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Integrating Renewable Generation into Grid Operations

Four International Experiences

April 2016

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U.S. DEPARTMENT OF ENERGY

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Richland, Washington 99352

Abstract

International experiences with power sector restructuring and the resultant impacts on bulk power grid operations and planning may provide insight into policy questions for the evolving United States power grid as the electric power systems around the world are responding to a multitude of factors including changing resource mixes and fuel prices, an aging generation fleet with potentially large retirements of baseload generation and numerous policies designed to meet climate goals. Australia, Germany, Japan and the UK were selected to represent a range in the attributes of electricity industry liberalization in order to draw comparisons across a variety of regions in the United States such as California, ERCOT, the Southwest Power Pool and the Southeast Reliability Region.

The study draws conclusions through a literature review of the four case study countries with regards to the changing resource mix and the electricity industry sector structure and their impact on grid operations and planning. This paper derives lessons learned and synthesizes implications for the United States based on the challenges faced by the four selected countries. Each country was examined to determine the challenges to their bulk power sector based on their changing resource mix, market structure, policies driving the changing resource mix, and policies driving restructuring. Each country's approach to solving those challenges was examined, as well as how each country's market structure either exacerbated or mitigated the approaches to solving the challenges to their bulk power grid operations and planning.

All countries' policies encourage renewable energy generation. To date, relatively high levels of variable renewable generation have been incorporated with few challenges. However, one significant finding included the Low/zero fuel cost of variable renewables and its potential negative impact on long-term resource adequacy. No dominant solution has emerged although a capacity market was introduced in the UK and is being contemplated in Japan. Germany has proposed the Energy Market 2.0 to encourage flexible generation investment. In Australia interconnections to other regions provide added opportunities for balancing that would not be available otherwise, and at this point, has allowed for integration of renewables.

Executive Summary

International experiences with power sector restructuring and the resultant impacts on bulk power grid operations and planning may provide insight into policy questions for the evolving United States power grid as resource mixes are changing in response to fuel prices, an aging generation fleet and to meet climate goals. This paper derives conclusions through a literature review of four countries drawing on the following two questions:

1. What are grid operations and planning practices for maintaining reliability and cost-effectiveness of a bulk power system, and how have they evolved in countries facing a rapidly changing resource mix?
2. How does industry structure facilitate or preclude the grid operations and planning practices discussed in the first question?

Four countries with restructured or restructuring electricity sectors and with rapidly changing resource mixes were examined to understand the challenges they faced in their bulk power grid planning and operations. Australia, Germany, Japan and the United Kingdom (UK) were chosen to create a set of countries and case studies with different market approaches and policies that cover a wide range of operational practices, system configurations and systems sizes. They provide a range of approaches to restructuring, the role of market competition and the role of regulatory oversight as well as meeting the challenges of a rapidly changing resource mix. From those challenges and the responses to those challenges, lessons learned were examined. Lastly, implications for the United States were drawn.

Background

All countries examined here have initiated a restructuring (liberalization) process with a goal to create more competition among generators and retail suppliers, which was hypothesized to impose downward pressure on electricity prices. Restructuring also makes the price discovery process more transparent leading to market-based signals for investment. The UK began restructuring in 1989 while Australia and Germany began in 1998. Japan has legislation in place to complete restructuring by 2020. Along with Australia, Japan has initiated a market structure similar to the Electric Reliability Council of Texas' (ERCOT) system[a]. Australia's restructuring is further along than Japan's with market levels in most states typically under private ownership. The German electricity market resembles a mix of California and ERCOT markets (an energy only market with vertically integrated utilities). The UK's current restructuring with energy and capacity markets is similar to markets in the Northeast United States such ISO New England.

Almost concurrently the four study countries decided to implement policies to increase the role of renewable power generation, mainly wind and solar photovoltaic (PV) and reduce the amount of carbon emissions from their power grids. The carbon reduction policy and restructuring thrusts were not originally linked, but they are inherently linked because they influence each other through reliability, power quality, flexibility requirements, and their impact on the wholesale electricity markets.

Table ES.1 provides side-by-side summaries of key characteristics associated with the electricity system size, renewables penetration, renewables incentives, and wholesale market structure for each of the study countries.

[a] ERCOT has an energy only market

Table ES.1. Key Characteristics of Electricity Generation in the Study Countries

Item	Metric	Measure	Australia	Germany	Japan	United Kingdom
Size of Power System		Capacity in GW (Year)	48[1] (2015)	192[2] (2014)	293[3] (2013)	77[4] (2014)
Generation Contribution from Variable Renewables	% of total energy generation	2000	0.05[5]	2[6]	2[7]	2[8]
		Most recent year (Year)	8[9] (2015)	16[10] (2014)	4[11](2013)	13[12] (2013)
Renewable Energy Incentives			FIT, RPS, carbon pricing	FIT, premiums, auctions, EU trading scheme[13]	FIT[14]	FIT, Contract for Difference, Renewable Obligations, Carbon market [15]
Market Structure	Wholesale Energy Market		Yes,	Yes,	Yes	Yes
	System Operator		System Operator	Four Transmission System Operators (TSOs)	Independent System Operator (ISO)	One TSO run balancing market
	Balancing Market		Yes	Yes	Yes	Yes
System Adequacy			Ancillary service markets	Long-term contracts	ISO can order energy companies to produce more	Capacity market

The table characterizes the relative size of the four case study countries, renewable energy penetration and incentives as well as the wholesale energy market structure.

Grid Systems Managed Penetration of Renewables

Australia, Germany and the UK with relatively high levels of variable renewable generation have been able to incorporate it with few challenges. Japan, with renewables at four % of generation may be able to incorporate variable renewable energy when its reforms are complete in 2020.

Long-Term Generation Resource Adequacy

Increasing variable renewable energy resources with Low/zero fuel costs are potentially leading to challenges in providing incentives for investment in long-term flexible resources. Variable renewable energy technologies incentivized by Feed-in Tariffs (FITs), Renewable Obligations (Contracts for Difference in the future) or Renewable Energy Credits are influencing wholesale energy markets with significant downward pressures on prices because of low/zero fuel costs. Some market experts believe Low/zero fuel cost renewable energy resources are incompatible with energy-only markets because they do not generate adequate signals for flexible generation investment. The low fuel cost issue, known as the "missing money," exacerbates the problem, and led the UK to institute a capacity market to ensure adequate flexible resources in the long term. The administratively operated mechanism requires constant adjustment to incentivize an adequate investment in generation capacity and may, in fact, convert generation investment from a market-driven solution to an administratively driven solution. Alternatively, if market barriers exist, an administratively driven market may provide a better solution. Japan, a proposed energy-only market like ERCOT, appears to be contemplating a capacity mechanism.

Low/ zero fuel costs of renewable energy hinder long-term resource adequacy as inadequate price signals fail to signal the need for flexible resources. Capacity markets and forward markets are two potential solutions.

Germany investigated the capacity market option as well, but rejected it in favor of a series of other policies, measures, and market designs to ensure long-term capacity adequacy (termed the Electricity Market 2.0). Both Germany and the UK have significant generation over-capacity due to slackening demand driven by the slowdowns in their economies, improvements in efficiency and the increasing availability of renewable generation due to attractive incentives.

The grid operator in Australia proposed several approaches to maintaining synchronous[b] generation. Lower energy and ancillary service market prices in Australia are reducing the competitiveness of thermal units, thereby driving out synchronous capacity. Currently, Australia depends on interregional connections to source capacity that has facilitated otherwise significant levels of renewable energy.

Short-Term Operational Requirements

Increasing variable renewable energy resources drive the need for flexible resources to meet system's balancing and ancillary service's needs. Larger ramps in generation caused by wind and solar installations require additional ancillary services to meet the new ramping requirements and maintain frequency. In addition, variable technologies also drive inertia requirement challenges as renewable resources increasingly replace synchronous resources. Australia is looking at additional investment in equipment to provide ancillary services to meet the higher requirements. Australia is also pursuing incentives for re-engineering existing generation units to operate as synchronous condensers. In Germany, wind in the north and solar in the south is driving down energy prices resulting in retirement of thermal capacity. Due to excess capacity in Germany and the UK and interconnections to other countries/states in Australia, Germany and the UK, the network is working. However in Japan, the division of the bulk power system into two frequencies (50 Hz and 60 Hz), reduces the ability to draw resources from the other system. With increasing amounts of renewables, all countries need to find ways to value and compensate the flexibility that flexible resources, storage, demand response and other resources provide.

Increasing variable renewable energy resources drive the need for flexible resources to meet system's balancing and ancillary service's needs. Markets need to find ways to value and compensate for the flexibility that storage and reserve capacity can provide.

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[b] Synchronous generation refers to where the peak of each electrical wave matches the position of the rotor. Synchronous generation can be more easily regulated than asynchronous generation.

Nodal pricing is a potential mitigation strategy to resolve transmission congestion with increasing renewables. Nodal pricing is location-specific and reveals price signals to stimulate market-based solutions through building additional transmission in congested areas or reducing investment in generation in areas with over-capacity. Nodal pricing in wholesale energy markets is not implemented in any of the four countries, although it has been discussed in most of them. However, neither the European Union (EU) nor the UK have implemented it. The UK believes that nodal pricing would decrease prices in Scotland and raise prices in England.[16] Germany views nodal pricing negatively, in that it may encourage market power as generators see the locational-specific pricing information, and is also concerned about the distributional impacts on consumers.[17]

Building additional transmission capacity is another strategy to increase renewables integration. Increasing transmission capacity may reduce renewable energy curtailment.

Building additional transmission capacity is another potential mitigation strategy to grid congestion caused by renewables integration. Currently Australia believes it is on track with transmission construction to accommodate more renewables in their grid.[18] The UK has commissioned construction of more transmission capacity from Scotland. Efforts are currently underway to alleviate Germany's north-south transmission bottleneck. In addition, interconnections to adjacent countries are being planned as a long-term solution. In the meantime, Germany and the UK curtail wind when transmission capacity is exceeded. The Australian operator has also proposed curtailments. Germany's curtailments reached 1.16% of renewables generation in 2014 while the UK's reached 1.6%. In Japan, vertically integrated utilities have refused solar facilities interconnection to the grid because of transmission and distribution issues associated with solar.

Lessons Learned and Implications for the United States

The challenges of a changing resource mix found in the four countries' bulk power systems were similar to challenges identified in the United States' context. Those challenges include maintaining resource adequacy, reliability and power quality in the face of increasing amounts of variable renewable energy generation. The case study countries, with the exception of Japan, currently have similarities to a number of regions including California ISO, ERCOT, MISO, and the ISO New England. Japan currently resembles the Southeast Region Reliability Council (SERC) or the Florida Reliability Coordinating Council (FRCC). The challenges in the four countries are either already being faced in the United States or are providing a preview of what will be seen soon in some U.S. regions. Regulators and grid operators in Australia, Japan, the UK, and Germany have already identified and implemented solutions to many challenges presented by restructuring and a changing resource mix, but some issues remain. It is too soon to know the implications of Japan's restructuring as it has just begun and will not be fully implemented until 2020. However, Japan's future electricity market may look like a mixture of the ERCOT market and Pennsylvania Jersey Maryland (PJM) market. Solutions to the low/zero fuel costs of variable renewable energy and the associated lowering of wholesale market prices below the cost of production for generation has driven different solutions in the energy-only markets of Australia, Germany and the UK. The UK added a capacity market to the energy market similar to ISO New England and PJM while Australia and Germany chose not to add a capacity market. Japan hasn't yet reach the level of renewable energy penetration to be faced with low/zero fuel cost issue but may be contemplating a capacity market.

The Australian market operator, like U.S. system operators, has called for increased autonomy over long-term generation and system control planning to accommodate the decreasing prices and potential failure to meet resource adequacy requirements. Australia is currently determining what mechanism they want to use to ensure adequate capacity and at the same time relying on the continued ability of states to source such services through regional interconnections. Stability in U.S. electricity networks, with similarly large balancing areas and wholesale markets in regions such as ERCOT and MISO, could hinge on similar factors such as the development of a mechanism to ensure adequate capacity and system control services, and the continued ability of states to source such services through regional interconnectors.

Germany’s solution to the low/zero fuel cost of variable resource problem is to develop market reform initiatives for short-term operations as well as a long-term planning focus. These market reform efforts provide potential solutions for areas of the United States with rapid expansion of renewable energy. Germany’s plan is to develop a more flexible power system that will ensure reliability in the presence of a very high share of renewable energy. The German balancing group model demonstrates one approach that can be implemented to aggregate decentralized generation and demand and incentivize local coordination of resource scheduling and balancing. Germany will face many of the same problems as California with its high renewables targets (55-60% vs 50% respectively) and ERCOT with its energy-only market. However, Germany does not cap the energy price like ERCOT does.

Japan's market liberalization has just started and is an ongoing process. The lessons learned from the introduction of solar may provide insights to the United States as it encounters challenges associated with rising retail costs, maintaining frequency and meeting steep demand ramps associated with a large influx of solar. On the other hand, ERCOT may provide lessons learned to Japan as the new Japanese restructured market was based on the ERCOT model, may have components like PJM if it incorporates the contemplated capacity market.

A lesson learned across all countries studied with regards to electricity restructuring and maintaining reliability and cost-effectiveness is that the changing resource mix will require constant regulatory attention to assure that market structures such as ancillary services, balancing markets and energy markets maintain their competitive frameworks. The implication for the United States is that restructured markets need to be constantly monitored as resource mixes change to assure that the market rules are providing the appropriate signals to bring forth both long-term and short-term electricity supplies and demand response. However, the approach to regulatory reform must provide for certainty in the markets. If regulatory reform does not provide certainty for stakeholders, financial markets may become leery of investment and future capacity will not be forthcoming due to the cost of funds.

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Acronyms and Abbreviations

AEMO – Australian Energy Market Operator
ANL – Argonne National Laboratory
BETTA – British Electricity Trading and Transmission Arrangements
CCS – Carbon Capture and Storage
CfD – Contract for Difference
DECC – Department of Energy and Climate Change
DETI – Department of Enterprise, Trade and Investment
DNO – Distribution Network Operators
EC – European Commission
EEX – European Energy Exchange
ENTSO-E – European Network of Transmission System Operators for Electricity
EPCO – Energy Power Company in Japan
ERCOT – Energy Reliability Council of Texas
EU – European Union
FIT – Feed-in Tariff
GW – Gigawatt
GWh – Gigawatt hour
ISO – Independent System Operator
kW – Kilowatt
kWh – Kilowatt hour
METI – Ministry of Economy, Trade and Industry
MISO – Midcontinent Independent System Operator
NEM – National Electricity Market
NETA – New Electricity Trading Arrangements
NREL – National Renewable Energy Laboratory
OCCTO – Organization for Cross-regional Coordination of Transmission Operators
Ofgem – Office of Gas and Electricity Markets
OTC – Over the counter trading
PJM – Pennsylvania Jersey Maryland independent system operator
PNNL – Pacific Northwest National Laboratory
PV - Photovoltaic
RE – Renewable energy
REC – Regional Energy Companies
RET – Renewable energy target
TSO – Transmission system operator
TWh – Terawatt hour
UK – United Kingdom

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1.0 Introduction

1.1 Purpose of Study

International experiences with power sector restructuring and the resultant impacts on bulk power grid operations and planning may provide insights into policy questions for the evolving United States power grid as resource mixes are changing in response to fuel prices, an aging generation fleet and to meet climate goals. Many countries in the European Union (EU) – including the United Kingdom (UK), Germany, France, Italy, and Spain – as well as other countries like Argentina, Brazil, Chile, Australia and Japan have undertaken electric power industry restructuring in different forms with varying experiences. These countries have significantly different resource mixes, geography, influxes of renewables, industry structures, regulation and legislative policy goals that have driven the changes over time. Australia, Germany, Japan and the UK were selected to represent a range in degree, form and attributes of electricity industry liberalization in order to draw comparisons across a variety of regions in the United States such as California, ERCOT, the Southwest Power Pool and the Southeastern Electric Reliability Council.

The study draws conclusions through a literature review of the four case study countries based on answers to the two following questions:

1. What are grid operations and planning practices for maintaining reliability and cost-effectiveness of a bulk power system, and how have they evolved in countries facing a rapidly changing resource mix?
2. How does industry structure facilitate or preclude the grid operations and planning practices discussed in the first question?

This paper derives lessons learned and synthesizes implications for the United States based on answers to the above questions and the challenges faced by the four selected countries. Each country was examined to determine the challenges to their bulk power sector based on their changing resource mix, market structure, and policies driving the changing resource mix and restructuring. Each country's approach to solving those changes was examined as well as how each country's market structure either exacerbated or mitigated the approaches to solving the challenges to their bulk power grid operations and planning.

1.2 Approach

Ten countries were initially considered because of their restructuring, resource mix and potential similarities to the United States' electricity regions. The ten countries initially considered included Argentina, Australia, Brazil, Chile, France, Germany, Italy, Japan, Spain and the UK. An initial analysis of the ten countries examined whether the country had a resource adequacy mechanism, the maturity of the wholesale market, and the degree of retail choice. Materials were prepared that answered the above questions and collaborators including Argonne National Laboratory, the National Renewable Energy Laboratory, the Pacific Northwest National Laboratory and the U.S. Department of Energy selected the countries that provided the most diverse set of attributes matching regions of the United States.

All countries were evaluated based on the degree to which the electricity market was completely restructured. Restructuring looked at the degree of divestment for:

- generation,
- transmission,
- distribution, and

- retail.

Additionally, characteristics of distribution ownership and management was examined, including whether there were provisions to exclude distributors from owning generation assets, as well as supplying the retail market. Transmission coordination was examined to determine how supply and demand were balanced. Lastly, the resource mix was examined to assure a diverse set of renewable or low-carbon penetration.

The ten countries were down-selected to four for this study. Australia, Germany, Japan and the UK were selected to create a set of countries and case studies with different market approaches and policies that cover a wide range of operational practices, system configurations and systems sizes. They also provide different approaches to restructuring, the role of market competition and the role of regulatory oversight.

The four case studies evaluated the drivers and impacts of policy and regulation on the electricity industry structure from the start of restructuring to the present. Each case study was performed in three parts: the regulatory and policy background for each country, the challenges, responses and proposed solutions, and lastly the lessons learned. The key findings from each country were summarized and placed at the beginning of each case study.

The regulatory and policy background section evaluated each country's electricity sector structure and policies prior to restructuring. Each country was described in terms of: the evolution of the resource mix; key policies affecting restructuring and generation mix, and key drivers of restructuring. Lastly, the current electricity market structure was assessed.

The challenges, responses and proposed solutions section described the challenges that arose as a result of the confluence of the changing resource mix and restructuring on the bulk power system. In addition, the different market mechanisms and technology requirements that were implemented to maintain reliability, affordability, and sustainability to meet the challenges faced by restructuring and the changing resource mix for each country were studied. The last part of the challenges and solutions section examined how each country's industry structure exacerbated or mitigated the impacts to the bulk power system. As such, the intended outcomes and unintended consequences of these changes were evaluated.

The last section of the paper, lessons learned, drew implications for the United States based on the impact of the changing resource mix on grid operations and planning and the implications of industry structure on handling the changing resource mix. The analysis in this section highlighted experiences with specific relevance to U.S. regions, as well as to the United States in general. This section compares and contrasts the lessons learned across the four case studies based on each of the sub-sections of the lessons learned: lessons learned with respect to the changing resource mix, industry structure, and insights and implications for U.S. policy.

1.3 Summary of the Selected Study Countries

The four countries provide a range of capacities, penetration of renewables and alternative incentives for renewable resource generation. The key features for each of the countries are listed below.

- Australia:
  - Restructured market initiated in 1998,
  - Restructuring varies by state but all have states have moved toward private ownership, and in geographic span, the NEM is one of the longest alternating current systems in the world, covering some 4500 kilometers,

  - Contains a single market operator for the country,
  - Generation, transmission and distribution and retail were unbundled,
  - However, vertical re-integration is under way,
  - Has rapidly growing wind and solar generation, increasing 50% and 26% between 2004 and 2013 respectively, and
  - One state (South Australia) contains a very high contribution of wind (43%) and solar (16%) of capacity although for the country overall penetration has only reached 8% of generation.
- Germany:
  - Market liberalization since 1998 with wholesale energy markets and competitive retail offerings,
  - Contains four transmission system operators (TSOs),
  - Forty percent of capacity from renewables driven primarily by Feed-in Tariffs (FITs) with penetration of wind in the north and distributed solar in the south,
  - FIT adjusted to moderate rapid growth of renewables,
  - Nuclear industry scheduled to be phased out by 2022, and
  - System adequacy assurance is predicated on relying on an energy-only market along with long-term contracts and transmission upgrades.
- Japan:
  - Restructuring to be complete in 2020,
  - Currently has highly regulated and vertically integrated electricity sector,
  - Restructuring when complete will look like a mix of ERCOT and PJM markets,
  - Nuclear generation was halted after the Fukushima incident, but some units have recently been approved for restart,
  - Only two nuclear reactors are currently operating. Nuclear power is still near zero,
  - Lowest overall penetration of variable renewable energy at 4 % among the case studies, and
  - Has a grid with two operating frequencies which complicates interconnection.
- The United Kingdom:
  - Oldest completely restructured market (among the case studies) initiated in 1989,
  - Openly traded wholesale and retail markets,
  - Only case study country to contain a capacity market which was initiated in 2014,
  - Previously was an energy-only market,
  - Vertically integrated generators and retailers,
  - Distribution has been unbundled but retailers may own both generation and distribution, and
  - Transmission capacity limits wind energy transport between Scotland and England.

Table 1.1 summarizes the key characteristics of the four case study countries.

Table 1.1. Key Characteristics of Electricity Generation in the Study Countries

Item	Metric	Measure	Australia	Germany	Japan	United Kingdom
Size of Power System		Capacity in GW (Year)	48[19] (2015)	192[20] (2014)	293[21] (2013)	77[22] (2014)
Generation Contribution from Variable Renewables	% of total energy generation	2000	0.05[23]	2[24]	2[25]	2[26]
		Most recent year (Year)	8[27] (2015)	16[28] (2014)	4[29](2013)	13[30] (2013)
Renewable Energy Incentives			FIT, RPS, carbon pricing	FIT, premiums, auctions, EU trading scheme[31]	FIT[32]	FIT, Contract for Difference, Renewable Obligations, Carbon markets [33]
Market Structure	Wholesale Energy Market		Yes	Yes	Yes	Yes
	System Operator		System Operator	Four Transmission System Operators (TSOs)	Independent System Operator (ISO)	One TSO run balancing market
	Balancing Market		Yes	Yes	Yes	Yes
	System Adequacy		Ancillary service markets	Long-term contracts	ISO to order energy companies to produce more	Long-term contracts, capacity market

The table characterizes the relative sized of the four case study countries, renewable energy penetration and incentives as well as the wholesale energy market structure.

1.4 Background of Restructuring and Climate Change Policy

1.4.1 Definition of Restructuring

Electricity sector restructuring has evolved in many forms in response to the varying circumstances across countries. In theoretical terms, complete restructuring of the electricity market requires privatization and unbundling of all sectors including generation, transmission, and retail. Because the transmission and distribution sectors are natural monopolies, they are usually privately owned but regulated. With the unique non-storable nature of electricity, markets are developed to provide for maintaining demand and supply balance through a number of market mechanisms including bilateral contracts, day-ahead markets, balancing markets and ancillary services markets. Joskow[34] indicates 12 key components to classic restructuring:

- privatization of state-owned monopolies,

- vertical separation of competitive components and regulation of natural monopolies,
  - usually requires information exchange barriers between the distribution entity and the rest of the company, if owned by same corporation, to reduce cross-subsidization,
- restructuring of generation to require multiple generators and reduce market power,
- transmission facilities organized along natural market regions with an independent system operator,
- creation of voluntary real-time energy and reserve markets,
- active retail entities that allow consumers to choose based upon prices. Markets also allow demand response to actively participate,
- regulatory rules to allow open access to transmission, and allocation mechanisms for scarce transmission resources,
- separates retail prices from transmission and distribution charges,
- where retail competition is not adequate, provision of retail prices based on wholesale market-based regulatory benchmarks,
- creation of independent regulatory bodies to enforce regulatory requirements for maintaining competitive prices and network reliability, and
- transition mechanisms to move from the old sector structure to the new liberalized sector.

There are many different approaches to reform in different countries as different countries and regions have chosen varying paths based on local circumstances. [35]

1.4.2 Drivers for Restructuring and Resource Change

Prior to restructuring most electricity sectors were vertically integrated monopolies that were either state-owned or privately owned but regulated. In some regions, the electricity sector prior to restructuring was characterized by cost over-runs, high operating costs and high retail prices. Restructuring was introduced with the aim to increase efficiency and lower consumer prices through competitive frameworks for generation and retail supply. Transmission and distribution were privatized, but regulated with incentives to drive efficiency. [36] With the increased competition comes superior customer service and improved technological progress.

Political concern for increasing greenhouse gases and the resultant increasing global temperatures have led to different incentives and policies to decarbonize industry, including the electricity sector, since the early 1990s.[37] A number of different policies including regulations and incentives have accelerated the growth of low-carbon technologies like renewable resources such as wind and solar.[38] Incentives include renewable portfolio standards with renewable energy credit markets, tax incentives such as investment tax credits and production tax credits, FITs, carbon taxes and cap and trade to name a few.[39] The goal of these policy tools was to spur low-carbon technology penetration. The policies tended to incentivize variable resources such as wind and solar.

The confluence of restructuring and climate policy have created challenges for an industry where supply has to meet demand on a minute by minute basis. The remainder of the paper examines experiences related to grid operations and planning in Australia, Germany, Japan, and the UK, followed by lessons learned and their implications for the United States.

2.0 Australia Electric Power Case Study

2.1 Key Findings

Australia's electricity industry restructuring process began in earnest in the early 1990s, leading to the creation of the National Electricity Market (NEM) in 1998. The NEM is one of the largest interconnects[c] in the world, with over 300 registered generators serving around 90% of Australian electricity demand.[40] All five states in the NEM have functionally separated generation, transmission, and distribution, with significant privatization of generation and distribution. Several federal authorities and a single market operator oversee the NEM. Table 2.1 provides summary statistics for Australia's electricity sector and key renewable energy policies. Table 2.2 provides a summary of market structure characteristics for generation, transmission, system operation, distribution and retail.

Electricity industry restructuring and environmental policies such as a national renewable energy target have contributed to a significant expansion of renewable energy generation in the NEM. Wind and solar output grew by about 26% and 50% annually from 2004 to 2013, respectively.[41] Together wind and solar capacity accounted for more than 20% of NEM peak demand by 2014.[42] Over 1.5 million households, about 15% of households in the NEM, have installed solar PV.[43] Projections call for strong continued growth in renewable energy penetration driven by market dynamics and supportive policies.

High levels of renewable energy penetration pose several challenges in the NEM. Wholesale power market prices have declined as a result of low bidding by wind generators, and high penetrations of distributed PV have reduced net demand. Low prices and demand have in turn reduced incentives for the continued operation of fossil-fuel generators with higher fuel costs. As a result, capacity withdrawals have exceeded capacity additions in recent years and may eventually lead to system reliability issues. System reliability issues could be exacerbated by the fact that new capacity additions are largely non-synchronous and non-dispatchable generators such as wind and solar. The substitution of synchronous generation with non-synchronous generation will reduce the NEM market operator's ability to control frequency, voltage, system inertia, and other system functions.

NEM stakeholders have implemented several measures and proposed several responses to the challenges posed by high levels of renewable energy penetration. The NEM can inherently support higher levels of renewable energy penetration due to the large balancing area and interregional interconnectors. The market structure has also enabled necessary transmission investments to accommodate the changing resource mix. The NEM market operator has proposed several solutions to system control issues, increased control over the generator dispatch process, measures to ensure minimum levels of synchronous generation, and expanded ancillary service markets.

The bulk power system challenges in the NEM have parallels with fully interconnected U.S. regions such as ERCOT, MISO, and PJM and the ability of these large markets to integrate renewables. However distributed solar penetration in Australia far exceeds U.S. penetration levels. With rooftop PV on about 15% of households, only Hawaii (12.5%) has experienced similar levels of distributed solar. The NEM has already begun to implement tariff structures that could make load more coincident with distributed generation output. The Australian response to rapid wind and distributed solar penetration may therefore be informative of future U.S. renewable energy contexts.

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[c] Other major interconnects in Australia include the Northwest Interconnected System and the South West interconnected system of Western Australia.

Table 2.1. Key Characteristics of Electricity Generation in the Australian NEM

Size of Power System	Capacity (GW)	2015	47.6[44]
	Load (GW)	2015	30.2[45]
	Generation (TWh)	2015	194[46]
Generation Contribution from Variable Renewables	% of total generation	2000	0.05%[47]
		2010	2.2%[48]
		2015	7.6%[49]
Mechanism for Renewable Promotion		FIT	State-run programs
		Renewable Energy Credits	National RPS
		Contract for Difference	
		Other	Carbon pricing mechanism (2012-2014)
Proposed or Enacted Policies to Address the Following Issue:	Technical issues	Interconnection permitting	National interconnection guidelines,[50] limited permitting requirements[51]
		Over-generation	Market operator has proposed curtailment[52]
	Markets	Incentives	Market operator has proposed incentives for wind generators to provide frequency control services[53]
		Misalignment	Frequency controlled ancillary service markets
	Goals/targets	RE goals or binding targets	33,000 GWh/year by 2020
		Key drivers for RE penetration	Renewable energy target, carbon pricing, FITs

Table 2.2. Summary of Electricity Market Structure for Australia

	Ownership	About 71% privately owned (by capacity)[54]
Generation	Resource adequacy mechanism	The Australian Energy Market Operator may enter into reserve contracts with generators in response to short-term risks to system reliability[55]
System Operation	Balancing Market Operator	System operator Australian Energy Market Operator
	Energy Market	Gross pool wholesale market, 5 minute dispatch intervals
Transmission	Ownership	Private owner/operators in three of five major states[56]
	Operator	
Distribution	Ownership	13 major electricity distribution networks, small regional networks with separate ownership, mix of public and private ownership
Retail	Retailers	Third-party retail competition
	Demand Response	Administered by distribution network service providers, "Power of Choice" reforms for demand response measures
	Retail Choice	Full retail contestability

2.2 Regulatory and Policy Background

2.2.1 Overview of Industry Structure Prior to Restructuring

Vertically integrated state-owned corporations comprised the majority of the Australian electricity industry for most of the 20th century. As of 1991, public utilities met about 93% of Australian electricity demand.[57] Centralized state authorities controlled generation and transmission in all six states as well as distribution in five states. The state authorities developed distinct networks with virtually no interstate electricity trading.

State authorities exercised a high level of regulatory control over the electricity industry. Each state government developed separate charters for electricity providers that required the provision of a safe and reliable supply of electricity. State authorities controlled tariff structures, generally requiring uniform tariffs within customer classes. Electricity businesses acted as natural monopolies protected by state-implemented trading rights that restricted the private generation of electricity.

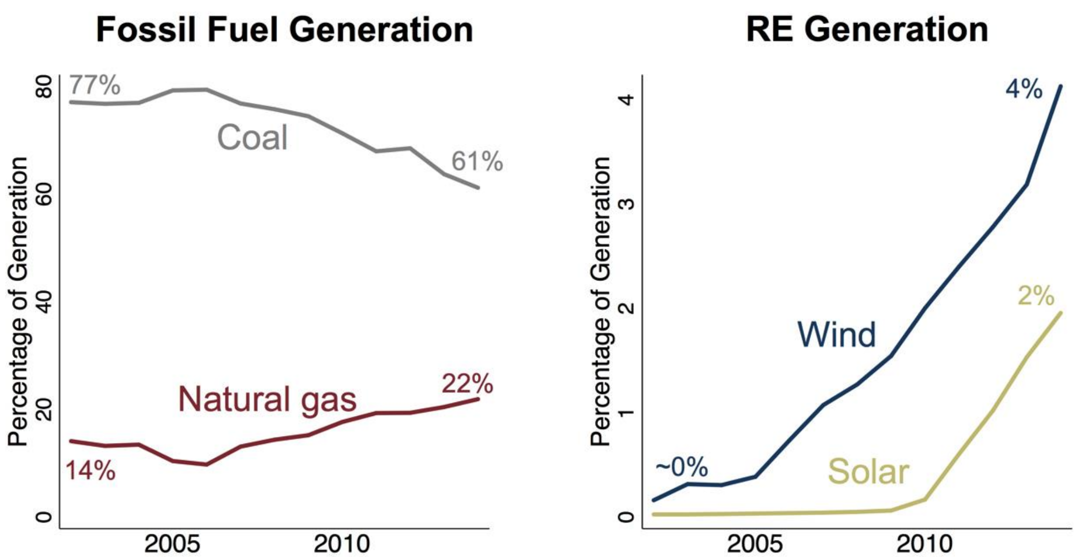
In 1991, the Industry Commission (IC) published findings of inefficiencies in the state-owned Australian electricity industry. The IC found that poor investment decisions had resulted in excess capacity, with reserve capacity reaching 40-70% for some Australian utilities in the 1980s. The IC found that excess capacity and overstaffing inflated Australian electricity prices. The report concluded that the centralized electricity structure imposed $2.2 billion (1991 Australian dollars) in annual costs on the Australian economy.[58]

2.2.2 Evolution of Resource Mix

Industry restructuring and environmental policies have driven a significant increase in generation from renewable energy (RE), particularly wind and solar, and a reduction in generation from coal. A national Renewable Energy Target (RET), which calls for 33,000 GWh/year of large-scale renewable energy generation by 2020, roughly 23.5% of projected generation in 2020, has been instrumental in the rapid increase in RE penetration. Wind projects have been the primary beneficiary of the RET, accounting for about 70% of registered RET generation from 2001 to 2015, while solar accounted for about 4.6% of registered RET generation.[59]

From 2004 to 2013, output from wind and solar generation grew annually by about 50% and 26%,[d] respectively.[60] By 2015, wind and solar capacity in the NEM reached 6.6% and 8% of total NEM capacity, respectively, and 4.9% and 2.7% of total NEM generation, respectively.[61] About 1.5 million or 15% of Australian households have installed rooftop solar PV.[62] In a related trend, coal's share of Australian generation fell from 77% in 2002 to 61% in 2014 (Figure 2.1).

Figure 2.1. Fuel Shares of Generation (2000–2014)[63]

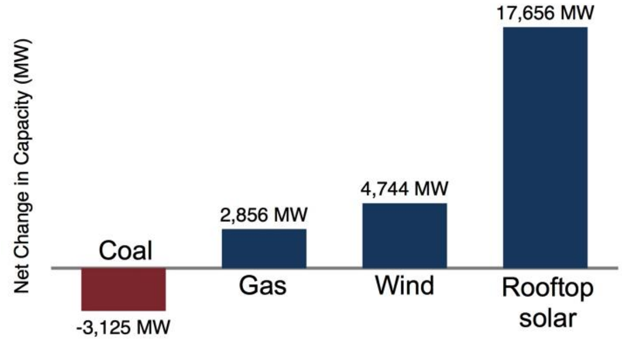


This figure shows the percentage of electricity generation provided by coal, natural gas, wind, and solar from 2000 to 2014. Note that the two axes are not on the same scale.

The Australian Energy Market Operator (AEMO) projects significant expansions of wind and solar capacity over the next 20 years; with some natural gas additions and a net reduction in coal generation capacity (Figure 2.2).

[d] Figures include generation outside of the NEM. The NEM comprises about 90% of electricity demand, these figures should be representative of growth rates within the NEM.

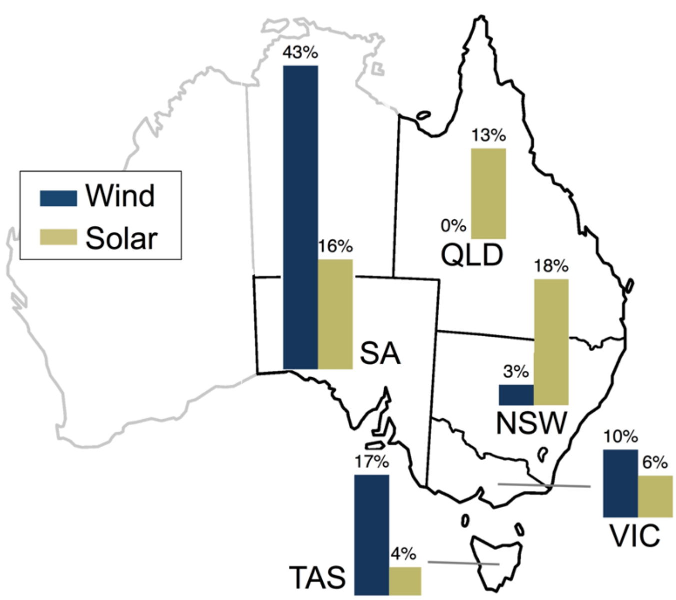
Figure 2.2. Projected Net Change in Generation Capacity 2015–2035[64]



This figure shows the projected net change in generation capacity by fuel source form 2015 to 2035. Projections call for a marked shift toward a larger proportion of decentralized variable generation (wind and solar).

RE penetration varies significantly by state (Figure 2.3). About 50% of the nation's RE capacity is installed in the state of South Australia, labeled "SA" in Figure 2.3, where wind and solar comprise more than 50% of the state's total capacity.

Figure 2.3. Wind and Solar Penetration (capacity) by State[65]



This figure shows wind and solar capacity as a percentage of total capacity in the five states that comprise the National Electricity Market. About 50% of the NEM's renewable capacity is located in South Australia (SA).

2.2.3 Key Restructuring Policies Affecting Power Grid Operations, Planning and Generation Mix

Several Australian states began restructuring electricity markets in the early 1990s, functionally separating generation, transmission, and distribution. The national restructuring process began in earnest with the establishment of the National Grid Management Council (1991), the passage of the National

Electricity Law (1996), and the establishment of the NEM in 1998. This process included the functional separation of generation, transmission, and distribution, with some states privatizing generation and distribution. The NEM amalgamated the generation, distribution, and supply of electricity in eastern and southern Australia. The NEM comprises over 300 generators, 13 distribution networks, and five states: New South Wales, Queensland, South Australia, Tasmania, and Victoria.[66] The end goal of the Australian restructuring process is a fully interconnected NEM with interregional trading regulated at the federal level.[67] Table 2.3 highlights six policies of the restructuring process that affect power grid operations, planning, and the generation mix.

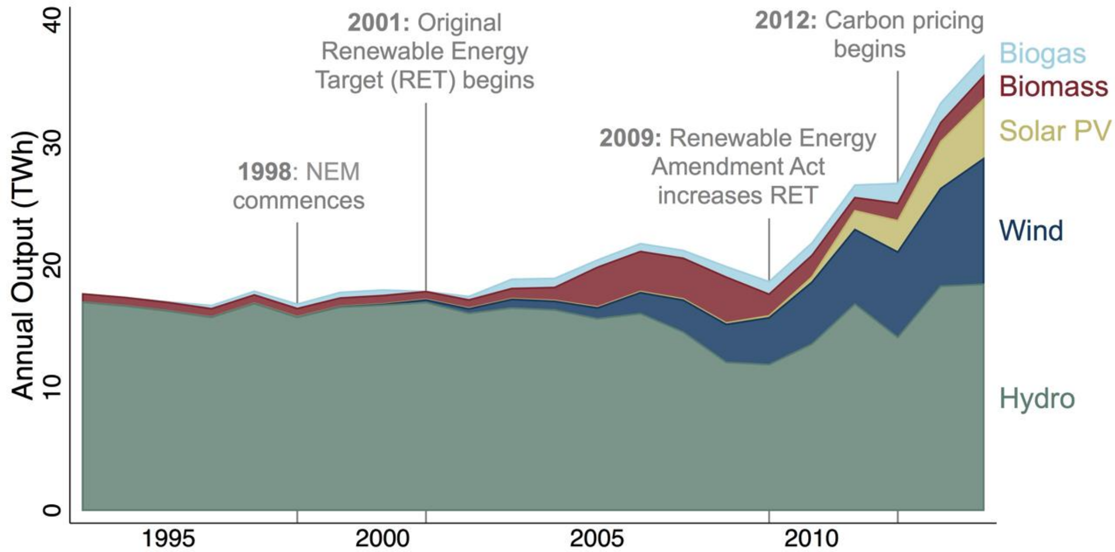
Table 2.3. Market Restructuring Policies

Policy	Description
Federal regulation	The Australian restructuring process replaced the state-level regulation of electricity systems with separate federal authorities for policy making (Standing Council on Energy and Resources), market operation (Australian Energy Market Operator), rule making (Australian Energy Market Commission), and regulation (Australian Energy Regulator).
Competitive generation	The restructuring process has gradually eroded centralized control over generation through reduced barriers to entry for competitive generators.
Generator dispatch	The AEMO is responsible for the dispatch of "scheduled" and "semi-scheduled" generation (see Section 2.2.4). Small-scale distributed generation (e.g., rooftop PV) is defined as non-scheduled generation and falls outside of the AEMO's jurisdiction.
Regional interconnection	The NEM created a fully interconnected system comprising about 90% of the nation's electricity load. The five regions of the NEM, corresponding roughly to the five states, are connected via a system of interregional transmission lines or "interconnectors."
Ancillary service markets	A corollary of decentralized control over-generation in restructuring was the decentralization of ancillary services. The AEMO now operates competitive markets for ancillary services.
NEM reliability standard	The NEM reliability standard mandates that un-served electricity demand in a given region may not exceed 0.002% of total electricity demand in that region in any given year. The reliability standard applies to all five NEM regions.

In addition to market restructuring, several national energy policies contributed to significant changes in the NEM's generation resource mix. First, in 2001 Australia implemented a national RET calling for an increase of 9,500 GWh/year of renewable energy by 2010. In 2009, the Renewable Energy Amendments Act increased the national RET by more than a factor of four to require that 20% of Australia's electricity come from renewables by 2020. Australia also implemented a carbon pricing scheme from 2012 to 2014.

Figure 2.4 illustrates the chronology of these events and their coincidence with significant expansions in non-hydro RE generation.

Figure 2.4. Chronology of Key Policy Events with Renewable Energy Generation Mix (1993–2014)[68]



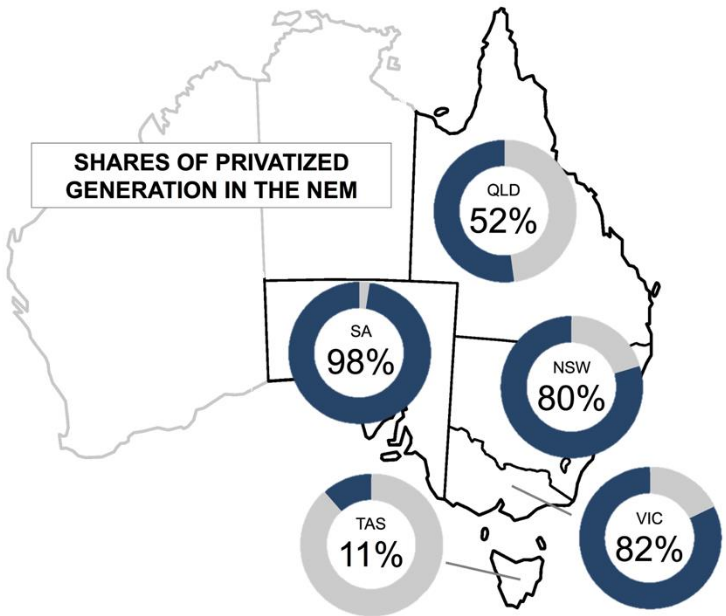
This figure shows four key policy events that shaped Australia's renewable energy generation resource mix from 1993 to 2014.

2.2.4 Electric Power Sector Market Structure

Regional NEM structures vary, however all states have moved toward privatized generation, transmission, and distribution. Although generation and distribution were functionally separated in the early stages of restructuring in the 1990s, generation companies have begun to acquire retailers to form "gentailers," resulting in increasingly concentrated generation and retail markets. Three vertically integrated generation and retail businesses supplied 71% of the retail energy market by 2015. In New South Wales, two vertically integrated generation and retail businesses control 37% of generation capacity and serve 68% of retail customers. Victoria's three major retailers also own 54% of generation capacity. South Australia's largest generator controls 42% of generation capacity and serves 50% of retail customers. Vertical re-integration is less prevalent in Queensland and Tasmania, where the majority of generation capacity is state owned.[69]

Figure 2.5 illustrates the extent of privatization of generation in the NEM. Privatization is especially advanced in New South Wales, South Australia, and Victoria, where transmission has also been fully privatized.

Figure 2.5. Percentage of Privatized Generation by State[70]



This figure shows the percentage of generation capacity owned by private businesses in the five NEM states. Privatization is especially evident in New South Wales (NSW), South Australia (SA), and Victoria (VIC).

The AEMO is the single market operator in the NEM, responsible for generator dispatch. All generators larger than 30 MW, except variable renewable generators, are required to participate in the AEMO-administered generation dispatch process as "scheduled" generators. The AEMO dispatches generation in the NEM through bid stacking in regional gross pool spot markets. The highest bid price needed to meet demand in a five-minute interval determines the dispatch price. The AEMO sets the NEM spot price according to the average dispatch price over a 30-minute interval. Generators can likewise bid ancillary services into eight frequency control ancillary service markets: two regulation markets (regulation raise and regulation lower), and six contingency markets (6-second raise and lower, 60-second raise and lower, and 5-minute raise and lower).[71]. The NEM does not have capacity markets.

Variable (or variable) generation sources could originally participate in the NEM outside of the AEMO dispatch process as "non-scheduled" generators. Non-scheduled generators do not pay for ancillary services and can only be curtailed for network security issues. However rapid wind penetration prompted the NEM to revisit this exemption. In 2009, the AEMO developed a third "semi-scheduled" generator registration category for variable sources larger than 30 MW. Semi-scheduled generators must submit dispatch offers and pay for ancillary services.[e] About 52% of NEM wind farms are currently semi-scheduled generators, the rest remain non-scheduled generators.[72]

[e] The AEMO applies a "Causer pays" principle under which generators pay for ancillary services according to a measure of their response to frequency deviations. Through "causer pays," generators that contribute fewer frequency control services pay more for ancillary services.

2.3 Grid Operations and Planning: Challenges, Responses, and Proposed Solutions

2.3.1 Challenges to the Bulk Power System due to Changes in Resource Mix over Time

Australia's shift toward a less dispatchable and less synchronous generation mix poses several challenges to the bulk power system in the NEM. For simplicity, we organize bulk power system challenges into three categories: capacity and reserves, transmission, and system control challenges.

2.3.1.1 Capacity and Reserve Challenges

High levels of distributed PV penetration may result in the under-utilization of generation capacity. Output from distributed PV generally peaks in midday, reducing load and output from non-PV generators. PV output tends to fall off sharply to about 28-38% of capacity in the late day when electricity demand peaks.[73] Falling PV output and rising demand requires market operators to ramp up non-PV generators to meet load. Thus, distributed PV could potentially reduce daily load (MWh) more than peak load (MW). This scenario requires the system operator to maintain more idle capacity during the midday PV peak to ensure sufficient capacity to meet the late day demand peak.[74] The AEMO found that meeting demand reliably in this "critical period" would be the most challenging power system design issue in a high-RE penetration future.[75]

Market operators rely on dispatchable reserve capacity, often natural gas generators, for system balancing and for contingencies, such as the loss of generators or transmission. Variable RE generators such as wind and solar are non-dispatchable and can increase the need for system reserve capacity, in some cases. The AEMO projected that NEM reserve capacity would have to increase from about 15-25% of demand to about 100-130% of demand to maintain system reliability in a 100% RE penetration environment.[76]

However several trends have contributed to projected reductions in reserve capacity. NEM capacity withdrawals exceeded new capacity entry from 2011 to 2015, partially in response to depressed prices associated with high-RE penetration. RE penetration can reduce NEM regional prices in two ways. First, wind generators generally bid much lower into the AEMO dispatch than conventional fossil-fuel generators, occasionally bidding negative prices at times of high wind and low demand. AEMO spot prices therefore tend to correlate with wind generation, with low spot prices during times of high wind generation, and high spot prices during low wind periods.[77] Second, high levels of distributed solar PV penetration have indirectly reduced NEM prices by lowering demand. Reduced demand effectively shortens the dispatch bid stack, resulting in lower-priced bids setting dispatch prices.

Sustained low wholesale prices reduce the incentive for more expensive generators to remain online. Thus RE-related price reductions contribute to capacity withdrawals. This can ultimately pose challenges with respect to having sufficient flexible generation to address system ramping needs with higher penetrations of variable RE generation. In addition, it has implications for having sufficient reserve capacity in the future.

The AEMO forecasts continued withdrawals of dispatchable synchronous generation sources replaced by non-dispatchable non-synchronous generators, mostly wind and solar (see Figure 2.2). Announced capacity withdrawals are about half of the NEM's current capacity surplus, and thus could effectively reduce NEM reserve capacity by 50%. The AEMO projects that capacity withdrawals could cause four NEM states to violate the NEM reliability standard within ten years.[78] The NEM bulk power system therefore faces a mismatch of requirements and trends: the NEM requires increased capacity reserves to maintain system reliability while prevailing trends are reducing capacity reserves.

2.3.1.2 Transmission Challenges

Additional transmission infrastructure may be required to connect remote renewable resources to load centers. The AEMO estimated that the NEM would require about 30,200 MW of transmission capacity to accommodate 100% RE penetration, about a 24,000 MW or nearly 400% increase over current transmission capacity.[79] To date, Australia has been able to make sufficient transmission investments to support new RE capacity, which has been a key challenge in many regions of the U.S. NEM transmission investments are undertaken on a case-by-case basis according to a regulatory test of the net market and reliability gains of transmission augmentation. Large investments in transmission, especially during the interconnection of the NEM, have resulted in significant transmission costs that comprise about 10% of retail electricity prices in the NEM.[80]

2.3.1.3 System Control Challenges

In general, the shift toward less dispatchable and less synchronous generation mixes reduces system control. We summarize two primary system control challenges posed by the changing resource mix in the NEM: balancing challenges and frequency control challenges.

Balancing Challenges

High levels of RE penetration make some regions more dependent on interconnectors to obtain balancing resources. All three states with greater than 20% wind and solar penetration (by capacity) sourced more than 10% of state capacity needs in 2014 through interconnectors.[81] South Australia, in particular, will become increasingly dependent on regional balancing with higher RE penetration. The Australian Energy Regulator (AER) projects that South Australia's balancing requirements will increase from about 13% of capacity in 2015 to 23% of capacity in 2018.[82] The AEMO has concluded that South Australia would experience significant system stability issues, including system outages, if disconnected from Victoria.[83] In another example, the interconnector between Tasmania and mainland Australia was lost in December, 2015 due to a tear in the undersea cable. As of the publication of this report, the island state has had to bring an additional 200 MW of emergency natural gas generators online due to the loss of the interconnector.[84] Higher reliance on balancing areas could increase strain on capacity-limited regional interconnectors.

Frequency Control Challenges

The AEMO is responsible for maintaining frequency in the NEM within a tolerance band around 50 Hz. The AEMO relies on frequency control ancillary services, provided by synchronous generators and dedicated synchronous condensers, to respond to frequency deviations during contingency events (e.g., generator loss). The NEM generation mix shift toward more non-synchronous capacity makes system frequency control more challenging for several reasons.

First, non-synchronous generators such as wind and solar do not generally provide frequency control services. Wind generators can technically provide frequency control by producing below capacity, thus providing a margin of output that could be ramped in an under-frequency event. However, ancillary service market prices have historically been too low to offset the loss of revenue from below-capacity wind generation and provide an incentive for wind generators to provide frequency control services.[85] In

February 2016, 29% of registered fossil-fuel generators participated in the ancillary service market. In contrast, none of the 46 registered wind and solar generators provided ancillary services.[86] Continued withdrawals of fossil-fuel generation could reduce the NEM ancillary service capacity and make states with high wind penetration dependent on with other states for ancillary services. In a recent example of state dependence on balancing, South Australia ancillary service market prices spiked above $9,000/MW when the state was temporarily islanded from the rest of the NEM in 2015,[87] a signal of the relative scarcity of ancillary services in the state with the highest RE penetration.

Second, high-RE penetration could lower NEM system inertia. In contrast to fossil-fuel generators, wind generators contribute effectively no system inertia, unless equipped to simulate inertial response (currently not required). Low system inertia could lead to rapid frequency deviations and generator tripping events. States with low local system inertia could become increasingly dependent on interconnectors for network support services. Low system inertia could possibly prompt the NEM to increase regulation-raise and regulation-lower capacity requirements (currently 130 MW and 120 MW, respectively for the entire NEM).[88]

2.3.2 Responses or Proposed Solutions to the Power System Impacts

Responses to the potential power system impacts of high-RE penetration have been limited to date, in part because the NEM's structure has reduced the need for large-scale reform (see Section 2.3.3). The Australian Energy Market Commission (AEMC) has largely focused recent efforts on the distribution side, with measures to facilitate the large-scale deployment of smart meters and customer demand responses capabilities. We summarize Australia's responses and proposed solutions in three areas corresponding to the challenges highlighted in Section 2.3.1: capacity and reserves, transmission, and system control solutions.

2.3.2.1 Capacity and Reserves Solutions

The AEMO has identified two paths to resolve capacity and reserve challenges. First, the AEMO could somehow ensure that sufficient synchronous generation capacity is available to meet growing reserve capacity requirements. The AEMO is investigating the cost-effectiveness of measures to "ensure minimum levels of synchronous generation remain online" in South Australia.[89] A second approach is to improve the capacity value of RE generators. The AEMO has proposed grid code performance standards to minimize generator tripping during frequency deviation events.[f] Under the grid code performance standards, non-synchronous renewable energy generators (e.g., wind, solar) would be required to provide network support services during grid disturbances.[90] In October 2015, Standards Australia published new standards for inverter systems (e.g., solar PV) that included low-voltage "ride through" and power quality guidance (Australian Standard for inverter energy systems AS/NZS4777.2). The AEMO has also proposed bypassing ancillary service markets, which do not provide sufficient incentives for wind generator participation, to require wind generators to provide frequency control services.[91] Both requirements could potentially reduce the need for new reserve capacity.

2.3.2.2 Transmission Solutions

Australia's RE targets were one of several factors driving significant investments in transmission system augmentation in Australia from 2004 to 2010. New network capacity comprised more than 50% of NEM transmission system expenditures from 2004 through 2010, peaking at 75% of expenditures in 2009 to 2010. Since that time the expenditure focus has shifted to replacing existing infrastructure.[92] The AEMO

[f] The NEM currently has generator performance standards for utility-scale synchronous generators.

has estimated that the NEM would require about 30,200 MW of transmission capacity, about a 24,000 MW or nearly 400% increase over current transmission capacity, to accommodate a 100% RE penetration. An additional interconnector between South Australia and the rest of the NEM has also been proposed as a measure to improve system stability in South Australia.

2.3.2.3 System Control Solutions

NEM stakeholders have advanced and proposed a variety of solutions to the system control challenges posed by the changing generation mix. We organize system control solutions into three categories: ancillary services; dispatch intervention; and demand response.

Ancillary Services

In general, the lower system inertia associated with a high-RE generation mix will require more ancillary service capacity. The AEMO has proposed to modify state-level contingency ancillary service requirements according to assessments of system inertia as needed, beginning with South Australia and Tasmania. The AEMO has proposed several measures to increase the availability of synchronous condensers (devices that provide system synchronicity and other ancillary services without generating electricity). The AEMO proposed a new market for network support contracts with generators capable of operating in synchronous condenser mode (effectively a new ancillary services market mechanism). Alternatively, the NEM could establish incentives for re-engineering existing generation units to operate as synchronous condensers. Last, the AEMO proposed the installation of dedicated synchronous condensers to raise system inertia. However, it remains unclear how these measures could be funded and regulated.[93]

Dispatch Intervention

The AEMO has proposed more authority over the dispatch process to ensure the dispatch of minimum levels of synchronous generation. Specifically, the AEMO could apply a constraint equation to the central dispatch process to limit the dispatch of low-inertia generators during periods of low system inertia. The AEMO has proposed curtailment of RE generators as a last resort.[94]

The AEMO has proposed the addition of a “protected events” clause to the National Electricity Rules that would allow the AEMO to intervene in the dispatch process during a regional islanding event. AEMO intervention could ensure sufficient synchronous generation and ancillary services to maintain system stability during islanding events.

The AEMO has proposed new technical standards that would require wind turbines to provide minimum levels of system inertia. Wind turbines are technically capable of providing system inertia, however wind owners currently face no incentive or obligation to provide these services. Mandating wind turbines to provide system inertia could be a controversial solution, given that such a mandate would effectively require wind generators to “spill” electricity to allow the generator to increase output in response to a frequency deviation. Energy storage technologies could alleviate this concern.[95]

In 2015, the AEMC finalized the *Generator Ramp Rates and Dispatch Inflexibility in Bidding* rule. The rule established minimum ramp rates for scheduled generators of at least 3 MW/minute or 3% of the generator’s capacity, whichever is greater.[96] The AER undertook the rulemaking in response to the perceived use of ramp rates by generators to achieve commercial outcomes,[g] not in response to demand variability associated with RE generation. Nonetheless, the rulemaking illustrates one possible avenue for ensuring adequate ramping capabilities in response to greater generation variability.

Distributed Generation Standards

In October 2015, Standards Australia published new standards for small-scale inverter systems (Grid Connections of energy systems via inverters, AS/NZ4777.2:2015). The standards require new inverter functionality that allows market operators to call upon distributed PV systems for ancillary services. The inverter standards include new requirements for voltage balancing, demand response capabilities, battery charging restrictions (for low voltage situations), and low-voltage "ride through" requirements. The standards implement "demand response mode" requirements that allow market operators to call upon distributed PV systems for load (modes 1–4) and generation control (modes 5–8) (Table 2.4).

Table 2.4. Demand Response Modes for Inverter Systems (Grid connections of energy systems, AS/NZ4777.2:2015)

Mode	Type	Requirement
0	Disconnect	Disconnect the device
1	Load control	Do not consume power
2	Load control	Do not consume at more than 50% of rated power
3	Load control	Do not consume at more than 75% of rated power, source reactive power if capable
4	Load control	Increase power consumption
5	Generation control	Do not generate power
6	Generation control	Do not generate at more than 50% of rated power
7	Generation control	Do not generate at more than 75% of rated power, sink reactive power if capable
8	Generation control	Increase power generation

Demand Response

Although primarily a distribution-side response, Australia has implemented significant demand response measures that could have implications for the bulk power system. In 2009, Victoria became the first state to advance metering reforms. Victoria required distribution businesses to install smart meters with remote communications by 2014. The program resulted in the installation of 2.8 million smart meters.[97] In 2012, the AEMC issued the "Power of Choice" review, calling for a series of demand side measures to improve the efficiency of the NEM. The Power of Choice review called for more responsive retail pricing, the competitive provision of smart meters, and improved consumer access to energy use information. The Power of Choice review resulted in a series of AEMC reforms in 2014 and 2015 to improve consumer demand response capabilities.[98]

[g] In a 2005 transmission loss event, the AER found that generators re-bid low dispatch rates in order to reduce the AEMO's ability to ramp down generation, thus minimizing generator losses from the event. The AER found that low dispatch rates reduced the AEMO's ability to respond efficiently to such events.

Under-frequency load shedding has been implemented in response to frequency deviations. For example, the AEMO used about 160 MW of customer load shedding to mitigate frequency deviations during a November 2015 islanding event in South Australia.[99]

In 2014, the AEMC finalized a rule that requires distribution businesses to move toward time-of-use tariff structures that better reflect customers' network costs by 2017. Distributors submitted proposed tariff structures in late 2015.[100] TOU tariff structures could theoretically reduce ramping requirements to meet evening peak demand during low PV generation periods.

2.3.2.4 Summary of Challenges, Responses, and Proposed Solutions

NEM stakeholders have implemented and proposed a variety of responses and solutions to the bulk power system challenges of the changing generation resource mix. Table 2.5 summarizes the bulk power system challenges, responses, and proposed solutions.

Table 2.5. Summary of Challenges, Responses, and Solutions

Challenges	Responses	Proposed Solutions
Capacity and reserves: Need for increased reserves to ensure system stability	No action to date	Increase reserves to 100-130% of demand in 100% RE scenario. Performance standards for RE generators.
Transmission: Possible expansions required to accommodate remote RE resources	Significant investments in transmission from 2004-2010	About 24,000 MW of new transmission capacity for 100% RE scenario, additional regional interconnects
System control: Increased state-level dependence on balancing, reduced frequency control, more significant generator ramping in response to generator variability	Demand response measures, move toward time-of-use tariff structures	More synchronous condensers, allow more AEMO intervention in the dispatch process, new technical standards for wind turbines

2.3.3 How Industry Structure Exacerbated/Mitigated Bulk Power System Impacts

Australian electricity industry restructuring, coupled with supportive environmental policies, played an important role in high-RE penetration in Australia.[101] In this sense, restructuring directly contributed to the challenges to the NEM bulk power system, but structural features of the NEM have also mitigated these bulk power system challenges.

2.3.3.1 NEM Features that Exacerbate Bulk Power System Impacts

The NEM generator dispatch process limits the ability of the AEMO, or any other authority, to implement near-term generation and system control measures to ensure system stability. The AEMO dispatches generators according to bid stacking, where the lowest bids are dispatched until demand is met. This process generally results in the dispatching of non-synchronous wind resources (which typically make low or even negative bids) before synchronous generators such as natural gas and coal. Synchronous generators therefore, may be eliminated from the dispatch stack due to economics, and the NEM does not have a capacity market to incentivize synchronous generators to remain online for their capacity value. The AEMO can only procure reserve capacity in the event of a short term risk to system reliability through a reliability and emergency reserve trader mechanism.[102] The AEMO has requested increased autonomy over the dispatch process to ensure that minimum levels of synchronous generation can be dispatched.

The NEM structure also limits the ability of the AEMO or other authorities to implement long-term generation and system control planning measures. Falling generation capacity, partially in response to depressed wholesale prices associated with wind energy penetration, could result in system reliability issues by as early as 2019. The AEMO currently has limited authority to ensure reserve capacity in response to short-term risks to system reliability and no long-term planning authority to ensure sufficient long-term capacity.[103,104] Further, capacity additions (mostly wind and solar) do not provide the same ancillary services as capacity withdrawals (mostly coal). The AEMO has no authority to ensure adequate supplies of ancillary services outside of ancillary service markets.

2.3.3.2 NEM Features that Mitigate Bulk Power System Impacts

The balancing capabilities of the NEM are a significant asset for RE penetration. The ability of some states to rely on interregional interconnectors to source capacity and system control services from neighboring states has facilitated higher levels of RE penetration than could have been possible absent this balancing capability. South Australia, in particular, relies heavily on its interconnector with Victoria, sourcing about 14% of generation through the interconnector in 2014.[105] The importance of balancing was demonstrated in November 2014, when South Australia lost connection with Victoria and was islanded from the rest of the NEM. The drop in frequency forced the AEMO to implement 160 MW of load shedding to mitigate frequency deviations as local generation could not ramp quickly enough. Further, the islanding event forced South Australia to locally source all system control services, causing a sharp price spike in the local ancillary service market.[106] The event illustrates the pivotal role of the NEM's balancing capabilities in facilitating high-RE penetration. The AEMO projects that South Australia could achieve 100% RE penetration with continued system stability due to its ability to balance with the rest of the NEM.[107]

The geographic extent of the NEM with interregional trade is a second significant asset to high-RE penetration. The NEM includes about 40,000 kilometers of transmission infrastructure and 730,000 kilometers of distribution infrastructure, making it one of the largest interconnects in the world.[108] Twenty-three wind farms in four states are registered as semi-scheduled generators: 11 in South Australia, 7 in NSW, 4 in Victoria, and one in Tasmania.[109] Solar PV generators are likewise geographically dispersed, with over 500 MW installed in every state except Tasmania.[110] The geographic dispersion of the NEM's RE resources and their interconnection through the NEM's transmission infrastructure reduce the potential system variability impacts of changes in resource quality in any one given location.

Last, the five-minute dispatch intervals of the AEMO dispatch process have mitigated NEM bulk power system challenges. The relatively short dispatch intervals allow the AEMO to control system variability more quickly and easily and could facilitate generator ramping in response to variable RE generation. A 2016 AEMC rule requiring minimum generator ramp rates could further mitigate bulk power system variability challenges.

2.4 Lessons Learned for Maintaining Reliability and Cost-Effectiveness with a Changing Resource Mix

2.4.1 Implications of Changing Resource Mix on Grid Operations and Planning

Over the past decade, the NEM has gradually shifted to a less dispatchable and less synchronous generation mix. The Australian case study illustrates that RE capacity is not a perfect substitute for synchronous capacity. The net shift toward RE capacity has eroded the NEM's system control capabilities, including frequency control, voltage control, and system inertia. These potential system control challenges have been somewhat mitigated by the balancing capabilities and geographic extent of the NEM. Nonetheless, continued high levels of RE penetration could require substantive changes to Australian grid operations and planning, including increased reserve capacity, transmission system expansions, and system control measures.

2.4.2 Implications of Industry Structure on Handling Resource Changes

The NEM industry structure has both exacerbated and mitigated Australia's ability to accommodate higher levels of RE generation. The market-based generation dispatch process decentralized near-term generation decisions and long-term generation planning. NEM authorities have limited ability to intervene in generation decisions and ensure the long-term availability of system control services. The result may be a shortage of synchronous generation capacity and system control services that could prompt system reliability issues in the near future. At the same time, the NEM's large balancing area and geographic extent have facilitated the NEM's ability to accommodate high-RE penetration. Another key feature has been a market structure that supports new investments in transmission, which has facilitated the integration of wind generation in particular. The ability of some states to use interregional interconnectors to source capacity and system control services has facilitated otherwise untenable levels of RE.

2.4.3 Implications for the United States

The challenges of a changing resource mix to the Australian bulk power system are similar to challenges identified in a U.S. context. Given current trends, the NEM in 2016 provides a preview of a large interconnect with the type of resource mix that may be seen on some U.S. networks in the near future, with higher levels of transmission-connected wind resources and distributed residential PV. With the exception of instability associated with islanding events (e.g., November 2015 islanding of South Australia, see Section 2.3.1), the NEM has demonstrated that higher levels of RE penetration (relative to current levels in the U.S.) are possible without significant structural changes to the bulk power system.

Nonetheless, projections of continued capacity withdrawals in the NEM coupled with increased requirements for reserve capacity prompt concerns of system reliability that could have parallels in the U.S. The AEMO, like U.S. system operators, has called for increased autonomy over long-term generation and system control planning. The long-term stability of the NEM could depend on two factors: the development of a mechanism to ensure adequate capacity and system control services, and the continued ability of states to source such services through regional interconnectors. Stability in U.S. electricity networks, with similarly large balancing areas and wholesale markets in regions such as ERCOT, MISO, and PJM, could hinge on similar factors. With higher penetrations of PV in coming years, Australia's primary system operational concern is meeting demand reliably in the early evening peak period when PV output declines and load increases, similar to concerns raised in California.

3.0 Germany Electric Power Case Study

3.1 Key Findings

Electricity market restructuring in 1998 opened up wholesale and retail markets for competition in Germany. This restructuring was immediately followed by market consolidation and the power sector has been dominated by four large, vertically integrated energy service companies ever since. However, the relative market share of these four companies has declined in recent years as the penetration of individually-owned distributed generation resources has increased.

This market transformation also coincided with the introduction of incentives for renewables, primarily in the form of FITs that have caused Germany to become a world leader in wind and solar generation. Germany is currently undergoing a second major reform that is focused on fostering a transition toward a low-carbon electricity future fueled by renewable resources and an eventual phase-out of nuclear generation in Germany. The rapid change in the German generation resource mix has been driven primarily by the provision of attractive FITs and priority grid access for renewables and much less by traditional restructuring efforts

The rapid expansion of wind and solar power causes operational and planning challenges that are currently being addressed through further market reforms with a key focus on enabling more flexibility in the system. It appears that Germany has decided to not pursue a capacity market and will instead institute a series of other policies, measures, and market designs to ensure long-term capacity adequacy, which has been termed the Electricity Market 2.0. An overview of the power system characteristics, planning and operational procedures, and reform efforts are summarized in the tables below (see Table 3.1 and Table 3.2). Some specific actions taken in recent years include:

- Formalizing plans to develop new transmission infrastructure to relieve north/south congestion and increase interconnection capacity with neighboring countries,
- Implementation of a gradual phase-out of FITs that are currently offered to renewable generators to a system based largely on auctions,
- Allowing negative pricing and implementing 15 minute resolution in the European intraday spot markets, and
- Strengthening the balancing requirements for balancing groups that aggregate schedules from a subset of the generators and consumers within a TSO service territory. This reduces the amount of balancing capacity reserves that must be procured by the TSOs and results in a more efficient allocation of resources.

Current electricity market reform efforts related to operations and planning with high penetrations of renewables are relevant to several ISO/RTO areas in the United States, particularly regions with aggressive renewables targets such as California and the CAISO system, and regions with no capacity markets and high prices caps, such as Texas and the ERCOT system. In Germany, decentralized solutions, both in terms of distributed resources as well as balancing groups for internal coordination, are important parts of the solution to current challenges being faced by the power system. The German example demonstrates that public energy-environmental policies can drive a rapid transition of the electricity supply system, however the costs of such policies must be weighed against the benefits.

Table 3.1. Key Characteristics of Electricity Generation in Germany

Size of Power System	Capacity (GW)	2014	192 GW[111]
	Load (GW)	2013	82.7 GW[112]
	Generation (TWh)	2014	598 TWh[113]
Generation Contribution from Variable Renewables	% of total generation	2000	1.6%[114]
		2010	7.8%[115]
		2014	15.5%[116]
Mechanism for Renewable Promotion		FIT	Yes[117], see also Table 3.6
		Renewable Energy Credits	No
		Contract for Difference	Shift from Feed-in Tariffs to feed-in premiums and auctions for new renewable capacity
		other	Priority grid access for renewables, EU Emission Trading Scheme
Proposed or Enacted Policies to Address the Following Issue:	Technical issues	Interconnection permitting	Energy Line Expansion Act of 2009
		Over-generation	Priority dispatch for renewables, which may still be curtailed for reliability reasons (1.16% of generation in 2014[118]).
	Markets	Incentives	Shift toward direct marketing, where renewables must offer in spot market and do not receive FIT during negative prices.
		Misalignment	
	Goals/targets	RE goals or binding targets	Goals[119]: 2025: 40-45% 2035: 55-60% 2050: 80%+
		Key drivers for RE penetration	Attractive Feed-in Tariffs for distributed generators, aggressive national RE goals

Table 3.2. Summary of Electricity Market Structure for Germany

Generation	Ownership	56% of capacity owned by large vertically integrated utilities (as of 2014).[120] Remainder from IPPs and individual distributed wind and solar PV owners.
	Resource adequacy mechanism	Energy-only market, no price cap Bilateral contracts are also common
System Operation	Balancing	Four Transmission System Operators (TSOs) in charge of real-time balancing. Balancing groups also do internal balancing.
	Market Operator	TSOs run real-time balancing market, power exchanges run day-ahead and intraday markets.
	Energy Market	Day-ahead and intraday as part of the European Energy Exchange (EEX) and EPEX Spot markets.
Transmission	Ownership	Four TSOs
	Operator	Four TSOs
Distribution	Ownership	Primarily owned by four large utilities, the rest is owned and operated by roughly 890 other smaller entities.[121]
Retail	Retailers	Four large utilities have 45% market share (as of 2013), there are 900 other smaller providers.[122]
	Demand Response	Limited so far, but may play an important role in providing flexibility in the future grid.[123]
	Retail Choice	Retail choice for all customers since 1998. In 2012, 20% of customers used a competitive supplier other than the default supplier in the area.[124]

3.2 Regulatory and Policy Background

3.2.1 Overview of Industry Structure and Policies prior to Restructuring

Prior to market liberalization in 1998, the German electric system was divided into discrete regions that were each operated by a single entity, acting as a regulated monopoly. This basic framework was established by the 1935 National Energy Act which defined these regional territories. Prices were controlled by state ministries under a cost plus rate-of-return principle. In 1997, just prior to market liberalization there were eight large energy supply companies that collectively produced 79% of all electricity generation in Germany. These large companies also owned and managed all transmission infrastructure in the country. The large energy supply companies were complemented by a consortium of approximately 80 smaller regional entities that collectively produced 10% of the national generation and also managed regional distribution and supply. There were also approximately 900 local municipal entities that were supplied by the regional entities, and who in turn supplied their own local end users.[125]

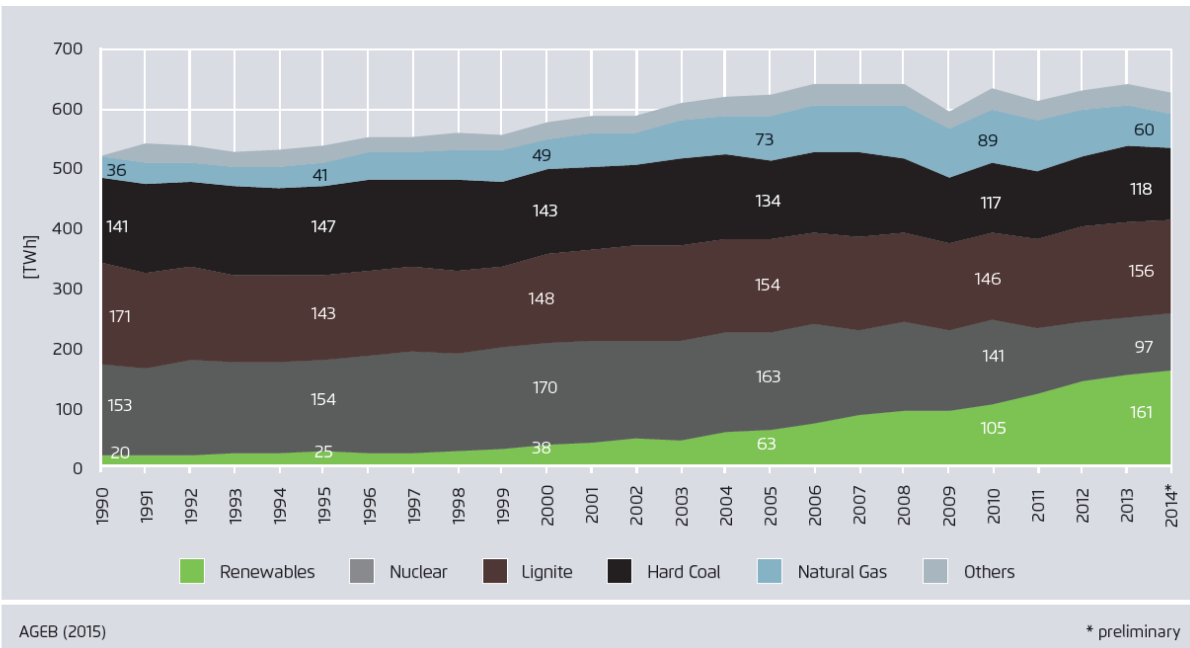
In 1996 the EU issued a directive to establish common rules for generation, transmission and distribution of electricity by its member states.[126] It also established an imperative for member states to transition toward competitive electricity markets and provided a common framework through minimum requirements for regulation and market structure. This in essence required member states to unbundle the potentially competitive elements of the monopolistic energy supply companies.

Through the National Energy Act of 1998 Germany took measures beyond these minimum requirements that led to full liberalization of the electricity sector. Germany dissolved the large generation and supply monopolies and established concession-based regional monopolies for transmission and distribution. It also removed barriers to entry for new generators and developed a framework to support non-discriminatory access to the grid.

3.2.2 Evolution of Resource Mix

The historical evolution of the electricity generation mix in Germany over the past 25 years is presented in Figure 3.1. Over this period, several trends can be observed. First, and most strikingly, there has been a rapid growth in renewable generation over the last decade due to supportive policies and incentives. Second, there has been a sharp reduction in nuclear generation in recent years due to regulatory mandates. Third, natural-gas–fired generation nearly doubled between 2000 and 2010, but has declined in recent years. The changes related to nuclear power and renewable energy are discussed in more detail below.

Figure 3.1. Electricity Generation in Germany by Energy Resource 1990–2014[127]



Renewable electricity generation in Germany has grown steadily since 2000, largely displacing nuclear generation.

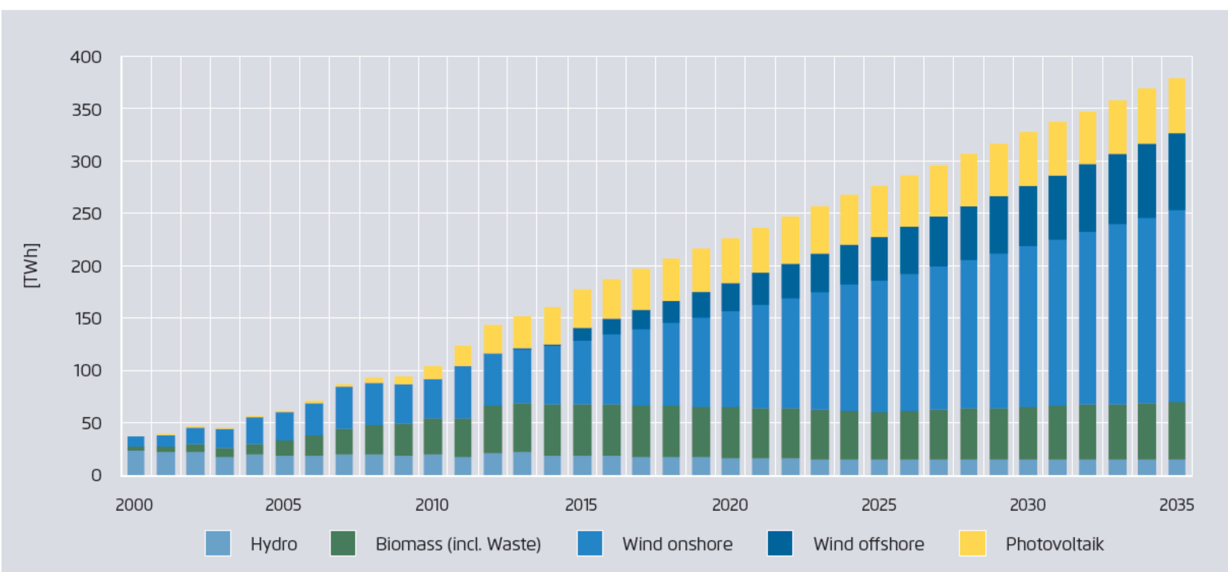
As illustrated in Figure 3.1, prior to market deregulation in 1998, roughly 60% of electricity generation in Germany came from coal, 30% came from nuclear and the balance was made up of natural gas and some renewables. Renewables during this period consisted almost entirely of hydroelectric generation. Market restructuring did not result in any immediate significant changes in the resource mix, and the generation pattern was relatively stable throughout the 1990s. However in 2000, the German government, led by former Chancellor Gerhard Schroeder, announced a plan to phase out their 19 nuclear power stations by 2020.[128] Consequently, nuclear generation decreased by about 17% between 2000 and 2010, from 170 TWh to 141 TWh. This course was reversed to some extent by Chancellor Merkel in 2010, when it was announced that Germany's remaining 17 nuclear stations would be recommissioned for an additional 8 to 14 years. However, this change in course was once again reversed shortly following the Fukushima nuclear incident in 2011. Nearly 40% of nuclear capacity in Germany (8,400 MW) was taken offline within a one week period and plans were announced to phase out the remainder by 2022 much of which is planned to be decommissioned in 2019 and 2020.[129] As a result, nuclear generation dropped by over 30% between 2010 and 2014, from 141 TWh to 97 TWh.

This decade of nuclear decline in Germany also corresponded with the implementation of several aggressive incentives for wind and solar generators. As a result, the capacity gap that has been left by decommissioned nuclear units has subsequently been largely filled by rapid growth in renewable generation. Figure 3.2 shows that this growth was primarily provided by wind, solar and biomass generation, while there has actually been a modest decline in hydroelectric generation. In 2014 renewables accounted for more than 25% of the total generation in Germany. Germany is particularly notable for its rapid adoption of solar generation given its modest levels of solar irradiation. As of July 2014, there were 37.5 GW of installed solar PV capacity in Germany, more than in any other country in the world.[130] Installed capacity by technology in 2014 is listed in Table 3.3.

This growth in renewable generation largely displaced generation from the nuclear units that have been phased out. The use of coal resources has also steadily decreased over the past 25 years in Germany, with generation falling from 312 TWh in 1990 to 276 TWh in 2014. Despite this decline, coal still accounts for almost 45% of the total generation in Germany.

Over the coming years, Germany will continue to phase out its nuclear generation, with the goal of becoming a nuclear-free nation in 2022. In addition, Germany has established one of the most aggressive renewable targets in the world, with the stated goal of producing 40-45% of its gross electricity generation from renewable sources in 2025, increasing to 55-60% in 2035 and at least 80% in 2050.[131] This projected future growth in renewable generation is indicated in Figure 3.2.

Figure 3.2. Gross Electricity Generation by Renewable Resources, Historical and Projected, 2000–2035[132]



Renewable generation is projected to grow significantly in Germany over the next 20 years. Almost all of this growth is associated with new wind and solar generation.

Table 3.3. Installed Generation Capacity in Germany by Technology in 2014[133]

Fuel Source	Installed Capacity (MW)	% of Total	Total Generation (MWh)	% of Total
Coal	49,321	25.6%	274	45.8%
Nuclear	12,068	6.3%	97	16.2%
Natural Gas	28,403	14.8%	60	10.0%
Other Conventional	18,697	9.7%	6	1.0%
Solar	37,488	19.5%	35	5.9%
Wind	34,638	18.0%	57	9.6%
Biomass	6,383	3.3%	49	8.2%
Hydropower	3,918	2.0%	20	3.3%
Other Renewables	1,447	0.8%	#N/A	#N/A
Total	**192,363**	**100%**	**598.0**	**100%**

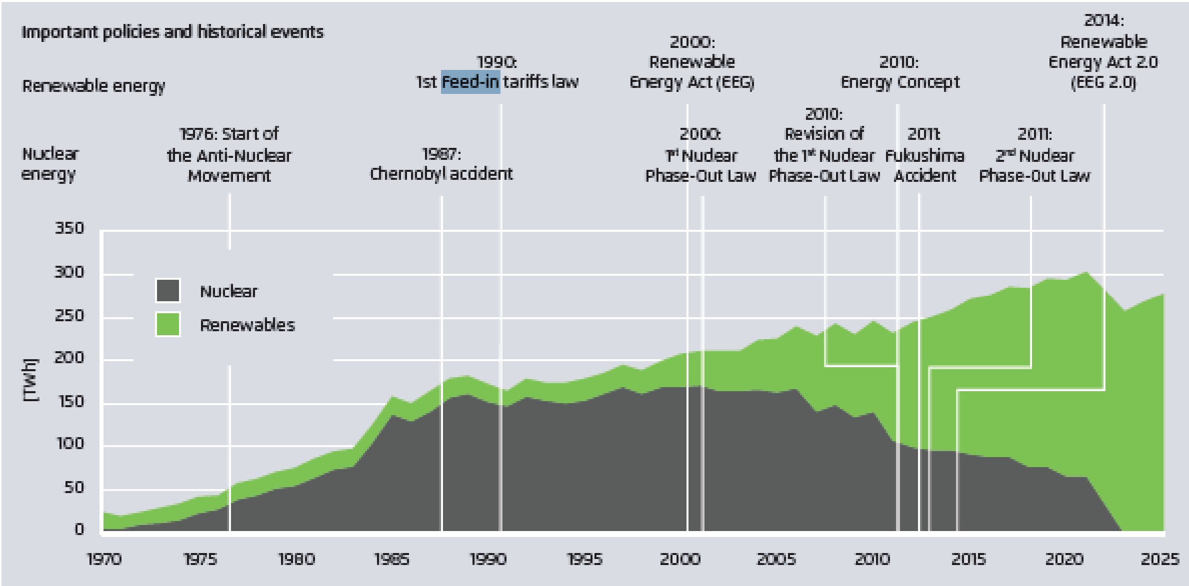
In 2014 there were nearly 84 GW of installed renewable generation capacity in Germany, accounting for more than 40% of all installed capacity in Germany.

3.2.3 Key Restructuring Policies Affecting Power Grid Operations, Planning, and Generation Mix

As discussed in the section above, the German electricity market restructuring of the late 1990s had a relatively modest impact on the generation mix in the system. The main drivers for changes in installed capacity are the policies related to nuclear power and renewable energy. This is re-iterated in **Error! Reference source not found.**, which shows the historical and expected future generation from these resources through 2025 along with important political events driving these changes. Hence, it is fair to assume that the ongoing changes in the electricity generation in Germany are driven by the country's desire to shift from fossil-fired generation and nuclear power toward renewable resources.

A key incentive mechanism to trigger investments in renewable energy in Germany has been Feed-in Tariffs (FITs). A FIT is a subsidy scheme that provides a guaranteed price for renewable generation over a certain time period. The cost of the FIT is recouped through a surcharge in the electricity retail price; they are therefore, funded by electricity rate payers and are not direct government subsidies. Such tariffs were introduced in 1991 and at that time primarily provided support for small hydro generation. FITs are available to all potential electricity producers in Germany, including residential consumers, and in more recent years they have played a crucial role in the rapid deployment of distributed rooftop solar PV and onshore wind in Germany.[134] An important potential stumbling block for this incentive scheme was surpassed in 2001, when the European Court of Justice ruled that FITs are not "state aid" and are therefore legal policy instruments. FITs are currently undergoing a transition now that the policy has met its primary objective of building-up renewable capacity and reducing technology costs. This transition involves a shift toward more competitive procurement of renewable energy resources (primarily auctions), a gradual reduction in the level of support provided that is linked to specific expansion targets for different technologies, along with a less favorable treatment and more exposure to competition with other resources in the electricity market.[135]

Figure 3.3. Nuclear and Renewable Electricity Generation and Related Political Events in Germany, 1970–2025[136]



The growth of renewable generation and the simultaneous decline of nuclear generation in Germany have been motivated by policies, regulations, and other political events.

The rapid changes in the generation mix driven by the policies discussed above have given rise to several challenges when it comes to planning and operation of the power grid. In particular, with the large increase in renewable generation, improved handling of uncertainty and variability is the key challenge and multiple measures have been implemented and proposed to increase the level of flexibility in the system, as discussed in more detail in Section 3.3.

3.2.4 Key Drivers of Restructuring

There have been two primary phases of market restructuring in Germany. The first was the electricity market liberalization that was instigated in 1998 and continued through the early 2000s. This period resulted in the formation of competitive markets for electricity generation and supply, largely in-line with the general trend toward power sector deregulation in other industrialized countries during the same period. As previously discussed, this transition did not directly impact the resource mix to a significant extent.

More than a decade later, in 2011, Germany officially embarked on a second major market reform with the passing of the Renewable Energy Sources Act (EEG). This act enabled the ongoing *Energiewende* to take shape, a term loosely translated as Energy Transition. However, the German term is typically used even in English contexts, as the related German efforts toward a cleaner energy future based on renewable energy are well known on a global scale. The nuclear phase-out was officially enacted in 2011, but the broader concept has been under development for decades and has roots in the prominent Germany anti-nuclear movement of the 1970s and 80s. There are a number of key drivers for the Energiewende, including 1) reducing emissions and abating climate change, 2) reducing reliance on energy imports and strengthening energy security, 3) stimulating the green economy, 4) eliminating risks associated with nuclear generation, and 5) supporting local ownership and local economies ("democratizing" the energy system).[137]

The Energiewende consists of specific goals across four dimensions that are summarized in Table 3.4. These goals are to be pursued while maintaining system reliability and ensuring that all potential consumers have equal access to the electric grid. However, they may not be fully compatible with the current German market framework for several reasons to be discussed in more detail below. Therefore, whereas the market transition of the late 1990s and early 2000s focused primarily on fostering market competition and a more economically efficient provision of electricity, the Energiewende goes a step further by setting ambitious energy-environmental goals driven by public opinion while also ensuring that the range of potential resulting operations and planning issues will be addressed.

Table 3.4. Goals of the *Energiewende* Pertaining to the Electric Sector in Germany[138] [(a)]

Dimension	Goals
Phase out nuclear	2022: 0%
Increase renewable generation	2025: 40-45%
	2035: 55-60%
	2050: 80%+
Reduce GHG emissions	2020: 40% reduction (vs. 1990)
	2030: 55% reduction (vs. 1990)
	2040: 70% reduction (vs. 1990)
	2050: 80-95% reduction (vs. 1990)
Reduce primary energy consumption	2020: 20% reduction (vs. 2008)
	2050: 50% reduction (vs. 2008)

(a) The Energiewende has established ambitious goals to increase renewable generation and reduce emissions in Germany.

3.2.5 Electric Power Sector Market Structure

3.2.5.1 In the years following the 1998 liberalization, there was strong market consolidation of the major energy supply companies via mergers and acquisitions. By 1998, the eight pre-liberalization companies had consolidated into six, and by 2004 only four remained. These four companies accounted for 95.6% of all electricity generation in Germany at the time. The current ownership structure of generation, transmission, distribution, and retail sectors in Germany are briefly described below. An overview of companies, market shares, and ownership in these sectors is summarized in Generation

The German electric power sector is dominated by four large energy service companies EnBW, E.ON, RWE, and Vattenfall. These companies maintain both generation and distribution assets and also provide retail services. Together, the four major companies currently account for 59% of generation in the country. While still significant, this does represent a decline in relative market share in recent years as the four largest energy supply companies in Germany accounted for more than 95% of total generation in 2004. This shift is largely due to the growth in distributed generation throughout the country and there are now over 1000 electricity producers in Germany, not including individual owners of rooftop solar PV systems. Private citizens and farmers own almost 50% of the renewable generation in Germany, largely made up from individual rooftop PV systems and onshore wind. These systems receive FITs for electricity that they feed into the grid; this specific pricing structure is discussed in more detail later. They are also afforded priority access to the grid. Large generators can bid their supply into competitive wholesale markets operated by power exchanges through the balancing groups, and can sell their electricity directly to consumers through bilateral contracts. The structure of the electricity market is discussed in more detail in Section 3.2.5.5.

Table 3.5. The section concludes with a short discussion of the electricity market.

3.2.5.2 Generation

The German electric power sector is dominated by four large energy service companies EnBW, E.ON, RWE, and Vattenfall. These companies maintain both generation and distribution assets and also provide retail services. Together, the four major companies currently account for 59% of generation in the country. While still significant, this does represent a decline in relative market share in recent years as the four largest energy supply companies in Germany accounted for more than 95% of total generation in 2004. This shift is largely due to the growth in distributed generation throughout the country and there are now over 1000 electricity producers in Germany, not including individual owners of rooftop solar PV systems. [139] Private citizens and farmers own almost 50% of the renewable generation in Germany, largely made up from individual rooftop PV systems and onshore wind.[140] These systems receive FITs for electricity that they feed into the grid; this specific pricing structure is discussed in more detail later. They are also afforded priority access to the grid. Large generators can bid their supply into competitive wholesale markets operated by power exchanges through the balancing groups, and can sell their electricity directly to consumers through bilateral contracts. The structure of the electricity market is discussed in more detail in Section 3.2.5.5.

Table 3.5. Summary of German Electric Industry Composition Prior to and Following Liberalization in 1998[141,142] [(a)]

	1997	1999	2004	2012
Generation	8 companies with 79% of electricity generation	6 companies with 74% of electricity generation	4 companies with 96% of electricity generation	4 companies with 59% of electricity generation
Transmission	8 companies with 100% market share	6 companies with 100% market share	4 companies with 100% market share	4 TSOs, owned in part by the four large multi-sector companies
Distribution	80 regional energy supply companies, 900 municipal utilities	Regional energy supply companies and municipal utilities (exact numbers unspecified)	50 regional energy supply companies, 700 municipal utilities	4 large companies control significant fraction of distribution system, (exact amount unspecified). Approximately 890 other distribution supply companies and 700 municipal utilities
Supply	5 large companies control 51%-59% of sales. In addition, 80 regional energy supply companies, 900 municipal utilities	6 large companies control 62% of sales. The rest is split between regional supply companies and municipal utilities	4 large companies control 73% of sales. In addition, 700 municipal utilities and some regional producers	4 large companies control 46% of sales. In addition, 700 municipal utilities and some regional producers

The Germany power sector was dominated by eight large energy supply companies prior to market liberalization in 1998. Following liberalization, they consolidated into four companies and increased their fraction of total market share. The German transmission infrastructure is owned and operated by four Transmission System Operators (TSOs). The other three segments are dominated by four large energy supply companies, although smaller entities are gradually increasing their market share.

3.2.5.3 Transmission

The transmission infrastructure in Germany is wholly operated by four separate entities, known as TSOs that each have been granted a monopolistic concession to operate in their respective territories. These TSOs are Ampiron, Transnet BW (ENBW), TenneT, and 50Hertz. In contrast to practices in the United States, where RTOs and ISOs operate transmission lines owned by separate entities (e.g. utility companies), the TSOs in Germany both own and operate the transmission infrastructure. This "TSO" model was a result of restructuring efforts in Europe and is commonly used across many European countries. Following market liberalization in 1998, Germany adopted a negotiated third-party access scheme for their transmission and distribution system, the only country in Europe to implement this approach.[143] There was no specific regulator tasked with curtailing market power in electricity transport, this was instead left to the cartel offices that already regulated the activities of the large energy service providers.[144] This approach was abandoned with the National Energy Act of 2005, which established a system of regulated third-party network access and an associated regulatory agency, Bundesnetzagentur, and also finalized unbundling of electricity production and supply.

3.2.5.4 Distribution

The four large energy supply companies also own and operate a large portion of the distribution infrastructure in Germany, with the rest operated by nearly 900 smaller regional and municipal entities.

3.2.5.5 Retail

The four large energy supply companies control roughly 45% of retail supply in Germany, with the rest provided by over 900 smaller regional and municipal entities. There is full retail competition with all customers being able to choose their electricity supplier on a month-to-month basis since 1998.[145]

3.2.5.6 Electricity Market Structure

Electricity in Germany is traded in two European exchanges that offer standardized financial contracts, the European Energy Exchange (EEX) based in Leipzig and the EPEX Spot based in Paris. There is a long-term forward market where purchasers can secure electricity delivery up to six years in advance. There is also a day-ahead market that closes at noon on the day prior to delivery, as well as an intraday spot market that trades in 15 minutes to one hour intervals. Activity on the spot market closes 45 minutes before delivery. Finally, companies can also engage in direct bilateral contracts, also known as over the counter trading. These trades are open until 15 minutes before delivery and still account for a large fraction of the total exchanges. On the European Exchanges, there is a single price zone for all of Germany that is shared with Austria as well. All the day-ahead and intraday trades occurring at the power exchanges are financial in the sense that physical delivery is not strictly required and deviations will be settled against prices in the real-time balancing market, which is operated by the TSOs.[146]

In daily operations, a set of balancing groups are responsible for maintaining the balance between supply and demand in their designated areas.[147] All electricity generators and consumers are assigned to a balancing group in Germany, and there are multiple balancing groups within each TSO. The balancing groups are not in charge of physically balancing the system (i.e., it is not a control area). Rather they are entities that aggregate the schedules from multiple generators and consumers and schedule resources accordingly. In turn, the TSOs are responsible for maintaining balancing capacity reserves that are called upon and deployed to physically balance supply and demand when imbalances occur in the balancing groups. [148] Balancing energy prices are determined accordingly based on the merit order curve of available reserves. The reserve capacity, which consists of multiple reserve products (including primary, secondary, and tertiary reserves), is procured by the four TSOs jointly through a tender auction on the German Control Reserve Market. There is a financial settlement between the TSOs and balancing groups, which depend on the actual deviations from their schedule.[149] Hence, the balancing groups have an incentive to balance resources internally to avoid being exposed to the balancing market operated by the TSO. There is no explicit capacity market for long-term resource adequacy in Germany. This is a topic that has been subject to substantial debate recently and that is discussed in more detail later in this report.[150]

3.3 Grid Operations and Planning: Challenges, Responses, and Proposed Solutions

3.3.1 Challenges to the Bulk Power System due to Changes in Resource Mix over Time

The changing resource mix in Germany, namely the rapid growth in variable renewable generation and simultaneous phasing out of baseload nuclear generation, has resulted in a number of issues and concerns for the bulk power system. Some of the major challenges are briefly discussed below.

3.3.1.1 Transmission Bottlenecks

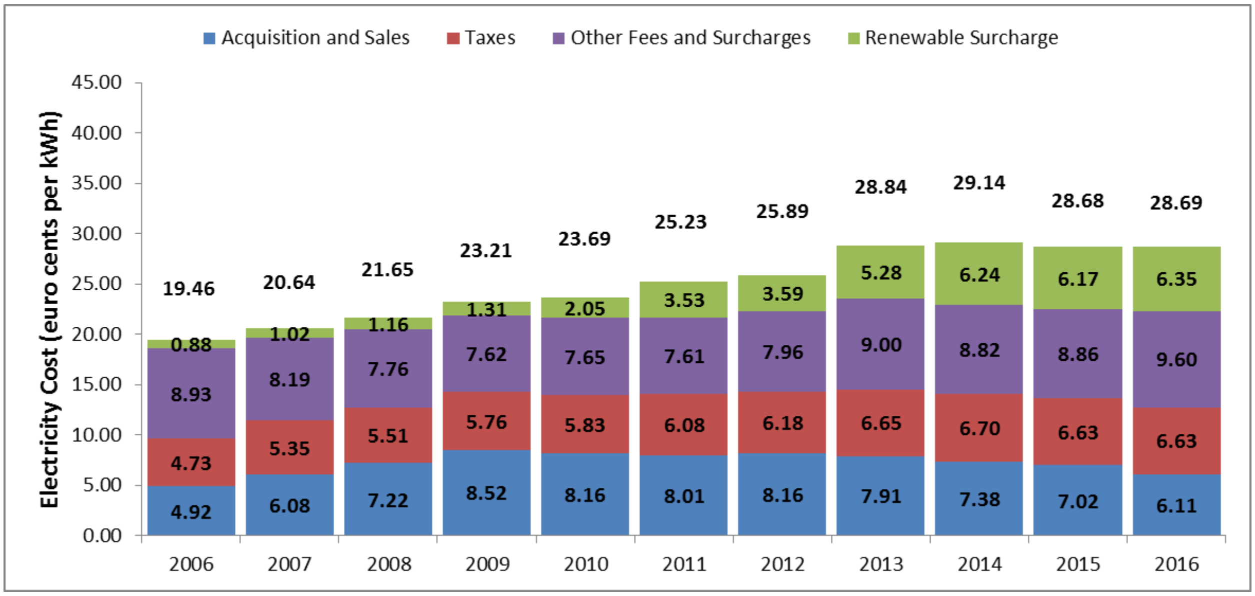
Much of Germany's onshore and offshore wind generation is located in the northern part of the country, while many of the load centers are in the southern and western regions. Furthermore, much of the retiring nuclear generation capacity is also located in the south. As a result there is currently a north/south transmission bottleneck in Germany that can lead to excess power availability in the north and shortages in the south. As Germany has only a single price zone (and this single zone is also shared with Austria), there is no market mechanism for resolving congestion in the day-ahead market. Instead, the TSOs are responsible for manually re-dispatching generators to balance supply and demand. The costs of this re-dispatching are distributed to customers through network charges and were estimated to be 115 to 133 million euro in 2013 and 187 million euro 2014.[151,152] The grid operator, 50Hertz, estimated that re-dispatch costs reached 500 million euros in 2015 and the president of the Federal Network Agency has warned that these annual costs could reach one billion euros by 2020 if further actions are not taken.[153] The transmission congestion, which is not reflected in day-ahead prices, is also a concern for some neighboring countries, which are exposed to loop-flows caused by the conditions in Germany.[154]

3.3.1.2 Over-Capacity

There is currently an excess of generation capacity in Germany, as is the case throughout much of Europe. The European Network of Transmission System Operators for Electricity (ENTSO-E) conducted a Scenario Outlook and Adequacy Forecast which found 100 GW of excess capacity in Europe, 60 GW of which is in a region relevant to Germany. This can be attributed to several factors. First, market liberalization lowered barriers to entry for new generators and increased the number of market entrants. Second, the coupling of markets throughout Europe has increased dispatch efficiency. Third, the rapid growth of renewables has displaced generation previously provided by traditional fossil and nuclear units. As a result of this over-capacity and the low/zero fuel costs of renewable generation, wholesale electricity prices in the Germany-Austria price zone have dropped significantly in recent years. This has reduced revenue for traditional generators and is causing many units to shut down for economic reasons. On the other hand, overcapacity is not a disincentive for renewable generation that is supported by a range of different incentive mechanisms. Thus, it has limited exposure to reductions in prices and continues to grow. It should be noted that retail electricity prices have not experienced the same decline as wholesale prices due to growing renewable surcharges and other network fees and taxes (

). When considering household prices, it is important to keep in mind that the average German household has a relatively low average electricity consumption (ca. 3,500 kWh/year in Germany compared to more than 11,000 kWh/year in the United States). Also, note that industrial consumers to a large extent have not been exposed to these surcharges and fees.

Figure 3.4. Retail Electricity Prices for Households Have Increased Steadily over the Past Decade[155]



Retail electricity prices have increased steadily since 2006 despite declining wholesale prices. This is primarily due to an increasing renewables surcharge. The increasing price trend has been mitigated to some extent in recent years due to the decline in wholesale prices, but not to the same extent.

3.3.1.3 Long-Term Resource Adequacy and Flexibility Needs

Even with the nuclear shutdowns that are taking place there is still more than sufficient generation capacity in Germany to serve demand in the near-term. However, there are some concerns over longer-term capacity adequacy. This is particularly important as it relates to the flexible resources needed to balance fluctuations in variable renewable generation resources. As German electricity markets continue to evolve and adapt to the changing resource mix, it will be important for policy makers to develop strategies to ensure adequate development of new flexible resources that maintain system reliability, as opposed to traditional, less flexible baseload capacity. These are general challenges of electricity market design with increasing shares of renewable energy that also apply to the United States.[156]

3.3.1.4 Ancillary Services

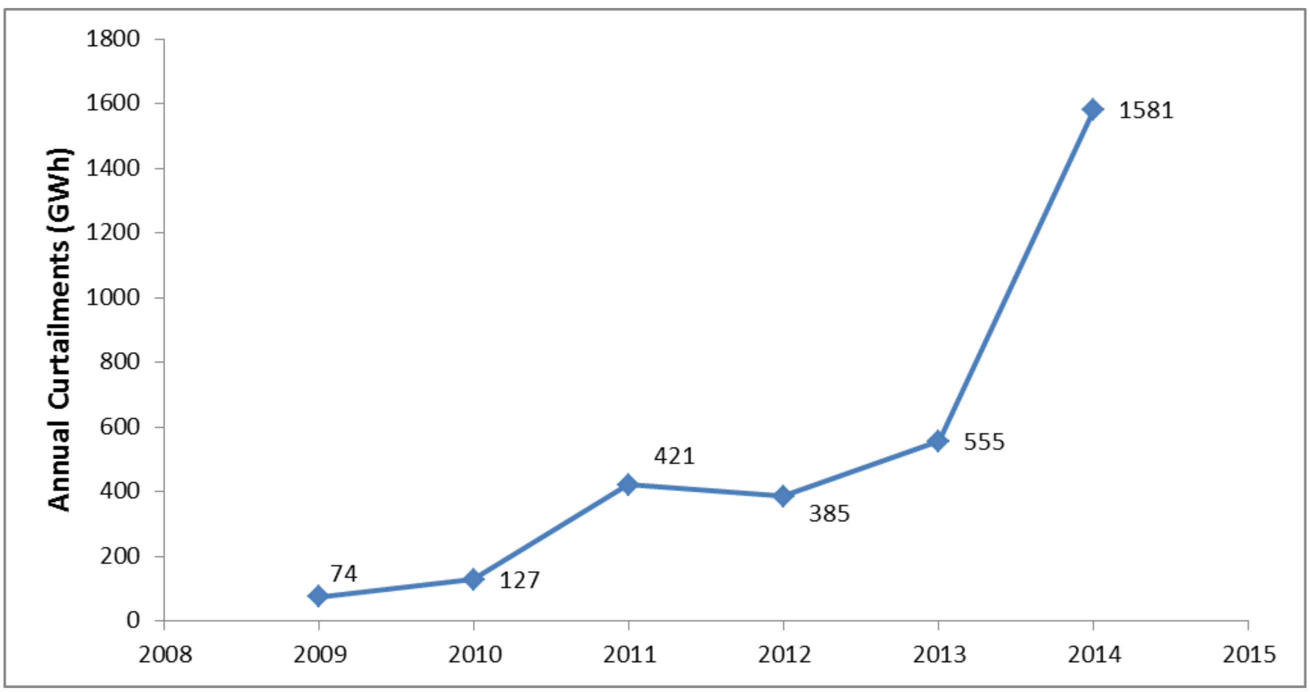
The need for ancillary services in Germany is also changing with the changing resource mix. In particular there is an increasing need for fast response resource to provide balancing over short time periods.[157] Currently most ancillary services in Germany are largely provided by traditional thermal generators and most renewable generators do not have the technical capability to provide these services. For example, in the current system, distributed generation units disconnect automatically when frequency disturbances are detected. Retrofits would be required to enable these resources to provide frequency and voltage control and avoid such disconnections.

3.3.1.5 Curtailment of Renewable Energy

Renewable energy resources receive priority dispatch in Germany and are generally not curtailed for economic reasons. However, curtailment still occurs at the TSO re-dispatch stage in order to maintain reliability in the grid.

shows that there is an increasing trend of renewables curtailment in Germany. Still, the total level of curtailment in 2014 was only 1.16% of the renewables generation, with about equal amounts of curtailment occurring at transmission and distribution levels.[158]

Figure 3.5. Curtailment of Renewable Energy in Germany in GWh, 2009–2014[159]



Curtailment of renewables has increased in Germany since 2009. In 2014 1.16% of renewable generation was curtailed, the majority coming from wind generators.

3.3.2 Responses and/or Proposed Solutions to the Power System Impacts

In this section, we briefly discuss some of the potential solutions to the challenges described above.

3.3.2.1 Transmission Bottlenecks

The Energy Line Expansion Act of 2009 seeks to develop new transmission infrastructure within Germany that will address the transmission bottlenecks in the German power system. It will also develop cross border interconnections to enhance trading opportunities with other countries. Germany is currently a net exporter of electricity in Europe, and prices in the Germany-Austria price zone are typically lower than prices in neighboring Netherlands and France. In 2013, Germany exported 72 TWh of electricity and imported 38 TWh.

There do not appear to be any plans to split Germany into multiple price zones in the day-ahead market, or to break-off Austria into its own price zone. Despite the theoretical advantages of a more locational pricing scheme, it has been argued that splitting the zones in this nature would reduce market liquidity and could lead to market power issues due to the high level of market consolidation in Germany. As a result, increased investments in transmission infrastructure to eliminate inefficiencies caused by internal bottlenecks will likely be an important component of future power sector development in Germany.

3.3.2.2 Compensation for Distributed Resources

The revised Renewable Energy Sources Act of 2014 reiterated the ambitious renewable generation targets that are presented in Table 3.6. It also requires new distributed generators to sell their generation into the market at the prevailing market rate, rather than receiving fixed FITs as they had in the past. However, in the short term, these generators will still receive additional premiums that are funded through renewables charges paid by consumers, and through 2016 these premiums will be calculated so that total compensation is equal to what would have otherwise been obtained through the FITs. Owners and operators of renewable generation are also now responsible for generating production forecasts for their generation resources and procuring their own resources to balance deviations from these projections.

This requirement only applies to units with capacities greater than 100 kW. Therefore individual rooftop solar owners will still qualify for the fixed FITs. As of August 2014, these tariffs for existing units were 8.9 cents/kWh for onshore wind generation and 9.23-13.15 cents/kWh for solar generation. Both of these rates are set to gradually phase down in coming years.[160]

Table 3.6. Feed-in Tariff for Various Renewable Generation Technologies[161]

	FiT Level	Phase Out
Solar PV	9.23-13.15 c/kWh	0.5% reduction per month Further adjustment based on installed capacity
Onshore Wind	8.9 c/kWh (first 5 years) 4.95 c/kWh (thereafter)	0.4% reduction per quarter Further adjustment based on installed capacity
Offshore Wind	15.4 c/kWh (first 12 years) 3.9 c/kWh (thereafter)	Intial FiT to decrease by: •0.5 c/kWh in 2018 •1.0 c/kWh in 2020 •1.0 c/kWh annually thereafter
Hydropower	3.5-12.52 c/kWh	0.5% reduction per year
Biomass	5.83-23.73 c/kWh	1.5% per year for landfill gas, sewage gas and mine gas 0.5% per quarter for biomass

Germany offers very attractive Feed-in Tariffs for renewable generation, which have spurred the growth of renewables over the past decade. Many of these incentives will be phased-out in coming years. All prices are in euro cents.

3.3.2.3 Market Redesign for Renewables Integration

The increase in variable renewable generation in Germany and other European markets led to two key market changes. The first occurred in 2007 and 2008 when the day-ahead and intraday markets were adjusted to enable negative pricing. This provided a firm economic signal of the increased need for flexible resources, as inflexible units would be forced to accept negative prices during periods of excess supply. Second, in 2011 the European intraday market transitioned from hourly to 15 minute time resolution. This action was taken in response to increasingly variable net load profiles caused by high penetrations of renewable generation, which in turn necessitated inefficient intra-hour manual dispatch and reserves balancing.

3.3.2.4 Operating Reserves Redesign

In recent years balancing groups have shown a tendency to rely heavily on the balancing capacity maintained by TSOs in order to resolve system imbalances in their territory. As many as 50-70% of balancing groups have found this to be a cheaper and easier option than balancing their territory internally via the intraday market.[162] This suggests that market incentives were misaligned as it is usually cheaper to procure balancing capacity on the intraday market than in real-time from a system-wide perspective. This current practice also increases the reserve capacity that must be maintained by each TSO and may lead to suboptimal system outcomes and over-reliance on TSO balancing capacity further leads to the risk that there may not be enough capacity available in a given period, potentially resulting is system reliability issues. As a result, the Federal Network Agency, the German government entity that regulates the electric sector, recently overhauled the imbalance settlement system and indexed the balancing fee charged to a balancing group to the spot market. Under this new framework, if more than 80% of nationwide balancing capacity is used in any period, balancing groups must pay the TSOs at least 1.5 times the prevailing spot price for any balancing services they obtain. Additional mechanisms are being explored that would further strengthen the incentives to match supply and demand within each balancing group.

System operators are also considering offering reserves products with higher temporal resolution. Currently, primary reserve capacity is procured weekly in one-day blocks, secondary reserve capacity is procured weekly in only two blocks (peak and off-peak). A concrete proposal to move to daily procurement has been put forth for consideration. The Federal Network Agency will further examine the possibility of instituting a balancing capacity bidding process so that reserves can be procured to match more closely the requirements presented by the presence of increased wind and solar generation.

3.3.2.5 Capacity Market vs. Electricity Market 2.0

There is some concern that the current compensation mechanisms in Germany are largely incompatible with the ambitious goals that have been set forth as part of the Energiewende. Of specific concern is the potential for insufficient long-term investments in the flexible generation resources that are needed to balance out fluctuations in renewable generation.

There is a fundamental debate in Germany, and throughout the world, as to whether appropriate incentives can be provided for flexible generation through an energy-only framework, or alternatively, if capacity markets may be required.[163] Under either approach, investors must be confident that they can recover the fixed costs of a peaking plant that is only dispatched for a small number of hours each year.

The Federal Ministry of Economic Affairs and Energy commissioned several expert analyses of the potential implementation of a capacity market in Germany**Error! Reference source not found.**.[164] The general conclusion of these studies was to advise against capacity market implementation and instead support the development and implementation of an updated energy-only market that can support the established renewable growth targets. This has come to be referred to as Electricity Market 2.0 in Germany.

The studies cited lessons learned from experiences in the United States to suggest that capacity market design is a complex undertaking and can take many years to get right. There are several mismanagement risks as the proper capacity levels are determined, capacity targets that are too high can drive up system costs while targets that are too low can lead to resource shortfalls and an unreliable power system. It has also been emphasized that there is currently excess generation capacity in Germany and no new generators will be required for roughly 10 years. Therefore, the low wholesale electricity prices that have led to unit closures in recent years are generally considered to be economically efficient market outcomes.[h]

Capacity markets provide revenue security by ensuring that generators have a fixed revenue stream regardless of their dispatch schedule. The expert analyses mentioned above outline several important considerations that they propose must be components of any future Electricity Market 2.0 design.

First, it is crucial that there is political and public acceptance of the potential high peak prices that may occur during periods of scarcity. Peaking units rely on relatively few periods of extreme prices to recover their fixed costs. On the surface, regulatory price caps may appear desirable to limit market power and offer consumer protections, but they also reduce incentives for much needed flexible generators to enter the market. There is currently no regulatory price cap in the German market and the commissioned studies suggest that this must remain the case. Retail consumers are typically shielded from such price peaks through average pricing schemes. Consumers that participate directly in the intraday market can also hedge their risk by obtaining forward contracts. The commissioned studies developed projections of future prices in the German power market which forecast that the maximum intraday spot price will not exceed 1,200 Euro/MWh in 2030. They also state that generators must be free to bid above marginal costs, however strong regulators are needed to ensure these generators do not abuse their market power in these instances.[165]

As previously discussed, the balancing responsibility of balancing groups must also be further strengthened.

As numerous separate European power markets are all part of a few European power exchanges, it is also important to strengthen the coordination with neighboring countries. For example, a common European framework could be established to value foreign capacity when developing capacity targets and compensation mechanisms. A variety of different capacity compensation mechanisms have already been implemented throughout Europe, as indicated in

[h] This is in the context of the large subsidies that are provided for renewable generation distorting the competitive market outcome.

Table 3.7, but there is no consensus on the best approach to maintain security of supply in the long run.

The European Commission recently issued a public consultation "to seek stakeholder's views on the issues that may need to be addressed in such a redesign of the European electricity market."[166] The Commission reviewed the 320 public comments that have been received to-date and concluded that there is general–though not unanimous–support for the following policy, regulatory and market design actions: 1) harmonization of public support schemes for renewables and full integration into markets through balancing obligations and discontinuing priority dispatch rules; 2) improved scarcity pricing to better reflect actual supply and demand across both time and geography; 3) maintaining energy-only markets that are potentially complemented by a strategic reserve; 4) establishing a common European Framework for generation adequacy assessment and cross-border adequacy standards; 5) improved dynamic pricing to facilitate demand response; and 6) stronger regional cooperation between TSOs.

Table 3.7. Capacity Compensation Mechanisms that Are Currently Implemented or Under Development in Europe[167]

Active Capacity Market	Capacity Market Being Implemented	Capacity Payments	Capacity Reserve
•United Kingdom	•France	•Greece	•Belgium
	•Italy	•Ireland	•Denmark
	•Hungary	•Portugal	•Finland
		•Spain	•Poland
			•Sweden

The UK operates the only active capacity market in Europe, while several other countries are in the processing of implementing one. Germany and all other European not listed here currently operate energy-only markets.

3.3.3 How Industry Structure Exacerbated/Mitigated Bulk Power System Impacts

It appears that the main driving force for changes in the German generation mix has been the EEG. In particular, its support for distributed and renewable resources in the system has had profound impacts on the operation and planning of the system, as discussed above. However, it is somewhat hard to assess how the more conventional electricity market restructuring efforts have influenced this transition, as these developments to a large extent have occurred in parallel.

The establishment of international power exchanges at the wholesale level has increased competition and contributed to coordinated exchange of energy both within Germany and with neighboring countries. Moreover, a much closer collaboration between TSOs has emerged as part of restructuring efforts, e.g. through balance netting and the joint establishment of a national market for ancillary services. These are all measures that contribute to more efficient integration of renewable resources over larger geographic areas. However, the limited representation of transmission congestion in the market clearing at the power exchanges, which rely on zonal prices (Germany and Austria together form a single zone), increase the need for TSO re-dispatch at the real-time balancing stage, which in turn drives up the cost of integrating variable renewables. The European trend toward flow-based market coupling, i.e., using transmission limits between zones that better reflect the physical flows in the transmission network, does at least partly address the inefficiencies of the zonal market clearing model.[168]

An interesting concept that has emerged in the German and Austrian electricity markets is the concept of balancing groups, as discussed above. This intermediate and decentralized aggregation step between generators, consumers, and the TSO increases the opportunity and incentives for local balancing of resources ahead of real time. In turn, this may favor the development of distributed solutions to the flexibility challenges posed by the rapid increase in renewable resources. Regional aggregation and economies of scale can still be exploited in real time through the joint balancing market operated by the TSOs.

Germany is now at a point in its electricity system evolution where the policies of the Energiewende and the original market restructuring policies intersect and give rise to the current market reforms that aim at efficiently addressing the higher levels of renewable energy in the operation and planning of electricity markets.

3.4 Lessons Learned for Maintaining Reliability and Cost-Effectiveness with a Changing Resource Mix

3.4.1 Implications of Changing Resource Mix on Grid Operations and Planning

Generous support schemes for renewables that were established in the early 2000s have led to a rapid expansion of renewable resources in Germany (most notably wind and solar). This has in turn led to falling power prices in the wholesale market due to the increase in supply and the abundance of renewable generation resources with low marginal costs. However, retail prices for households have risen due to increasing network and renewables support charges. The reduced wholesale prices have caused some of the traditional large utilities to close their thermal generators. As a result, these utilities have begun to consider shifting fundamental business models away from baseload fossil generation toward an enhanced focus on networks, distributed generation and offshore wind operations.

Germany's concrete goals of increasing renewable generation, decreasing emissions, and eliminating nuclear generation have further triggered large investments in distributed renewable generation and led to the emergence of distributed ownership of generation assets. These policy goals have been coupled with market reforms to address the challenges related to planning and operation of power systems with high shares of renewables, with particular focus on finding solutions to support the increasing need for flexibility in the Germany power system.

3.4.2 Implications of Industry Structure on Handling Resource Changes

The fundamental liberalization and restructuring of the Germany electric market that was initiated in 1998 has largely proceeded in parallel with the on-going energy transition (the Energiewende). These market reforms have enabled increased collaboration between TSOs, leading to joint procurement of operating reserves across Germany, and more competition in wholesale markets across Germany and Europe. They have also resulted in closer coordination within Germany and between the countries in the region, as part of the trend toward an integrated European electricity market. The integrated market has also contributed to lowering the cost of integrating renewable resources in Germany and throughout Europe. The rise of distributed generation, especially for solar PV, has led to a fundamental shift in ownership model with small distributed owners and independent consumers now provide roughly half of the renewable generation in Germany. This trend has created operational challenges at the distribution level and has caused many large, traditionally utility companies to rethink their business models and investment strategies.

The German power system has a network of balancing groups that serve as an intermediate aggregator between generators, consumers, power exchanges, and the TSOs. The balancing groups in Germany do not physically balance supply and demand in real-time (in contrast to balancing authorities in the U.S.). However they are responsible for procuring and maintaining balancing capacity reserves for their territory and are subject to financial consequences if imbalances occur that require action by the TSO. This reduces the balancing requirements of the TSOs and in essence provides incentives for decentralized and local balancing and coordination of resources. These balancing groups are playing an increasingly important role as the penetration of distributed, variable renewable generation continues grow in Germany.

3.4.3 Implications for the United States

In many regards the German power system shares several similar attributes with California, as both systems provide strong policy support for renewable energy that has led to the rapid expansion of solar and wind resources. California recently revised their renewables target to 50% of total generation by 2030, which is comparable to the German target of 55-60% by 2035. There are also similarities to Texas and the ERCOT market in terms of relying on an energy-only market with high/no price caps to ensure resource adequacy in the long run. After intensive analysis, Germany appears to have decided that capacity markets are not essential to maintaining long-term resource adequacy in a high-renewable future.

Ongoing market reform initiatives for short-term operations as well as long-term planning focus on the challenges brought about by low/zero fuel cost variable renewable energy. These market reform efforts provide potential solutions for areas of the United States with rapid expansion of renewable energy.

The key focus for ongoing market reforms in Germany is to develop a more flexible power system that will ensure reliability in the presence of very high share of renewable energy. Decentralized technology solutions through distributed resources such as PV, demand response and storage have been, and will continue to be, an important part of the solution in Germany. Germany is considering making investments in inverter retrofits to upgrade aging infrastructure and enable distributed generation resources to provide frequency stability and other short-term balancing services.[169] The German balancing group model demonstrates one approach that can be implemented to aggregate decentralized generation and demand and incentivize local coordination of resource scheduling and balancing, while still taking advantage of wider geographical aggregation effects in the real-time balancing market.

In conclusion, the German example demonstrates that a rapid energy transition can be achieved with strong policy and public support, but also that costs are substantial and must be weighed against benefits.

4.0 Japan Electric Power Case Study

4.1 Key Findings

For over two decades, Japan's power market has continued to restructure, liberalize, and transform Asia's third-largest energy market, resource mix and economy.[170] As Japan's energy landscape has evolved, its grid operations and planning also have undergone major changes. The most recent catalyst to change was the March 2011 disaster at Tokyo Electric Power Co.'s (TEPCO) Fukushima nuclear power plant. Since then, Japan has restarted its power market liberalization process, introducing retail competition, breaking up large vertically integrated utilities, and establishing a nationwide independent system operator (ISO) for electricity supply, transmission and distribution. Japan has also begun transitioning to a lower carbon economy with generous Feed-in Tariffs (FITs) to spur the increased adoption of renewable energy, distributed generation, demand response and energy efficiency programs.[171]

As Japan changes its resource mix, shuttering significant nuclear baseload generation and making plans for a massive influx of distributed renewable energy, grid operations and planning practices for maintaining reliability and cost-effectiveness of its power system continue to evolve.[172] Japan's power sector liberalization is expected to increase competition and grid reliability for residential consumers and help drive retail electricity costs down by about 15%.[173] However, keeping up with rising electricity demand will be challenging. Japan's electricity demand is projected to rise by about 22% to 1,177 billion kWh from 2013 to 2030.[174]

Power sector liberalization has encouraged new market participants, yet there are still barriers to entry. Participants must find their own customers and pay a consignment charge to supply customers through transmission lines owned by regional utilities.[175] Once restructuring is complete, Japan's electricity market will be one of the largest open retail electricity markets in the world. The last phase of restructuring began on April 1, 2016 for electric retail markets and is planned two years later for the wholesale electricity markets. Power companies will spin off their power transmission and distribution operations into separate units. At the moment, 10 vertically integrated electricity power companies (EPCOs) handle all aspects of electricity operations within specified regions.[176]

Japan's responses and proposed solutions for power market restructuring have helped add considerable renewable energy capacity. However, utilities have not added most of the 88 GWs of planned renewable energy capacity that was approved, which is primarily made up of solar, due to concerns over reliability and over-supply.[177,178] As a result, as of April 2015, only about 22 GW were operational.[179] Projects are encountering problems connecting to the grid and selling the electricity to the regional utility firms, slowing the process for solar penetration.[180] In the summer of 2014, solar generation accounted for 10% of supplies.[181] However, a number of challenges remain in realizing Japan's goals of incorporating a higher proportion of variable renewable energy resources.

The United States has already adopted most of the responses suggested for the case study countries in restructuring its power market, albeit in different ways. For example, Japan's recent establishment of the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) created a wholesale power market similar to the Electric Reliability Council of Texas (ERCOT).[182] OCCTO's main functions are to review the EPCOs' supply-demand and grid plans for changes in the plans and order EPCOs to increase power generation and interchange if supply gets tight.[183] As in U.S. ISO markets, utility transmission assets in Japan will be under transaction and scheduling management by OCCTO (the ISO) with open access for generators and retailers.[184]

Japan's rapid closing of nuclear power plants and large additions of variable energy sources may require additional flexible generation such as peaking plants and a capacity market. As the United States makes plans to transition to a lower carbon economy and shutter coal plants, this may provide a valuable case study.

In the aftermath of the Fukushima disaster, Japan updated its Feed-in Tariff program, modeled after Germany's program, to spur the adoption of clean energy sources. The attractive Feed-in Tariff encouraged over investment and contributed to increased electricity prices.[185] Even after a consumption tax is subtracted, Japanese consumers pay the highest rates in world for solar power at 30 to 35¢(US)/kWh; considerably higher than the 18¢(US)/kWh consumers pay in the UK, the world's second highest rate for solar power.[186] In response to rapidly rising electricity costs and challenges to integrating solar power into their grid, the government made plans to slow down the expansion of solar power.[187]

Table 4.1 provides key characteristics of the size of the Japanese electricity system in capacity load, and generation. Table 4.2 provides the restructured market context for the challenges associated with increasing renewables in a restructured system.

Table 4.1. Key Characteristics of Electricity Generation in the Japan

Size of Power System	Capacity (GW)	2013	293[188]
	Load (GW)		
	Generation (TWh)	2013	950[189]
Generation Contribution from Variable Renewables	% of total energy generation	2000	2.3%[190]
		2010	3.5%[191]
		2013	<4% OR 42 TWh[192]
Mechanism for Renewable Promotion		FIT	43¢/kWh solar for residential (10 years) and commercial, industrial and utility scale generation (20 years)[193]
		Renewable Energy Credits	
		Contract for Difference	
		Other	
Proposed or Enacted Policies to Address the Following Issue:	Technical issues	Interconnection permitting	Current barrier is consignment charge to utilities[194]
		Two different frequencies on two separate grids.	Japan has plans in place to establish a national grid to address supply security and inefficiencies caused by a divided grid running on two frequencies,[195]
		Over-generation	
	Markets	Incentives	
		Misalignment	

	RE goals or binding targets	20% by 2020
Goals/targets	Key drivers for RE penetration	A key driver for solar has been the Japanese FIT, which pays a premium of 42 yen (about 43 cents) for every kWh of electricity that solar owners send to the grid for projects permitted in the first year of the FIT.[196]

The table discusses key characteristics of the Japan electricity industry indicating the system generation, load and capacity. The table also highlights mechanisms for incentivizing renewables and low carbon generation as well as the over-arching issues and solutions.

Table 4.2. Summary of Electricity Market Structure for Japan

Generation	Ownership	Mix of independent power producers and vertically integrated utilities[197]
	Resource adequacy mechanism	10 big EPCOs committed to provide all capacity except for adequate reserve margin into JEPX,[198] Japan is proposing a capacity mechanism[199]
System Operation	Balancing	Independent system operator (ISO) for electricity supply, transmission and distribution[200]
	Market Operator	Organization for Cross-regional Coordination of Transmission Operators (OCCTO)[201] main functions are to review EPCO's supply-demand and grid plans for changes in the plans and order EPCOs to increase power generation and interchange if supply gets tight.[202]
		Japan Electric Power eXchange (JEPX), the primary exchange for electricity and its support body for transmission in wider areas, improved regulation of third party access to grid lines, and introduced separation of transmission and distribution sector.[203]
	Energy Market	Single price
Transmission	Ownership	Vertically integrated utility ownership. Independent power producers must pay a consignment charge to supply customers through transmission lines owned by regional utilities.[204]
	Operator	Independent system operator (ISO) for electricity supply, transmission and distribution[205]
Distribution	Ownership	Vertically integrated utility ownership[206]
Retail	Retailers	Independent power suppliers and vertically integrated utilities. Government regulation of third party access to grid lines[207]
	Demand Response	
	Retail Choice	Retail competition for industrial market (50kW to 2,000kW)[208]

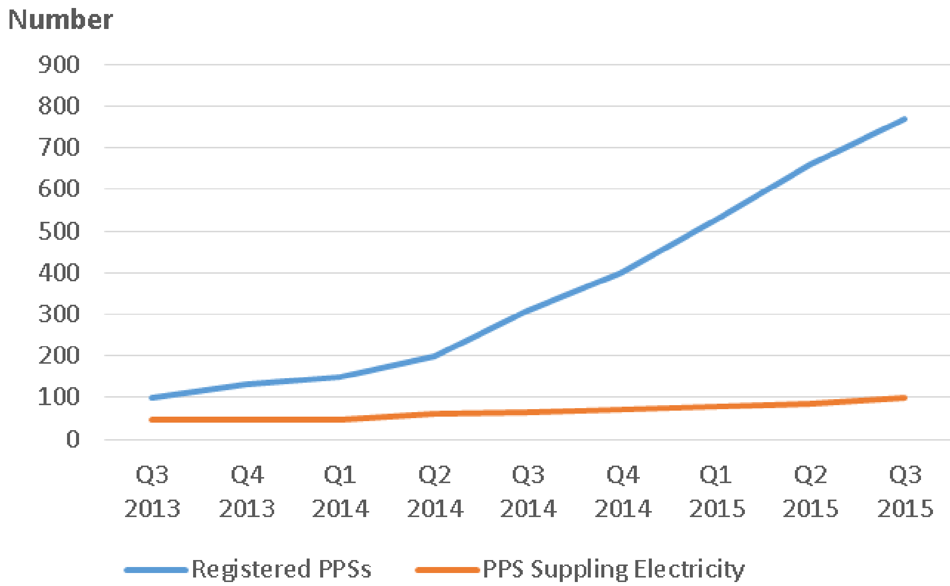
The table discusses the market structure for the Japanese electricity industry indicating ownership of generation, transmission, distribution and retail. The table also indicates the primary pricing mechanisms available to provide market signals to consumers and generators.

4.2 Regulatory and Policy Background

4.2.1 Overview of Industry Structure and Policies prior to Restructuring

Japan's electricity industry structure prior to the beginning of liberalization in 1995 was dominated by regional utilities that controlled generation, transmission, distribution and retail supply. The utilities essentially provided services to customers as monopolies in each region.[209] After restructuring began, Japan's industry structure and policies were dominated by TEPCO, the country's largest vertically integrated power utility, as well as the other nine regional utilities.[210,211] As a result of the ongoing market liberalization and restructuring, TEPCO faces new competition from at least 100 companies that have registered to sell electricity in the prior to Japan's retail power market liberalization in April 2016.[212] When markets opened to competition, over 750 applicants registered to be power producers and suppliers in Japan (see Figure 4.1). However, fewer than 100 of them are supplying power to the industrial market that was already deregulated. Small suppliers have doubled their share over the last three years, but still only account for about 5% of Japan's supply.[213]

Figure 4.1. Japan Power Suppliers Surges Ahead of Liberalization.[214]



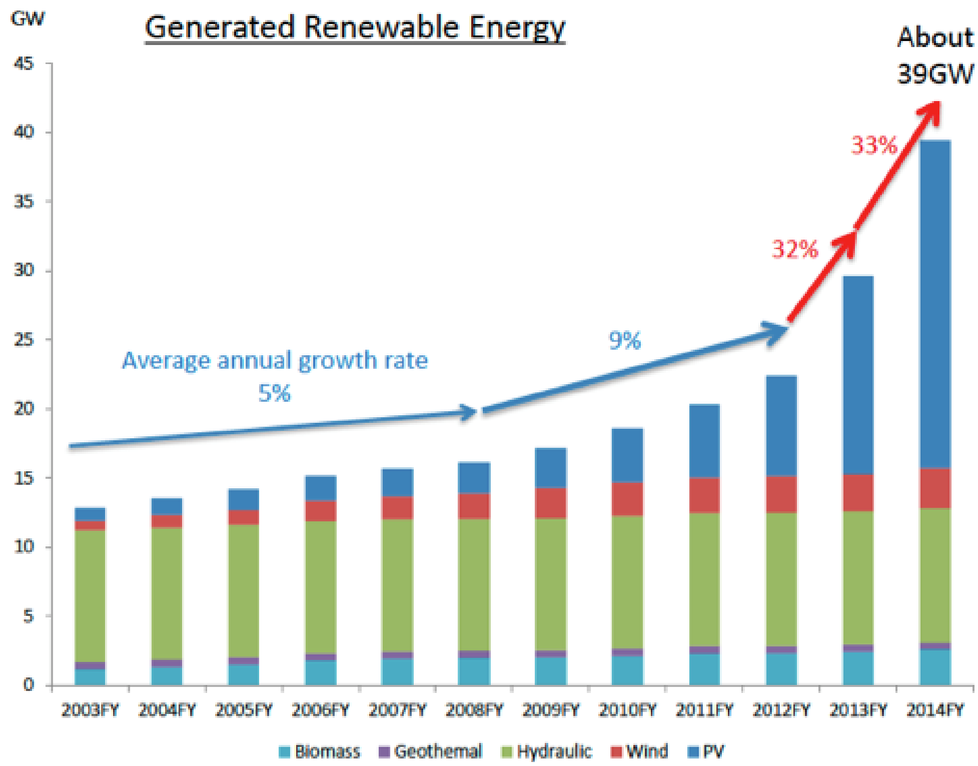
This figure highlights the rapid increase in power supplier competition that precipitated ongoing power market reforms. Note the large differential in registered power producers and suppliers (PPSs) and the number actually supplying electricity.

4.2.2 Evolution of Resource Mix

Japan's energy mix is rapidly changing (see Figure 4.2). Political leadership continues to be an influential factor. Japan shut down its 50 nuclear reactors following the Fukushima disaster tragedy, which supplied about a third of the country's power.[215] In 2012, Prime Minister Shinzo Abe was elected and reversed the nuclear moratorium with plans for Japan's energy mix to be made up of 20% nuclear power and 20% renewable energy by 2030.[216] However, Japan's new clean and nuclear energy goals may be ambitious due to strict nuclear safety requirements and competition from 41 new coal-fired power plants planned to be built in the next decade to help lower electricity costs.[217] Nuclear provided less than 1% of total generation in 2014[218] (see Figure 4.3).

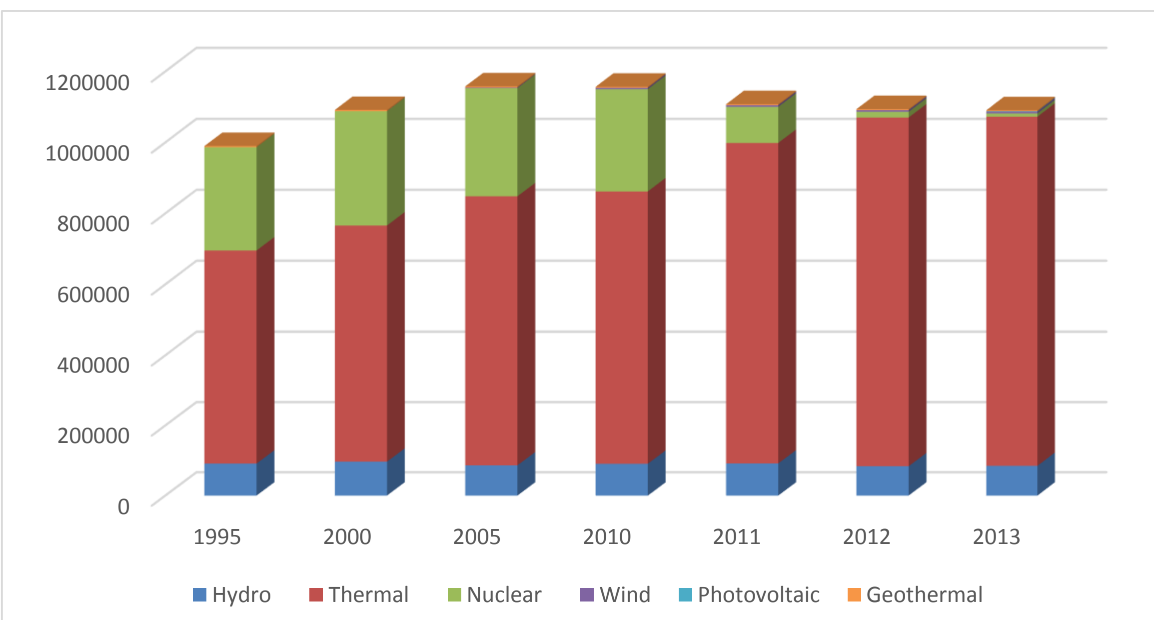
In the aftermath of the Fukushima disaster, Japan updated its Feed-in Tariff program, modeled after Germany's program, to spur the adoption of clean energy sources. The attractive feed-in-tariff encouraged investment and increased electricity prices. Even after a consumption tax is subtracted, at 30-35¢/kWh (US), Japanese consumers pay the highest rates in world for solar power; considerably higher than the 18¢/kWh consumers pay in the UK, the world's second highest rate for solar power.[219] While the FIT has increased the amount of electricity generated from renewable sources, its share of the total power supply remains small. At the end of March 2015, the amount of electricity generated from renewable sources grew 1.9 times from before the FIT system was introduced to 12% of total generation in fiscal 2014; hydro accounted for 9% and other renewables 3%.[220] Solar power accounts for 96% of variable renewable energy electricity produced in the first three years since the tariff was introduced. Utilities were required to buy electricity from solar power suppliers at high prices and large numbers of businesses sought certification as power suppliers. Yet fewer than 30% of the certified solar power-generation facilities have so far gone into operation due to access issues. Ministry of Economy, Trade and Industry (METI) recently announced that certification for the operators may be revoked if businesses fail to install and start operating solar panels.[221]

Figure 4.2. Generation Capacity of Renewable Energy[222]



This figure highlights installed capacity of renewable energy by resource type in Japan.

Figure 4.3. Evolution of Japanese Electricity Resource Mix (millions kWh)[223]



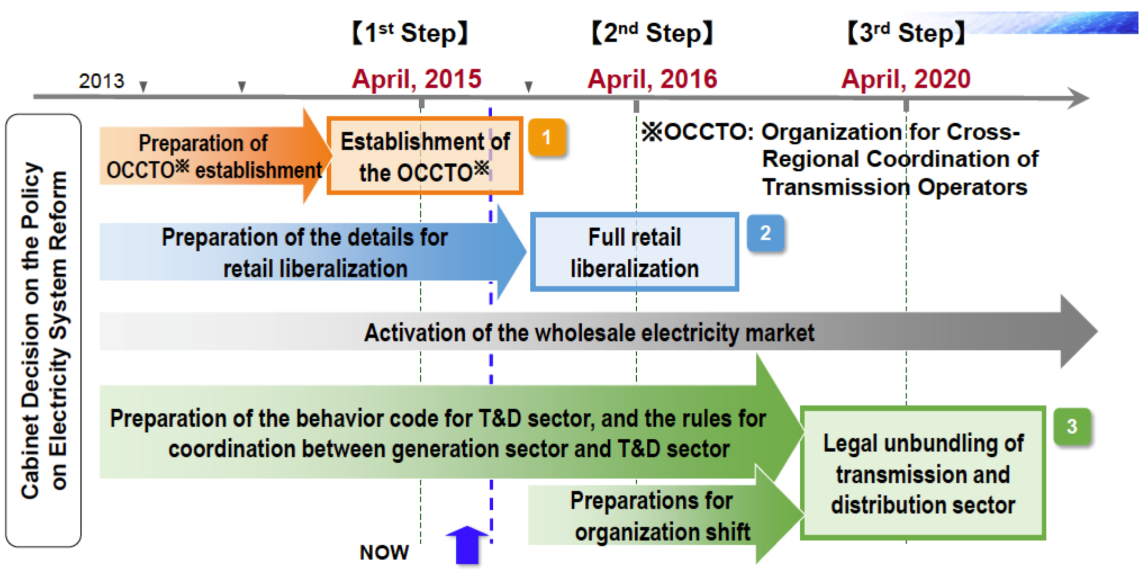
This graphic shows the decline in nuclear power after the 2011 Fukushima accident and its replacement with thermal generation. Note hydro remains fairly constant.

4.2.3 Key Restructuring Policies Affecting Power Grid Operations, Planning and Generation Mix

Japan's most significant electricity market reforms started in 1995, enabling independent power producer (IPP) to provide wholesale electricity services.[224] In 2000, Japan introduced retail competition for the industrial market (over 2,000kW) and regulation of third-party access to the power grid.[225] In 2004, customers with demand over 500 kW were also allowed to choose their supplier followed by customers with demand over 50 kW in 2005.[226] Also in 2005, Japan established the Japan Electric Power eXchange (JEPX), the primary exchange for wholesale electricity and its support body for transmission in wider areas, improved regulation of third-party access to the power grid, and introduced separation of transmission and distribution sector.[227] In 2008, Japan modified wheeling rate rules.[228] Japan is in the process of restructuring now and has plans out to 2020. Japan's current Power System Reform Program is being planned in three major restructuring steps that are transforming that nation's power grid operations, planning and generation mix (see Figure 4.4). [229]

Step 1. Establishment of the Organization for Cross-regional Coordination of Transmission Operators (OCCTO): In November 2013, Japan established the Organization for Cross-regional Coordination of Transmission Operators (OCCTO), which is similar to the U.S. Independent System Operator (ISO).[230] OCCTO became operational in April 2015.[231] OCCTO is responsible for reviewing grid plans and balancing supply and demand. OCCTO has the authority to order EPCO's to increase power generation and interchange when supply is needed (see Figure 4.5).[232]

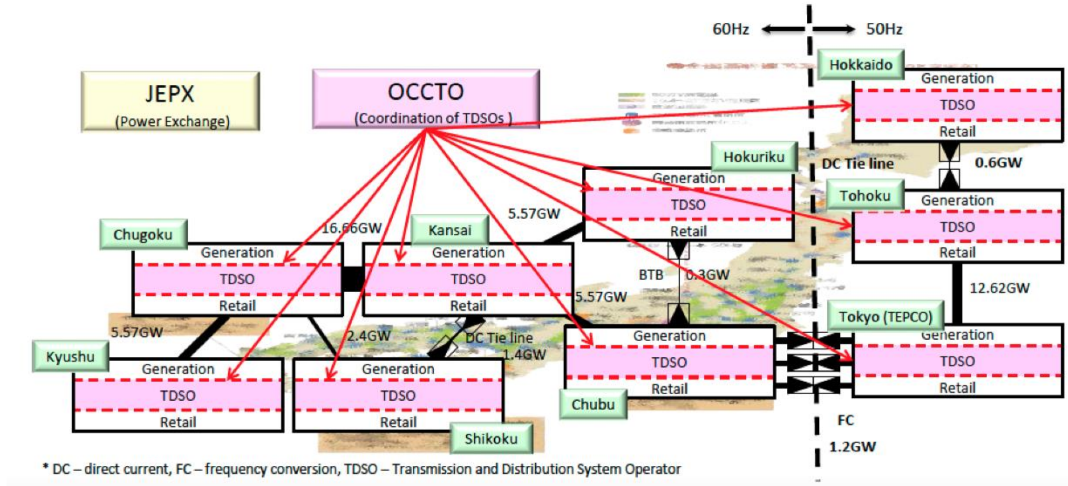
Figure 4.4. Japan's Three Restructuring Steps[233]



This figure highlights Japan's three major restructuring steps: 1) Establishment of the Organization for Cross-regional Coordination of Transmission Operators (OCCTO); 2) Full Retail Liberalization; and, 3) Legal unbundling of transmission and distribution sector from power generation.

Step 2. Full Retail Liberalization: The second reform aimed at creating full retail competition passed in May 2014. This reform mandates that all classes of customers (residential, commercial and industrial) be open for competition in 2016. The reform expands retail competition for users under 50 kW in 2016, and maintains regulation of the retail tariff on the incumbent 10 big EPCOs until 2020.[234]

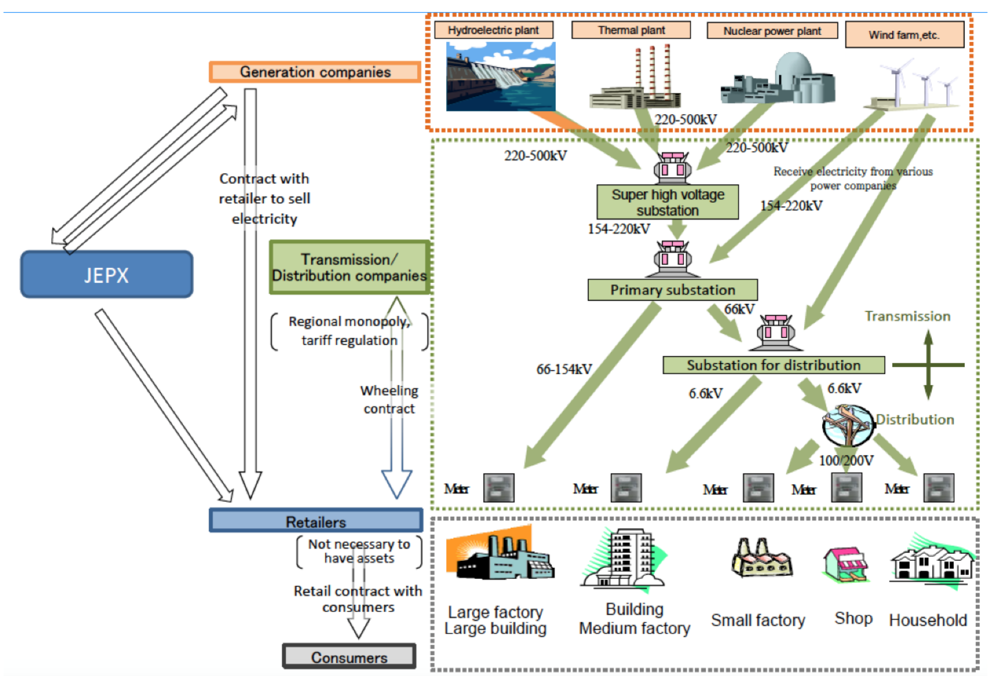
Figure 4.5. Organization for Cross-Regional Coordination of Transmission Operators[235]



This figure highlights OCCTO's coordination of Japan's Transmission and Distribution System Operators (TDSOs).

Step 3. Legal unbundling of transmission and distribution sector from power generation: A third reform aims to separate generation from transmission and distribution and end utility retail tariffs in 2020. Japan's 10 large vertically integrated utilities will be broken up into four different businesses, including transmission, distribution, generation and a holding company.[236] Retailers and generators will operate in a competitive market and transactions and scheduling will be managed by OCCTO[237] (see Figure 4.6). When the reforms are completed in 2020, the Japanese electric system will mirror ERCOT.[238] However, should Japan elect to introduce a capacity market, it will look more like PJM or ISO New England.

Figure 4.6. The Future Design of Japan's Electricity Market[239]



This figure highlights the future design of Japan's electricity market after the OCCTO, opening retail competition and unbundling transmission and distribution sector from power generation.

Policies Driving Resource Change. In July 2012, the government updated its Feed-in Tariff that is guaranteed for a 20-year period.[240] The tariff requires major power companies to purchase electricity generated by solar, wind, geothermal, biomass and medium- to small-scale hydro power at fixed prices - initially 38¢ (US)/kWh for large projects, which declines in later years.[241] The tariff is funded by a surcharge on electricity bills.[242]

4.2.4 Key Drivers of Restructuring

Japan's goals for restructuring are to secure stable energy supply and transition to a lower-carbon energy mix while increasing competition to lower electricity prices. One of the key drivers for restructuring was the Fukushima nuclear disaster, which led the government to shutter the majority of its nuclear plants and increasingly rely on coal and LNG imports. Japan is one of the world's largest importers of LNG, coal, crude oil and oil products. Japan introduced a new version of the renewable energy Feed-in Tariff to transition to a lower carbon economy, reduce its reliance on fossil fuel imports and increase the amount of renewable energy its mix. Retail liberalization and unbundling of generation, transmission, distribution and retail supply will drive increased competition and may help reduce electricity prices.[243]

4.2.5 Electric Power Sector Market Structure

Japan remains as one of the few developed economies where regional utilities have a monopoly for power supply.[244] Japan's electrical grid capacity, intra-regional transmission and market structure continue to be additional barriers to market growth and efficiency.[245] These barriers are expected to be removed by 2020 with completion of restructuring.

Generation. Generation is a mix of competitive and non-competitive suppliers. Ten vertically integrated utilities, one from each region provide most generation. In addition, there are several wholesale generators, municipal utilities and one large wholesale generator, J-Power, providing generation capacity. Until the Fukushima disaster, nuclear power represented about 27% of the power generation.[246]

Transmission and Distribution. Transmission is largely owned and operated by the 10 large utilities. The Organization for Cross-regional Coordination of Transmission Operations' (OCCTO) makes determinations associated with access. The transmission system has a 50 Hz system in in the eastern part of Japan and a 60 Hz system in the western. Japan's interconnection capacity is 1.2 GW Under the Electricity Business Act, the 10 utilities are required to unbundle their transmission and distribution from supply and generation. Thus, tariffs for transmission and distribution will be managed as regulated monopolies. [247] Legal unbundling of transmission and distribution will not occur until 2020.[248]

Retail. Retail competition has been open to customers with demand greater than or equal to 50 kW. This group of customers' accounts for 62% of load. However, only 2% chose someone other than one of the 10 utilities that distributed electricity regionally. Almost no one outside of Tokyo and Kansai shifted suppliers. [249] Market liberalization plans include efforts to establish a switching support system. Under this scheme, new retailers can obtain the information necessary on customers for switching retailers. The information is standardized from transmission and distribution system operators (TDSOs) throughout the system. The new retailer will be able to complete a switching process including changing a wheeling contract between retailers and TDSOs throughout the system.[250,251] As of April 1, 2016, all levels of retail demand are open to full competition.

Wholesale markets. There is only one wholesale market in Japan, the JEPX. The market is transparent but limited. [252] Japan's power sector liberalization is improving liquidity in the wholesale market. Since

March 2013, the 10 big EPCOs committed to provide all capacity except reserve margins into JEPX.[253] OCCTO can order EPCOs to increase power generation and interchange if supply gets tight.[254]

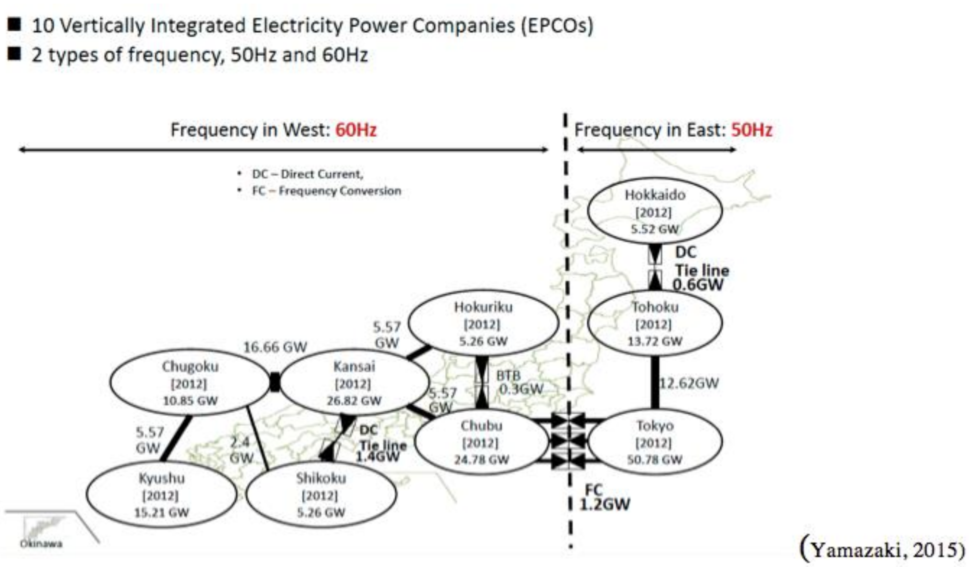
4.3 Grid Operations and Planning: Challenges, Responses, and Proposed Solutions

4.3.1 Challenges to the Bulk Power System due to Changes in Resource Mix over Time

Japan's rapid adoption of renewable energy systems could cause destabilization of grid voltages and frequencies that require updates to the electricity infrastructure. Another challenge is the intermittency of wind and solar additions that require flexible generation for their use to maintain frequency and required ramps. The biggest challenge to Japan's bulk power system is the closing of a significant portion of the country's nuclear generation. Currently, primary energy and electricity production in 2030 will continue to rely predominantly on fossil fuels, according to the Ministry of Economy, Trade and Industry (METI).[255] In 2030, oil, coal and LNG are projected to provide 56-58% of the electricity generation. Renewables will comprise 22–24% and nuclear power 20–22%. Nuclear comprised about 30% before the Fukushima disaster.[256]

Japan's grid has two different frequencies (60Hz in the West and 50Hz in the East) which limits the transmission of electricity to different regions, and thus limits Japan's ability to compensate for supply shortfalls across the interconnect. The grid's frequency conversion stations have a small aggregate capacity of 1.2 GW, limiting power exchange between regions and preventing wide-area averaging of renewable energy contributions.[257] Figure 4.7 highlights Japan's interconnection capacities and divided grid.

Figure 4.7. Reliability Challenges Due to Differences in Japan's Transmission Frequency[258]



This figure highlights that the eastern sector of Japan operates its transmission at 50 hertz while the western operates at 60 hertz. This divide creates significant reliability challenges in the Japanese market. Until transmission issues are solved, it will be challenging to import generation from the East to serve customers in the West.

There is also a lack of competition, hence strong price controls are in place. An examination of how the retail market shares of various operators changed during restructuring highlights that the ten main electric power companies have been able to maintain a market share of 70 to 80 % of the market since the electricity liberalization. However, new market entrants helped reduce electricity prices.[259] While no reason was given, Japan also sees variable renewable resources as a challenge to maintaining a stable grid system. They also see the future of nuclear generation in their future mix as a challenge given the cost of nuclear in a competitive generation market.[260]

4.3.2 Responses and/or Proposed Solutions to the Power System Impacts

To increase cross regional competition, market analysts have recommended that Japan integrate markets and reduce line congestion of tie lines through the Organization for Cross-regional Coordination of Transmission Operations' (OCCTO) function by reinforcing their capacities. Another suggestion is to maintain the "postage stamp" cost allocation scheme for network fee, even after introducing full retail competition.[261]

Solar is growing much faster than wind generation due to a 42 yen/kWh (about 39¢(US)/kWh premium for projects permitted in the first year of the tariff.[262] A key driver for solar has been the Japanese FIT. Solar penetration is increasing much faster than other renewables. The FIT is guaranteed to residential buyers for 10 years and to commercial, industrial and utility-scale installations for 20 years.[263] Japan's Feed-in-tariff helped add about 22 GWs of renewable energy capacity. An additional 82 GW of PV projects are in the queue. The 2030 goal calls for between 92 GW and 94 GW of renewable resources.[264] The rapid rate of variable renewable energy additions combined with the closing of significant nuclear baseload generation may require more flexible generation to support stable grid operations. Japan is investigating whether a capacity payment may be required to maintain flexible resource capacity. Japan is also evaluating approaches to mitigate the risks associated with nuclear investments.[265]

In response to rapidly rising electricity costs and challenges integrating solar power into their grid, the government made plans to slow down the expansion of solar power.[266] In January 2016, METI announced plans to revise the law governing the FIT to achieve a cost-effective expansion of renewable energy use and hold down the financial burden on consumers. METI's new plans emphasize efficiency. Opponents of the tariff revision fear that the FIT revision will discourage potential renewable energy producers from entering the market or force out community-based small-scale operators.[267]

METI is also considering introduction of a bidding system in which prospective renewable power producers submit tenders – in place of the current system of setting fixed prices – in order to reduce the burden of high electricity bills on consumers. Under the new bidding system for solar power facility operators, priority will be given to those who offer their electricity at the cheapest prices. There will be a limit to the total cost of purchasing the power. For long-lead time renewable energy sources such as wind and geothermal power, a system of advanced fixed purchase prices for prospective operators over several years will be introduced.[268] Critics of the new bidding system warn that market uncertainties such as future price trends may curtail investment in renewable electricity generation.[269]

4.3.3 How Industry Structure Exacerbated/Mitigated Bulk Power System Impacts

Japan's monopolistic regional structure has limited its ability to make substantial progress on the introduction of renewables.[270] Japan's grids are still monopolized and some utilities have blocked access, arguing solar supply is unreliable - a claim being reviewed by the Ministry of Economy, Trade and Industry. Exacerbating this challenge, Japan's utilities have transmission access and demand limits for interconnection.[271] There are plans to change this inefficiency when OCCTO is established as the ISO. Continued high growth of renewables creates some grid operations and planning challenges.[272]

4.4 Lessons Learned for Maintaining Reliability and Cost-Effectiveness with a Changing Resource Mix

4.4.1 Implications of Changing Resource Mix on Grid Operations and Planning

Japan's restructuring is ongoing since 1995 and is not scheduled to be complete until 2020. Thus, understanding the lessons they will learn associated with a completely restructured economy requires additional time. However, they are in the process of moving to renewables while the restructuring is underway.

4.4.2 Implications of Industry Structure on Handling Resource Changes

Japan's utilities are hampering entry to the grid by solar power producers as they are running into challenges integrating large increases of solar power.[273] Utility industry push back comes after almost $30 billion on solar energy was installed in a single year, almost as many panels as exist in Spain.[274] Power exchange from the east to serve customers in the west will be limited until issues associated with Japan's two frequency grid are resolved.[275,276]

4.4.3 Implications for the United States

Japan's market liberalization has just started and is an ongoing process. The lessons learned from the introduction of solar may provide insights to the United States as Japan encounters challenges associated with rising electricity costs, maintaining frequency and meeting steep demand ramps associated with a large influx of solar and other variable renewable energy sources. A similar pattern can be seen in the U.S, where electricity prices in more than 11 states increased four times faster after deregulation than before, when comparing U.S. electricity prices, according to a study published in the International Journal of Energy Economics and Policy.[277]

In January 2016, METI announced plans to reform its Feed-in Tariff, increasing its emphasis on energy efficiency measures to lower costs for consumers.[278] Opponents of the tariff revision fear this may deter new renewable energy producers and force out small operators.[279] Previously, U.S. investments in renewable energy have waned when the government suggested reducing incentives from the renewable portfolio standard.

Lastly, the drawn out drawn-out process of restructuring the electricity industry in Japan provides an example of how partial liberalization can impede the penetration of low carbon electricity generation. When the electricity market is effectively restructured, can competition drive down prices and open the market to innovative solutions to power grid challenges.

5.0 United Kingdom Electric Power Case Study

5.1 Key Findings

The Energy Market Reform (The Energy Act of 2013) provides additional restructuring of the UK electricity sector. The current vertically integrated and somewhat concentrated industry structure along with opaque-bilateral trading led the UK regulator, Office of Gas and Electricity Markets (Ofgem), to add market rules to provide more transparency and liquidity to the wholesale markets in an effort to improve market signals for investment and thus for long-term resource adequacy and reliability.

The major challenges facing the UK electricity sector is the increasing amount of wind generation in the resource mix and the near-zero marginal costs of production along with a lack of nodal pricing. The near-zero marginal costs may not provide adequate market signals to flexible generation to maintain capacity to meet demand in the medium to long run. Additionally, the lack of nodal pricing does not signal producers that regional over-capacity exists, and thus capacity continues to be built in those regions. The Contract for Difference introduced in 2013 is likely to exacerbate the low/zero fuel cost problem as it provides for a subsidy to make up the difference between the cost of production for wind and nuclear and the market price of electricity, removing the effects of market price signals.

In response to the inadequate long-term market signals provided by wind and solar, the UK instituted a capacity market in 2014 and announced reforms in 2016 to assure both long-term and near-term capacity. There may be problems with meeting flexible capacity needs in 2018/19 because the transmission system operator (TSO) and the regulator may have substantially under-forecast long-term demand. The TSO assumed continued efficiency improvements in demand which if they do not occur will mean more capacity is needed. In addition, with aging capacity to be shut down, the UK may not have adequate supply to meet demand. On the other hand, administratively-driven capacity markets have incentives to over-forecast demand because the TSO and Ofgem do not want any reliability issues. The UK government is looking at nodal pricing, but has not yet committed to nodal pricing. They have committed to investing in transmission to provide added capacity to reduce the current transmission constraint.

Most of the responses have already been implemented in different ways in the United States. Two points may be of use to U.S. policy. First, a changing resource mix requires constantly fine tuning the markets and market structures to fix issues that arise because of the non-storable nature of electricity. Second, there may be better solutions to the near-zero marginal cost of variable resources than the capacity market such as a combination of forward markets and real-time markets for energy.

Table 5.1 provides key characteristics of the size of the UK electricity system in capacity load, and generation. The table also indicates the mechanisms for renewable energy resource promotion along with the technical and market issues associated with market restructuring and increasing variable generation. Table 5.2 provides the restructured market context for the challenges associated with increasing renewables in a restructured system.

Table 5.1. Key Characteristics of Electricity Generation in the United Kingdom

Size of Power System[280]	Capacity (GW)	2014	77
	Load (GW)	2014	54
	Generation (TWh)	2014	322
Generation Contribution from Variable Renewables[281]	% of total generation	2000	2
		2010	4
		2014	13
Mechanism for Renewable Promotion		FIT	Yes[282]
		Renewable Energy Credits	Carbon markets[283]
		Contract for Difference	Yes[284]
		Other	Renewable Obligation Certificates (ROCs)[285]
Proposed or Enacted Policies to Address the Following Issue:	Technical issues	Interconnection permitting	Connect and Manage[286]
		Over-generation	Payment for curtailment,[287] Increased transmission investment[288]
	Markets	Incentives	
		Misalignment	Capacity Markets[289]
	Goals/targets	RE goals or binding targets	15% by 2020[290]
		key drivers for RE penetration	ROC, FIT, Meeting 2020 targets[291]

The table discusses key characteristics of the UK electricity industry indicating the system generation, load and capacity. The table also highlights mechanisms for incentivizing renewables and low-carbon generation as well as the over-arching issues and solutions.

Table 5.2. Summary of Electricity Market Structure for the United Kingdom

Generation	Ownership	Completely privately owned. [292]
	Resource adequacy mechanism	Capacity markets[293]; Long-term bilateral contracts[294]
System Operation	Balancing	National Grid, transmission system operator[295]
	Market Operator	National Grid operates balancing market and capacity market[296]
	Energy Market	Bilateral contracts are primary mechanism;[297] Single price system wide for balancing market;[298] Day-ahead and half-hour day-ahead on the APX Exchange;[299]
Transmission	Ownership	Independently owned[300]
	Operator	Independent system operator[301]
Distribution	Ownership	Several private companies[302]
Retail	Retailers	Open access to all retail suppliers, but may include distribution network operator in the retail competition[303]
	Demand Response	Demand response allowed in balancing market;[304] Allowed in capacity market[305]
	Retail Choice	All allowed; Largest 6 companies feed 95% of customers[306]

The table discusses the market structure for the UK electricity industry indicating ownership of generation, transmission, distribution and retail. The table also indicates the primary pricing mechanisms available to provide market signals to consumers and generators.

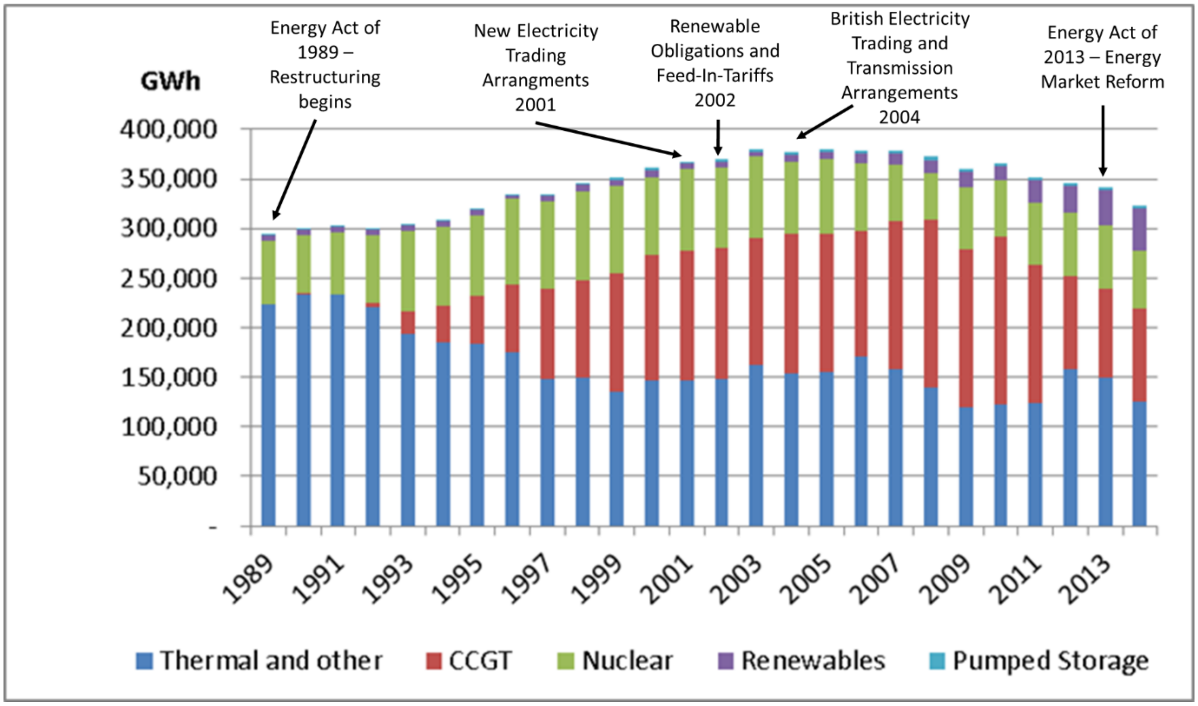
5.2 Regulatory and Policy Background

5.2.1 Evolution of Resource Mix

The UK's electricity mix has not really changed in terms of the ability to provide firm power. The addition of natural gas began in 1991 with enactment of a law allowing its use in electricity generation and then peaked in 2010. Gas-fired generation increased due primarily to the abundance of natural gas associated with North Sea drilling. Rising natural gas costs have decreased its use since 2010 (see

Figure 5.1).[307] Non-thermal renewables (wind, hydro and solar generation) followed a pretty level trajectory at between 5 and 6 terawatt-hours (TWh) until 2002 when the wind generation began to increase. By 2014 non-thermal renewables reached 42 TWh or approximately 13% of net generation primarily due to increases in wind capacity. Total renewables generation reached 64.7 TWh or approximately 19% of total generation.[308] Variable renewable energy capacity reached just more than 18 GW or approximately 24% of capacity (see Figure 5.2). [309,310]

Figure 5.1. The UK Changing Resource Generation and Policy Implementation from 1989 to 2014[311]

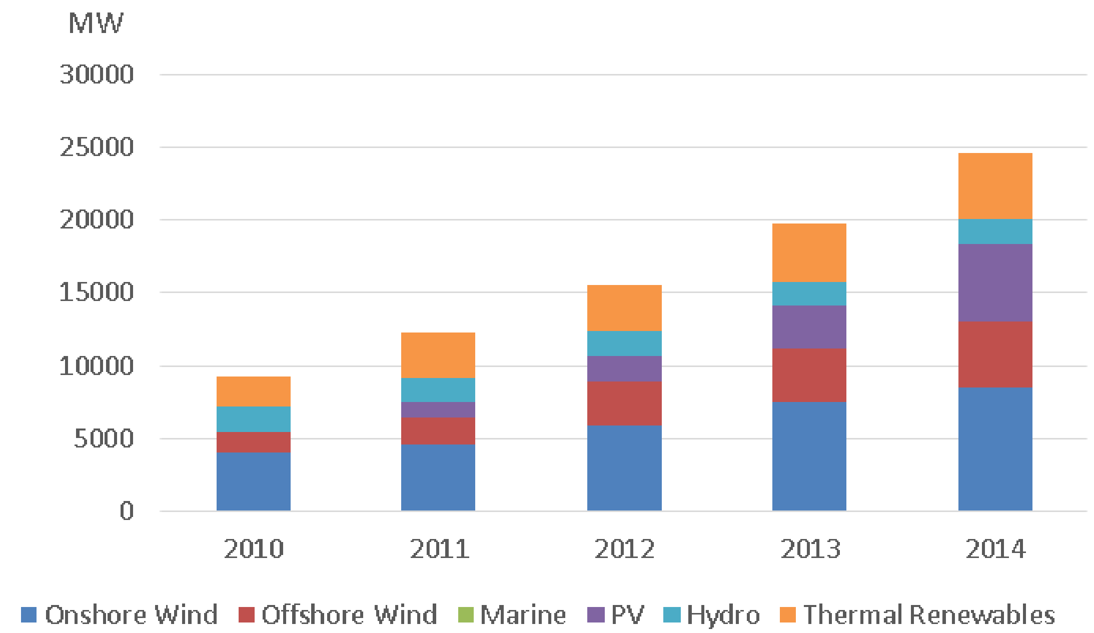


This figure illustrates the UK's changing resource generation from the beginning of privatization until the most recent data from the UK government. Note the decrease in coal- and nuclear- produced electricity and the replacement with natural gas. Note the relatively small amount of wind-generated electricity, which is a large share of the renewable's category. Thermal and other refers to conventional thermal using fossil fuels and steam turbines and other including combined heat and power, Renewables refers to non-thermal renewables such as hydro, wind and photovoltaics. The graphic also highlights major policy enactment associated with restructuring and climate change policy. The Energy Act of 1989 provided the framework for privatization.[312] The Renewable Obligations and FITs were instituted in 2002.[313] The Electricity Pool was replaced by the New Electricity Trading Arrangements in 2001 and in turn was replaced by the British Electricity Trading and Transmission Arrangements in 2004.[314] The Energy Act of 2013 changed policy from Renewable Obligations to Contract for Differences and instituted market reform to assure energy security with capacity markets.[315]

Nuclear generation declined from a high 31% in 1998 to 20% in 2014. Combined Cycle Gas Turbines (CCGT) generation declined from a high of 58% of net generation in 2010 to 32% in 2014.[316] Coal generation initially declined as natural gas rose. However, the decrease continued as the EU Large Combustion Plant Directive called for reduced particulate, SO_X and NO_X pollution. The directive called for large combustion plants to retrofit; opt out after 20,000 hours and before December 31, 2015; or close before January 1, 2008. The original opt out reduced coal generation capacity by 8 GW. Two plants converted to biomass. Only one plant remains and will close at the end of 2015.[317]

Following the worldwide recession, the UK demand for electricity has declined and natural gas generation with it.[318] In a policy paper presented to parliament in 2015, the Secretary of State declared the need for natural gas to meet carbon goals and believes that most of the growth in natural gas generation will occur during the next decade. In the same document, she also indicates that the UK will invest in nuclear capacity to meet carbon reduction goals.[319]

Figure 5.2. The UK Renewable Electricity Capacity 2010 to 2014[320]



This figure illustrates the UK's changing renewable resource mix from a breakdown of capacity. Wind reached 17% of capacity and PV have reached just more than 7% of capacity at just more than 18 thousand MW.

5.2.2 Key Restructuring Policies Affecting Power Grid Operations, Planning and Generation Mix

5.2.2.1 Overview of Industry Structure and Policies prior to Restructuring

The electricity sector was brought under government control in The Electricity Act of 1947. In 1957, the UK government established two bodies to control all generation, transmission and distribution. The sector was governed by the Central Electricity Generating Board (CEGB) and the Electricity Council. Most electricity was produced by the CEGB as it owned and operated almost all generation assets. The CEGB also owned and operated the transmission system. The UK distribution system was divided among 12 area boards that purchased most electricity from the CEGB. Restructuring began with the Energy Act of 1989, when the sector was privatized. Distribution and transmission were privatized but regulated as monopolies.[321]

5.2.2.2 Early Restructuring to Increase Cost-Effectiveness and Regulatory Reform

Restructuring began in 1980s with the Energy Act of 1983.[322,323,324] The Electricity Act of 1989 set out the framework for the regulatory structure with the Gas and Electricity Markets Authority (GEMA) as the regulator. GEMA is jointly governed by the Office and Gas and Electricity Markets (Ofgem) and the Secretary of State for Energy and Climate Change also known as the DECC.[i] GEMA, an independent regulator, relies upon Ofgem for regulation of the electricity sector. Generation, transmission,

[i] The Department of Enterprise, Trade and Investment in Northern Ireland corresponds to DECC.

distribution, supply and interconnection all require licenses to participate. Over time, the UK's separate regions, England, Wales, Scotland and Northern Ireland were integrated into one system.[325]

The Electricity Act of 1989 transferred the assets of the CEGB to National Power, PowerGen, Nuclear Electric, and The National Grid Company. National Power and PowerGen were fossil-fuel generators while the government held complete ownership of the nuclear generating assets through Nuclear Electric. The National Grid Company was responsible for the transmission grid and held two pumped storage facilities. Twelve RECs held the distribution assets in England and Wales and were privatized in 1990. National Power was completely privatized in 1995 and became RWE nPower.[326]

The New Electricity Trading Arrangements (NETA) replaced the Electricity Pool of England and Wales in 2001. The NETA opened the electricity market to bilateral trading between generators, suppliers, traders, and customers and was intended to increase market participation, provide greater choice and increased efficiency. The Energy Act of 2004 integrated the electricity industries of England, Northern Ireland, Scotland and Wales and was known as the British Electricity Trading and Transmission Arrangements (BETTA).[327]

Due to price pool manipulation and lack of competition, the power-generation industry was further broken up and privatized during the 1990's and early 2000's. The nuclear industry was privatized and PowerGen and National Power assets were sold in parts to other generating companies. The two pumped storage facilities were also sold to non-distribution entities. Regional Energy Companies were only allowed to generate 15% of their own electricity sales.[328]

European Union directives (96/92/EC) promoted rules for an independent transmission system operator, access to wholesale markets and the domestic market. The directive drove the UK regulations in 2011 for Great Britain and 2011 and 2013 in Northern Ireland. The packages unbundled electricity transmission from generation and supply in the internal market and provided for open access.[329]

5.2.2.3 The Energy Act 2013

The most recent restructuring act, The Energy Act of 2013, continued the reform of the electricity sector. The transmission system operator, National Grid, is regulated by Ofgem through the Electricity Market Reform (The Energy Act of 2013). As such they provide a set of requirements that National Grid must meet. The regulatory model is the RIIO model which stands for Revenues equals Incentives + Innovation + Outputs. The RIIO-T1 price control governs the prices that can be charged for transmission of electricity. Ofgem provides incentives for delivering electricity effectively and dealing with disputes. In addition, Ofgem provided financial incentives for National Grid to effectively deal with decisions on Contracts for Difference (CfD) qualifications, capacity market qualification, Capacity Agreement Notices and Capacity Market Register decisions.

The Energy Act of 2013 also contained the UK's approach to electricity's contribution to carbon emissions reduction. The Energy Act of 2013 was the culmination of a carbon reduction planning process started by the Climate Change Act of 2008. A series of climate acts in 2009 and 2011 set up targets to reach a 50% reduction from 1990 levels by 2027 with the ultimate target of reducing emissions by 80% from 1990 levels by 2050.[330] One major study was a study on pathways to 2050, which evaluated alternative approaches to reducing carbon emissions.[331] The Committee on Climate Change, a UK government body, forecasts demand to reach 368 TWh, up from 319 TWh in 2022. They plan to meet this demand by deploying 8-16 GW of nuclear, as well as other low carbon technologies such as carbon sequestration, offshore wind, solar and marine technologies.[332] The Energy Act 2013 provides for low-carbon energy generation through CfDs, a capacity market to ensure security of supply, and an emissions performance standard to limit CO_2 emissions.[333] The act maintained previous elements of reform.

Low-Carbon Generation

The CfD provides low-carbon plants (renewables, nuclear power and carbon capture and Storage [CCS]) with the difference between the price required for the project to break even and the average price for electricity. As the market price fluctuates the generator receives/pays based on the difference between strike price[j] and the market price. Hence in periods of high market prices, the generator would pay back the government any overage above the market price they received for electricity sold. The contract is between the government and the generator and is administered by National Grid, the transmission operator. The goal of the contract is to provide a more efficient mechanism[k] for maintaining a lower cost of low-carbon plants.[334]

The CfD contract is placed for 15 years and is adjusted for inflation. The strike price is based on auction to assure that the most cost-effective projects are chosen first.[335] There are separate reference prices for variable and baseload generation. The CfD provides a subsidy for the difference between the bid price and the market price.[336]

Prior to the introduction of the CfD, renewable energy was subsidized using Renewable Obligation Certificates (ROCs) and FITs. ROC policy came into effect in 2002 and required electricity suppliers to provide an increasing amount of their electricity from renewable resources set by the DECC each year. Renewable generators sell ROCs to suppliers and the suppliers present them to the government to show they met the requirement or pay a penalty for noncompliance. The added cost of supplying renewable energy is passed on to consumers as increased retail prices.[337] DECC closed ROCs for solar up to and including 5 MW for 2015/2016.[338] The UK will end onshore wind subsidies by April 2016. The ROCs are being phased out as CfDs are put in place.[339]

The FIT required suppliers to pay a set amount per kWh to small renewable resource owners and required the government to know the levelized cost of generation for renewables. The FIT scheme was paused in December 2015 with caps on the quantity of FITs that can be deployed each year.[340] The UK government also closed grandfathering of projects that expanded from their original size for biomass co-firing and biomass conversion as well as solar. The closure is intended to lower costs to consumers by moving future projects to the CfD scheme.[341] FIT deployments will be capped to limit government expenditures.[342]

Capacity Markets

The capacity market was set up to assure the UK that appropriate short-term and long-term capacity is available to the UK electricity market to meet peak demand periods during the winter plus a defined margin. The auction for capacity is performed under a “Dutch Auction” where the prices are reduced until the amount of capacity is met. The market clearing price is set when the amount required is met.[343,344] The capacity market offers 1, 3 and 15 year capacity contracts[345] with two auctions per year. The 15-year agreement was limited to new builds.[346]

CO_2 Performance Targets

The Emissions Performance Standards (EPS) provide for limits on CO_2 that fossil-fuel plants emit and can be applied to existing fossil-fuel generators in the event that that they renovate to extend their life.

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[j] The strike price is the price agreed between the government and wind generator based upon the examined costs of production.

[k] The FIT or Feed-in Tariff is for smaller generators and is a fixed price for each type of renewable energy source paid by the purchaser.

The EPS can be suspended for energy security reasons. The Act also places monitoring and enforcement along with the appointment of an enforcing authority.[347]

5.2.3 Key Drivers of Restructuring

The primary drivers of early restructuring were to introduce competition and provide for regulatory reform, or deregulation to the extent practical.[348] The drivers behind the 2013 Energy Market Reform act were to meet goals of carbon reduction by incentivizing investment in secure generation, provide for energy security and lower the costs to consumers of low-carbon resources such as nuclear and renewable resources.[349] The 2013 Energy Act also was design to speed permitting for significant infrastructure like windfarms.[350]

5.2.4 Electric Power Sector Market Structure

The BETTA are driven by a set of codes, which govern how generators, traders, retailers and transmission companies relate to each other. The BETTA provides the mechanism for electricity price determination as well as governs transmission.

5.2.4.1 Generation

Generation has been unbundled from transmission and distribution and is 100% privately owned including distributed generation companies. Generation is licensed by Ofgem prior to being allowed onto the grid. Generation is dominated by the largest seven companies. Six of the seven generators also are retail suppliers.[351,352,353]

5.2.4.2 Transmission Grid

National Grid is responsible for meeting transmission constraints, as well as balancing generation and demand. There are two additional transmission owners in Scotland, but their assets are operated by National Grid.[354] They also are responsible for maintaining and investing in transmission assets. They enter the balancing market, a limited market, to accomplish the balancing task. Generators as well as users can enter the balancing market to provide either demand reduction or generation.[355] The UK grid has operated as a single transmission network connecting Scotland, Wales and England into a single grid since 2005.[356] Transmission pricing is regulated with one price for all geographical areas.

National grid is prohibited from owning or operating electricity generating assets or electricity distribution assets. They neither buy nor sell electricity in either the wholesale or retail markets. They are allowed to buy and sell small quantities of electricity or demand response in the balancing market in order to balance supply and demand.[357,358]

5.2.4.3 Distribution

Distribution system charges are highly regulated by Ofgem. The distribution price contains the same components contained in the transmission pricing.[359] The unbundling indicates that a regulated price for distribution is set between Ofgem and the distributor. Distribution costs are in addition to the transmission price and the energy price. In addition, there is open access on the distribution system for any retail supplier.[360] In Great Britain, there is no prohibition on ownership of a distribution network and a retail supplier.[361] In 2014, there were six licensed distribution network operators (DNOs) serving 14 distribution areas in Great Britain and one DNO in Northern Ireland. In addition to the major DNOs, there are several smaller independent DNOs that mainly serve commercial entities and new housing developments.[362]

5.2.4.4 Retail

The retail electric supply is all privately owned and highly concentrated with the largest 6 suppliers each maintaining between 11% and 25% market shares. Smaller retail suppliers have been growing, increasing to a 5% share in January 2014, up from a 2% market share from the previous year.[363] Vertical integration is an issue for UK generation and supply as retailers also account for 70% of generation. The low liquidity in the wholesale electricity markets is probably a result of the high level of vertical integration between generation and supply.[364]

5.2.4.5 Wholesale Prices

Trading for wholesale supplies of electricity can occur through bilateral contracts ranging from “on-the-day”, to several years in length. In addition to bilateral contracts, the balancing market allows National Grid, the TSO, to take offers of generation or demand response half hourly to balance supply and demand on the grid. The imbalance price is the cash out value if generators and load-serving entities generate or demand more or less than for which they contracted. The TSO keeps the grid balanced second by second.[365] The system price is a one-price system at the UK balancing point. National Grid also offers tenders for reserves and other ancillary services.[366] In addition, the APX Power UK Exchange provides a spot and prompt market for a day-ahead auction and a half-hour day-ahead auction. The prompt market trades base, peak load, and weekend products, as well as combination blocks.[367] Ofgem is evaluating how to prevent non-competitive practices in the non-residential suppliers. Liquidity in the wholesale markets is a concern.[368]

5.3 Grid Operations and Planning: Challenges, Responses, and Proposed Solutions

5.3.1 Challenges to the Bulk Power System due to Changes in Resource Mix over Time

The primary challenge to the UK bulk power system due to the change in the resource mix, especially due to increasing renewables, has been the congestion between Scotland and England as large wind farms in Scotland have been shut down for a few days to reduce congestion.[369] The one-price mechanism in the UK dictates there is only one system price regardless of where generation or demand occurs. Thus, there is no nodal pricing to reflect congestion in the grid. However, despite these issues National Grid achieved a 99.99999% reliability for 2014/2015. That translates to an outage time of 0.05 minutes per year![370] Wind curtailment reached 659 GWh (about 0.2% of total generation and 2% of variable generation) in 2014, up from approximately 50 GWh in 2011, according to the Renewable Energy Foundation.[371] National Grid pays wind producers for their curtailed hours, which increases consumer costs.[372]

Longer-term challenges to the bulk power system may arise due to the inflexibility of variable renewable generation and it’s low/zero fuel costs. Without significantly high balancing market prices in an energy-only market, the ability to attract sufficient flexible reserves may be difficult.[373] In addition, other market factors may exacerbate the issues associated with low- to zero- costs. The short-term markets are illiquid to due vertical integration of generators and suppliers and because bilateral trades are opaque rather than transparent. Also, the BETTA relies on arbitrage from the balancing mechanism to send signals to generators and demand response. With the short-term wholesale markets being illiquid, correct signals are not being provided to either generation or demand response. Green noted that the day-ahead auction is also illiquid, all of which provide for incorrect signals being sent to the market for investment decisions.[374]

According to Green, with variable resources in the generation mix, recovering flexible facility costs will be risky because the capacity factors associated with flexible generation are lower than planned for, returning less profit than expected, and thus reducing the incentive for investment. With increasing amounts of low or zero cost renewables, the problem becomes worse over time, especially when subsidies either through ROCs or CfDs will continue to push prices down during peak wind or solar generation periods.[375]

Keay[376] added to Green's point when he indicated there are six areas where there are market problems when variable resources are a part of the resource mix: 1) there are no useful signals for market operations, e.g., the marginal cost of wind and solar is near-zero and variable resources are inflexible (they generate or they do not); 2) subsidies, such as the FIT, distort markets because they bring on renewables and the price signals needed to bring new production on line do not receive appropriate price signals; 3) increasing renewables with zero marginal costs drive ever lower market prices which force producers' returns below long-run marginal costs; 4) current markets do not provide effective signals for investment; 5) administratively driven FITs do not provide signals for the optimal mix of low-carbon generation; and 6) current markets provide no useful signals for demand response. Clearly as renewables become a larger portion of the resource mix, a solution to maintain price signals for flexible resources is needed. However, current capacity is adequate to meet needs. Winter demand is approximately 54 GW and winter capacity is near 77 GW according to Ofgem statistics.[377]

The UK government instituted the capacity market to fix the price signal problem indicated by Keay and Green above. Two problems exist with the first run of the capacity market. First, the amount of capacity that bid into the market indicated that there wasn't really a need for the capacity market as devised yet. Thus, the payments required under the mechanism provide an additional burden on ratepayers.[l] Second, National Grid's and the DECC's assumptions behind the capacity market provided only for a very narrow range of forecasts for electricity growth. National grid assumed strong increases in energy efficiency, and thus electricity intensity declines sharply leading to a forecast that demand will continue to decline or grow only slightly. According to NERA, even slightly smaller declines in energy intensity (slower improvements in energy efficiency) lead to sharply increasing demand through 2034, which could lead in the long run to shortfalls of generation. The lower demand projection means that the breakeven price National grid chose may not be large enough to meet demand. National Grid was assuming that some of the difference would come from plants that opted out but would still operate at energy market prices. However, some plants have opted to close after not receiving a capacity margin contract.[378]

National Grid also ignored the amount of capacity that interconnectors could provide to meet capacity shortages in their calculations of the amount required in the capacity requirement. The result increased the overall amount that consumers will have to pay for the amount of capacity procured that could have been supplied by interconnector capacity. Newbery indicates that the excess capacity procured had the effect of undermining investment in new conventional generating capacity as the new generators are disadvantaged compared with plants that have a capacity agreement. Thus the BETTA or competitive market will no longer influence investment decisions correctly. The capacity market also lowers revenues for new entrants reducing the investment stimulus. The lower price has an adverse effect on renewables and

[l] Very little long-term capacity was needed as more than enough capacity bid into the short-term market below expected prices indicating that adequate resources were available to meet demand. Every bid under the market break-even price will receive the equilibrium price whereas they would have only received the price they bid in balancing market otherwise.

nuclear as the lower price reduces the amount of renewable generation that the government can purchase under its levy controls. Lastly the lower price reduces the incentive through arbitrage for investment in interconnectors with other markets at a time when the UK needs more interconnection.[379] Joskow indicates that although the capacity market concept is simple, the implementation has been complicated and thus additional iterations will be needed to implement it. Additionally he noted that alternative approaches to revenue adequacy may be useful.[380]

Klessman et al.[381] indicate that the UK wind producers face greater risk when compared with wind producers in Germany and Spain. The UK wind producers face price risk from inadequate price signals, policy risk and balancing risk. The added risk has slowed the penetration of wind in the UK relative to Germany and Spain. They argue that quota schemes, like the ROCs in the UK, force wind producers to face certificate price risk, as well as electricity price risk. In addition, even though National Grid provides balancing for transmission, the balancing price risk falls upon the wind generator. The CfD appears to be structured to remove this problem, and allows the UK government to limit their budget exposure. However, the CfD does not completely limit the UK budget exposure risk. As wind penetration increases and energy prices are driven lower during high wind generation periods, the governments' exposure will increase.

Increasing wind in the resource mix may challenge the natural gas provisioning system as CCGT plants are required to balance the system during periods of high wind variability. During these periods, the physical infrastructure may not be able to provide enough gas to CCGTs to meet demand. The periods of high demand may increase gas supply costs increasing the cost of CCGT generation. Without adequate price signals, the long-term viability of CCGT plants may be in question.[382]

The changing resource mix combined with variable generation's inflexibility and the requirement for generators to supply the required number of ROCs to the Office of Gas and Electricity Markets has impacted the UK budgets and led to quotas for renewables. The mix of declining demand and increasing renewable generation drove the amount of estimated subsidy by consumers above expectations causing the current the UK government to end subsidies through ROCs to onshore wind and solar.[383,384] The UK government's outlays will become more controllable using the CfD rather than the ROC because it will be an administratively driven program.

Lastly one of the unintended consequences from the introduction of the capacity market has been the increase in small diesel peaking plants, which are being subsidized[m] by the capacity market auctions. The small diesel peaking generators are much more flexible and less costly than the CCGT generators. They have added significantly to carbon as well as NO_X and SO_X pollution.[385] On March 1, 2016, DECC announced the pollution limits would be placed on the diesel peaking plants by 2019.[386]

5.3.2 Responses and/or Proposed Solutions to the Power System Impacts

The capacity market appears to shore up the long-term capacity problem. The challenge may arise in the methodology that National Grid used to determine the amount of capacity that was needed.[387]

To solve the problem of liquidity in the wholesale markets, Ofgem instituted a number of rules forcing the eight largest generators and the six vertically integrated generators/suppliers to participate in hedging, forward markets and day-ahead markets. The Supplier Market Access Rules lay out the requirements for the required market participants.[388] The rules force the larger market players to post prices for two 1-hour periods, thus reducing opaqueness and illiquidity in the wholesale markets.[389] The results of the Supplier

[m] The capacity market subsidizes flexible generation because the overall market price is lower than flexible generation breakeven prices. Otherwise, there wouldn't be a need for the capacity market.

Market Access rule are mixed with increasing liquidity in the first year but reversing after that. The rules have provided for easier access, thus reducing market barriers, and increasing product availability.[390]

Green suggested that instead of a one-price system, the UK should institute a nodal price system with locational marginal prices (LMP) to provide feedback to generators where over-capacity exists. Without the LMPs to provide feedback, there is little incentive for generators to adjust new investment other than through penalties in the balancing mechanism.[391] The Competition and Markets Authority undertook an investigation into locational pricing. Their paper recognizes the issue, but indicates that locational pricing would supply Scotland with lower prices because of the overall amount of wind energy that would be available, but that England would have higher costs due to less low-marginal cost wind.[392]

The UK government has decided to subsidize transmission of renewables by lowering the transmission rates for distant transmission and raising transmission rates to generators closer to demand. The effect of this change in subsidy will encourage renewables, which are either offshore or in northern Scotland far from demand.[393] The UK government has also responded to wind curtailment by allowing Scottish Power, one of the transmission owners, to invest £2-£3 billion in transmission and equipment to connect more onshore and offshore wind and increase the capacity to England.[394]

5.3.3 How Industry Structure Exacerbated/Mitigated Bulk Power System Impacts

The concentration of vertically integrated generation and supply in the UK may both mitigate and exacerbate the bulk power planning and operations challenges. The combination of bilateral trading and vertical integration leads to opaqueness and illiquidity in the wholesale markets. The illiquidity and opaqueness makes market access difficult and provides a barrier to entry reducing efficiency and competitive pricing.[395] New wholesale market rules may be removing this issue.

On the other hand, the concentrated vertical structure of generation and supply has mitigated the impacts of the incorrect marginal cost signals. Being both the supplier and generator allows the vertically integrated entities through power purchase agreements to understand the long-term costs of both flexible and inflexible resources. And although National Grid must keep the transmission grid balanced, the supplier is responsible for balancing their own supply and demand, purchasing the correct amount of generation to meet his demand. Thus vertically integrated companies have a better opportunity to match generation and demand. Even with the approach to incorporating low-carbon resources, the vertically integrated nature of the UK system will continue to allow suppliers to balance the generation with demand in the long-term given the stickiness of consumers, e.g., their lack of switching suppliers.

5.4 Lessons Learned for Maintaining Reliability and Cost-Effectiveness with a Changing Resource Mix

5.4.1 Implications of Changing Resource Mix on Grid Operations and Planning

The primary lesson learned from the UK is that the low/zero fuel costs of variable renewables may need a market mechanism to ensure that long-run marginal costs can provide for the investment needed to drive generation in both the short run and the long run. Vertical integration may also help resolve the capacity assurance mechanism. However, the UK, following other countries' leads, opted to enter the capacity market. Nevertheless, capacity markets need to be carefully planned and reviewed. The markets will probably need to be reinvented several times to make the corrections needed to make market rules clear, and provide for robust long-term investment decisions. (On March 1, 2016, DECC announced capacity market reforms.[396]) Perhaps a better choice would be to develop wholesale energy markets that provide appropriate signals for both long-term and short-term portions of the market. The long-term market[n] would provide signals that reflect the investment climate for new-build generation and the short-term markets would reflect need to have adequate capacity to meet short-term imbalances. Such mechanisms have been proposed by Joskow.[397] The market also needs to provide for demand response adequately as it can be a good measure to balance the market.

An additional lesson learned is that, like California in the early 2000s, structuring a market can have unintended consequences. Not having thought about the potential of getting diesel peaking plants and specifically excluding them from the mix of generators in the capacity market option, the UK now has a fleet of carbon, SO_X and NO_X polluting diesel generators.

5.4.2 Implications of Industry Structure on Handling Resource Changes

A very general lesson learned with regards to electricity restructuring and maintaining reliability and cost-effectiveness is that the changing resource mix will require constant regulatory attention to assure that the market structures maintain their competitive frameworks. Pure competition provides the basis for the lowest-priced market equilibrium and when only a few players make up the market, the potential for discriminatory behavior begins to appear. Concentrated vertically integrated entities provide barriers to entry and require more regulatory intervention to attain competitive markets. The UK, by regulating transmission and distribution but allowing vertical integration, and allowing retail suppliers to own distribution and generation, have potentially reduced the nature of competition through barriers to entry even though regulations require open access.

5.4.3 Implications for the United States

The implication for the United States from the UK example is that restructured markets need to be constantly monitored as resource mixes change to assure that the market rules and signals are providing the appropriate signals to bring forth both long-term and short-term electricity supplies as well as demand response. However, the approach to regulatory reform must provide for certainty in the markets. If regulatory reform does not provide the certainty for stakeholders, financial markets may become cautious of investment and future capacity will not be forthcoming due to lack of funding. For example, the pulling of ROC subsidies from wind and solar in the UK is providing uncertainty to the future of onshore wind and solar even though it appears that at least onshore wind is expected to continue to receive subsidies through the CfD process.

[n] The UK capacity market has an administratively determined quantity, while the market proposed by Joskow would have an equilibrium determined by the market.

6.0 Lessons Learned

6.1 Lessons Learned for Reliably Managing Generation Resource Change

Lessons learned were derived through a review of four countries' electricity sectors with varying degrees of resource mix change and restructuring. Across the four study countries, various levels of restructuring occurred with one country remaining as vertically integrated utilities from generation to retail (Japan)[o], two countries having unbundled generation, transmission, distribution and retail while maintaining significant vertical integration (Germany and the UK); and the last country moving towards private ownership and unbundled generation, transmission, distribution and retail, but vertically re-integrating over time (Australia). All studied countries provide incentives for renewable energy generation as a part of their goal to reduce greenhouse gas emissions. To date, relatively high levels of variable renewable generation have been incorporated with few challenges. The continued growth of renewables however, has the potential to cause issues with balancing in the long term unless managed adequately. The issues arise in resource adequacy, reliability, and power quality. The net shift toward variable renewable energy capacity requires increased flexibility to manage system control capabilities, including frequency control, voltage control, and system inertia. Lastly, the declining costs of some renewables and their faster than projected growth has led some countries to revise their incentives. This section highlights the most important findings.

6.1.1 Integration of Relatively High Levels of Variable Renewables

Currently all study countries have been able to integrate renewable energy into their electricity systems. The state of South Australia has relatively high capacity levels of variable renewables (43%) but still manages to maintain system control and stability through interconnections with other states. Germany and the UK have managed to maintain stable and reliable systems as well. Japan's regional utility monopolies have maintained control by refusing to allow more solar onto their grids. The Japanese utility stance may change as the electricity sector will be totally unbundled by 2020.

6.1.2 Resource Adequacy Potentially an Issue in the Long-Term

The increased renewable generation has led to decreases in wholesale prices of electricity as the near-zero marginal costs of variable renewable energy drives ever lower wholesale prices as penetration increases. Although over-capacity exists in Germany and the UK, there are worries in Australia as well that in the long term, the low wholesale prices will not elicit enough flexible capacity to meet resource adequacy needs. However, there is no one solution yet from all countries.

The low/zero fuel costs of variable renewables may necessitate a market mechanism(s) to ensure that long-run marginal costs can provide for the investment needed to drive generation in both the short run and the long run. Vertical integration may help resolve this capacity assurance challenge[p]. However, in the UK, following other countries, Ofgem opted to develop the capacity market approach. Nevertheless, capacity markets need to be carefully planned and reviewed. The markets may need to be reinvented several times to make the corrections needed to make market rules clear, and provide for robust long-term

[o] Japan will be completely restructured by 2020, but is only beginning the process to be completely unbundled in 2016.

[p] Restructured markets typically unbundle generation from retail in order to drive competition as well as provide transparent wholesale and retail markets.

investment decisions. Germany has also investigated the capacity market but rejected it for now in favor of a series of other policies, measures, and market designs to ensure long-term capacity adequacy (termed the Electricity Market 2.0). The grid operator in Australia proposed several approaches to maintaining synchronous generation. The AEMO has proposed more authority over the dispatch process, the addition of a "protected events" clause that would allow the AEMO to intervene in the dispatch process, and proposed that wind turbines provide minimum levels of system inertia. In Japan, METI may be contemplating a capacity market.

An alternative to administratively driven capacity markets would be to develop wholesale energy markets that provide appropriate signals for both long-term and short-term portions of the market. The long-term market would provide signals that reflect the investment climate for new-build generation and the short-term markets would reflect the need to have adequate capacity to meet short-term imbalances. Such mechanisms have been proposed by Joskow.[398] The administratively driven capacity markets require the transmission system operator to forecast the level of future capacity while the Joskow approach relies on the market to determine how much capacity is needed in the future. The forward market would also provide for demand response adequately as it can be a good resource to balance the market. The capacity market needs to be structured to accept demand response.

However, resource adequacy assurance may be addressed, to some extent for countries with a significant amount of vertically integrated generation and retail supply (Germany and the UK) because of practices and responsibilities that allow them to balance their generation with their demand. Being both the supplier and generator allows the vertically integrated entities through long-term contracts to understand the long-term costs of both flexible and inflexible resources. Even with increasing amounts of low-carbon resources, the vertically integrated nature of the system will continue to allow suppliers to match generation and demand in the long-term due to the stickiness of consumers, e.g., their lack of switching suppliers.[q]

6.1.3 Balancing Not an Issue Now but May Become a Challenge with Increasing Variable Generation

Industry structure in Germany and the UK also enables balancing despite challenges in Germany. Economics and policy incentives are causing renewables to supplant thermal generation in northern Germany and solar in the southern Germany. Currently though, the network is working. Although system operators must keep the transmission grid balanced in real time, the retail supplier in the UK and balancing group[r] in Germany are responsible for balancing their own supply and demand by purchasing the correct amount of generation to meet their demand. Both groups face penalties for not matching supply and demand.

6.1.4 Interconnections Help Integrate Renewable Energy

Strong transmission and market connections with other countries and regions helps integrate renewable energy. Australia allows inter-regional balancing, substantially improving each region's ability to host variable renewable generation in isolation. Germany has strong interconnections providing both ancillary and reserve capacity from other parts of Europe. Also Germany has recently instituted a national market for ancillary services, providing lower cost resource allocation than would be available through regional

[q]Vertically integrated generation and supply are better able to forecast long-term demand when their consumers aren't switching because there is stability in the quantity of electricity consumed.

[r] The balancing group in Germany is an intermediate aggregator responsible for procuring and maintaining capacity reserves for their territory.

provision. The UK has significant transmission capacity between Scotland and England, allowing substantial amounts of wind generation to flow from areas with high-quality resource to load centers. Despite significant capacity, transmission congestion remains a barrier to further integrating wind generation in Scotland. Japan's two-frequency grid limits the amount of flexible capacity from other regions that is available for reserves and ancillary services.

6.1.5 Nodal Pricing May Provide Useful Signals for Investment in Generation

Locational-differentiated pricing provides useful price incentives for investment in renewables and flexible generation alike. In systems with single prices, generators do not receive the price signals on where new generation should be placed, potentially resulting in transmission congestion. Germany has a single price, and often manually re-dispatches generation as a result. Furthermore, the single price zone coupled with north-south transmission congestion has created loop-flow problems with neighboring power systems. The UK faces transmission congestion between Scotland and England. One proposal for dealing with the congestion is providing locational-differentiated prices between Scotland and England, in order for the energy prices – the basis for operational and investment decisions – to internalize the costs of congestion.

6.1.6 Increased Variable Generation Requires Greater System Control

High penetration rates of variable generation erodes frequency, voltage and system control. The net shift toward renewable energy capacity has eroded Australia's system control capabilities, including frequency control, voltage control, and system inertia. These potential system control challenges have been somewhat mitigated by the balancing capabilities and the geographic extent of the NEM. Nonetheless, continued high levels of renewable energy penetration could require substantive changes to Australian grid operations and planning, including increased reserve capacity, transmission system expansions, and system control measures. Australia is proposing and Germany is requiring distributed generation to be updated to be capable of providing frequency and voltage control.

6.1.7 Distributed Generation Requires Greater Control

In some countries, distributed generation is providing a large percentage of total generation. The need for direct or indirect control by the system operator in order to maintain reliability will increase as distributed generation increases. As distributed generation becomes a larger share of the total generation on a system, direct or indirect control by the system operator will be increasingly important for maintaining reliability. Australia is investigating more tightly integrating small-scale renewable energy into the bulk power system operations. For example, Victoria required distribution businesses to install smart meters with remote communications by 2014. In addition, Germany now requires new distributed generators to sell their generation into the market at the prevailing market price, rather than receiving fixed Feed-in Tariffs. These market prices send more efficient operational and investment signals to distributed generation owners.

6.1.8 Adjusting Renewables Subsidies

Declining total costs of renewable resources coupled with high subsidies drove growth in penetration rates much faster than expected. Thus Germany, Japan and the UK are adjusting their subsidy approaches to provide a more cost-effective approach to renewables penetration. The UK through their Contract for Difference approach allows competitive bidding for a specified quantity of renewables, thus introducing a market element in determining the level of subsidy. Japan is also implementing a bidding system to acquire renewable generation more cost-effectively.

6.1.9 Renewables Integration Will Require Increased Flexible Generation

Industry structure in the four countries has both mitigated and exacerbated their ability to accommodate higher levels of renewable energy generation. The market-based generation dispatch process in Australia limits the ability to intervene in generation decisions and ensure the long-term availability of system control services. In Australia, the result may be a shortage of synchronous generation capacity and system control services that could prompt system reliability issues in the near future. Australia has also instituted a minimum ramp rate for generators participating in the energy market. Germany instituted negative market pricing which is expected to signal the need for more generator flexibility. The UK's and Germany's vertical structure may allow companies to internalize the cost of flexible generation. At the same time, the ability of the study countries to access large balancing capacity in other geographic areas through interconnectors to other states or nations have facilitated their ability to access ancillary services to accommodate renewable energy penetration. Japan's ability to accommodate renewables across their grid may be limited by the two different operating frequencies in their interconnected grid.

6.1.10 Renewables Integration Requires Signals for Increased Reliability

As variable renewable generation achieves higher penetration levels in global electricity systems, grid operators will need generators, including inverter-based renewable resources, to contribute to reliability services (ancillary services). Australia relies on a "causer-pays" approach, where grid participants that increase the need for ancillary services pay for those services, including renewable energy. Australia is also considering increasing ancillary service requirements in response to the evolving capabilities of the resource mix and requiring wind generators to provide frequency control services, in addition to creating new requirements for system inertia and synchronous condensers. Germany is considering requiring wind and solar generation technologies to contribute essential reliability services to the system.

6.2 Implications for the United States across Countries

The challenges of a changing resource mix to the four countries' bulk power systems are similar to challenges identified in the United States. Those challenges include maintaining resource adequacy, reliability and power quality in the face of increasing amounts of variable renewable energy generation. The range of variable renewable penetration across the countries provides a view of the challenges facing the U.S. grid as renewable penetration continues. Some regions of the United States are already facing similar issues. At the same time, the studies demonstrate that higher levels of penetration than are currently being experienced in most of the United States are possible without significant structural change to the bulk power system.

Solutions to the problem of low/zero fuel costs of variable renewable energy and the associated downward pressure on short-term wholesale market prices below the long-term full cost of production for flexible generation has driven different solutions in the energy-only markets of Australia, Germany and the UK. The UK added a capacity market to the energy market similar to ISO New England and PJM while Australia and Germany chose not to add a capacity market. Japan hasn't yet reached the level of renewable energy penetration to be faced with the low/zero fuel costs of variable renewable energy.

The Australian market operator, like U.S. system operators, has called for increased autonomy over long-term generation and system control planning to accommodate the decreasing prices and potential failure to meet resource adequacy and system control requirements. Australia is currently determining what mechanism they want to use ensure adequate capacity and at the same time relying on the continued ability of states to source such services through regional interconnectors. Stability in U.S. electricity networks, with similarly large balancing areas and wholesale markets in regions such as ERCOT, MISO, and PJM, could hinge on similar factors such as the development of a mechanism to ensure adequate capacity and system control services, and the continued ability of states to source such services through regional interconnectors.

Germany's solution to the zero-marginal cost of variable resource problem was to develop market reform initiatives for short-term operations as well as a long-term planning focus. These market reform efforts provide potential solutions for areas of the United States with rapid expansion of renewable energy. Germany's plan is to develop a more flexible power system that will ensure reliability in the presence of a very high share of renewable energy. They plan to develop decentralized technology solutions such as PV, demand response and storage. The German balancing group model demonstrates one approach that can be implemented to aggregate decentralized generation and demand and incentivize local coordination of resource scheduling and balancing. Germany faces many of the same problems as California with its high renewables targets (55-60% vs 50% respectively) and ERCOT with its energy-only market. However, Germany does not cap the energy price like ERCOT does.

An additional implication is that restructured markets need to be constantly monitored as resource mixes change to assure that the market rules and signals are providing the appropriate signals to bring forth both long-term and short-term electricity supplies as well as demand response. However, the approach to regulatory reform must provide for certainty in the markets. If regulatory reform does not provide a stable investment climate, investors may become risk averse and future capacity growth may be inadequate.

The completion of Japan's market liberalization has just started and has been an ongoing process since 1995. The lessons learned from the introduction of solar may provide insights to the United States as it encounters challenges associated with rising costs, maintaining frequency and meeting steep demand ramps associated with a large influx of solar. On the other hand, ERCOT and PJM may provide lessons learned to Japan as the Japanese restructured market was based on the ERCOT model and may in the future look like the and PJM model.

7.0 Conclusions

International experiences with power sector restructuring and the resultant impacts on bulk power grid operations and planning may provide insight into policy questions for the evolving United States power grid as the electric power systems around the world are responding to a multitude of factors including changing resource mixes and fuel prices, an aging generation fleet with potentially large retirements of baseload generation and numerous policies designed to meet climate goals. Australia, Germany, Japan and the UK were selected to represent a range in the attributes of electricity industry liberalization in order to draw comparisons across a variety of regions in the United States such as California, ERCOT, the Southwest Power Pool and the Southeast Reliability Region.

The study draws conclusions through a literature review of the four case study countries with regards to the changing resource mix and the electricity industry sector structure and their impact on grid operations and planning. This paper derives lessons learned and synthesizes implications for the United States based on the challenges faced by the four selected countries. Each country was examined to determine the challenges to their bulk power sector based on their changing resource mix, market structure, policies driving the changing resource mix, and policies driving restructuring. Each country's approach to solving those challenges was examined, as well as how each country's market structure either exacerbated or mitigated the approaches to solving the challenges to their bulk power grid operations and planning.

Across the four study countries, various levels of restructuring occurred with one country remaining as vertically integrated utilities from generation to retail (Japan)[s] two countries having unbundled generation, transmission, distribution and retail while maintaining significant vertical integration (Germany and the UK); and the last country moving towards private ownership and unbundled generation, transmission, distribution and retail, but vertically re-integrating over time (Australia).

All studied countries provide incentives for renewable energy generation as a part of their goal to reduce greenhouse gas emissions. To date, relatively high levels of variable renewable generation have been incorporated with few challenges. The continued growth of renewables however, has the potential to cause issues with balancing in the long term unless managed adequately. The issues arise in resource adequacy, reliability, and power quality. The net shift toward renewable energy capacity requires increased flexibility to manage system control capabilities, including frequency control, voltage control, and system inertia. Lastly, the declining costs of some renewable resources and their faster than projected growth has led some countries to revise their incentives.

One significant finding included the low/zero fuel cost of variable renewables and its potential negative impact on long-term resource adequacy. No dominant solution has emerged although a capacity market was introduced in the UK and is being contemplated in Japan. Germany has proposed the Energy Market 2.0 to encourage flexible generation investment. In Australia interconnections to other regions provides added opportunities for balancing that would not be available otherwise, and at this point, has allowed for integration of renewables.

The case studies derived an additional eight findings from the cases studies. The finding were:

- Balancing is not currently an issue but may become a challenge with increasing variable renewable generation. Industry structure in Germany and the UK enables balancing. Although system operators must keep the transmission grid balanced in real time, the retail supplier in the

[s] Japan will be completely restructured by 2020, but is only beginning the process to be completely unbundled in 2016.

UK and balancing group in Germany are responsible for balancing their own supply and demand and face penalties if they do not.

- Interconnections help integrate variable renewable energy by allowing access to neighboring capacity. Strong transmission and market connections with other countries and regions helps integrate renewable energy. Australia, Germany and the UK have interconnections to other states/countries/regions to receive both ancillary and reserve capacity. Japan's two-frequency grid limits the amount of flexible capacity from other regions that is available for reserves and ancillary services.

- Nodal pricing or locational differentiated pricing, may provide useful price incentives for investment in renewables and flexible generation alike. In systems with single prices, generators do not receive the price signals on where new generation should be placed, potentially resulting in transmission congestion. Germany and the UK have a single price.

- Increased variable renewable generation requires greater system control. High penetration rates of variable generation erodes frequency, voltage and system control. Australia is proposing and Germany is requiring distributed generation to be updated to be capable of providing frequency and voltage control.

- As a corollary to previous finding, distributed generation requires greater control. As distributed generation becomes a larger share of the total generation on a system, direct or indirect control by the system operator will be increasingly important for maintaining reliability. Australia is investigating more tightly integrating small-scale renewable energy into the bulk power system operations. In addition, Germany now requires new distributed generators to sell their generation into the market at the prevailing market price.

- Rapidly increasing penetration of variable renewable resources due to declining total costs of renewable has forced some countries to adjust their renewable subsidies. Germany, Japan and the UK are adjusting their subsidy approaches to provide a more cost-effective approach to renewables penetration.

- Variable renewable energy resources will require increased flexible generation and incentives to value it appropriately. Industry structure in the four countries has both mitigated and exacerbated their ability to accommodate higher levels of renewable energy generation and acquire the flexible resource required.

- As variable renewable generation achieves higher penetration levels in global electricity systems, grid operators will need generators, including inverter-based renewable resources, to contribute to reliability services (ancillary services). Australia relies on a "causer-pays" approach and is considering increasing ancillary service requirements. Germany is considering requiring wind and solar generation technologies to contribute essential reliability services to the system.

The challenges of a changing resource mix to the four countries' bulk power systems are similar to challenges identified in the United States. Those challenges include maintaining resource adequacy, reliability and power quality in the face of increasing amounts of variable renewable energy generation. The range of variable renewable penetration across the countries provides a view of the challenges facing the U.S. grid as renewable penetration continues. Some regions of the United States are already facing similar issues. At the same time, the studies demonstrate that higher levels of penetration than are currently being experienced in most of the United States are possible without significant structural change to the bulk power system.

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