, "they flood the grid in liberalized power markets, they can potentially decimate wholesale power prices for all generators" (BNEF 2018, p. 5). This can lead to destabilized power markets and result in high levels of curtailment of wind and solar in favor of coal generation in the absence of mechanisms to prevent this outcome.

Global disparities in the cost of capital also have a bearing on overall project cost, and PST in turn. "Despite decreasing technology costs and strong demand for renewable energy in emerging markets around the world, the cost to finance clean energy projects in low- and middle-income countries is often higher than in wealthier countries [see Figure B- 4]. The weighted cost of capital (WACC) to finance a typical wind or solar project in emerging economies in 2017-18, for example, was 5-11%, compared with 2.5-6.5% in OECD countries" (BNEF 2018, p. 14). Yet cost of financing is only one factor and overall LCOE can still be low despite high financing costs, as in the case of India which has levelized costs for solar and wind around $40/MWh due to a very competitive environment (BNEF 2018).

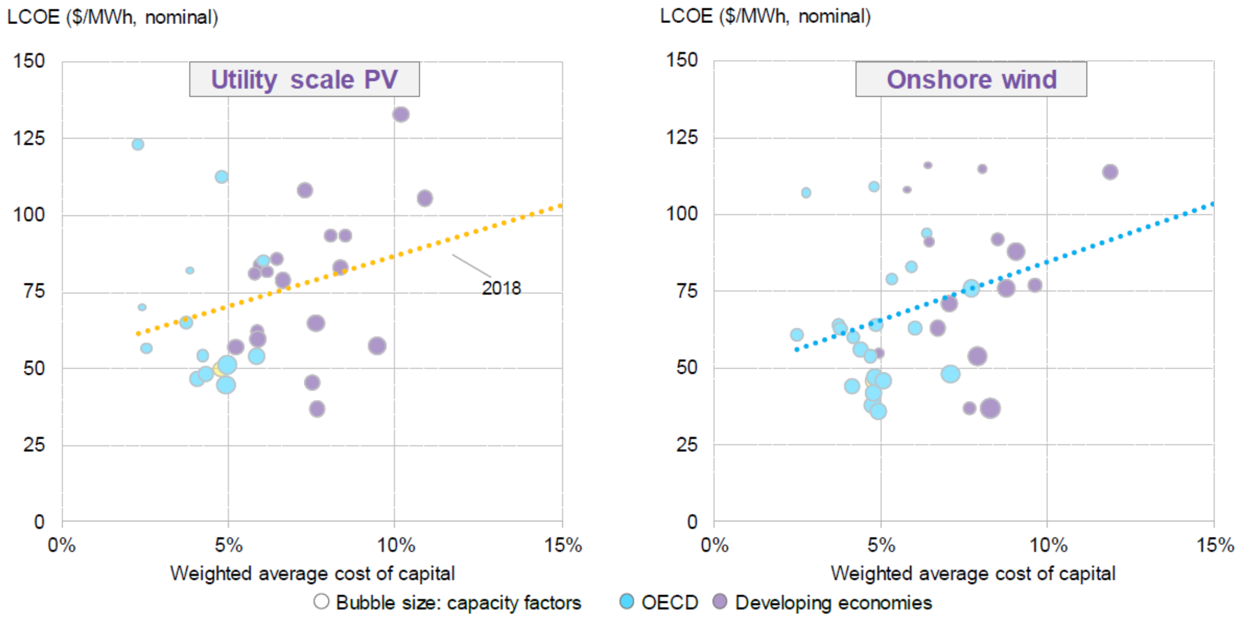

Figure B- 4. Impact of financing costs on country LCOE benchmarks for utility-scale PV (left) and onshore wind (right). The weighted average cost of capital (WACC) is a measure of how much it costs to finance a project.

Source: BNEF 2018

These various cost factors, paired with and often directly related and tied to technological advancements, are driving power sector transformation on a global scale.