ENERGY TRANSITIONS COMMISSION

Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility

An analysis of flexibility challenges, costs and solutions in renewable-based power systems prepared by Climate Policy Initiative for the Energy Transitions Commission

January 2017

Disclaimer

This working paper has been produced by Climate Policy Initiative in support of the work being undertaken by the Energy Transitions Commission (ETC).

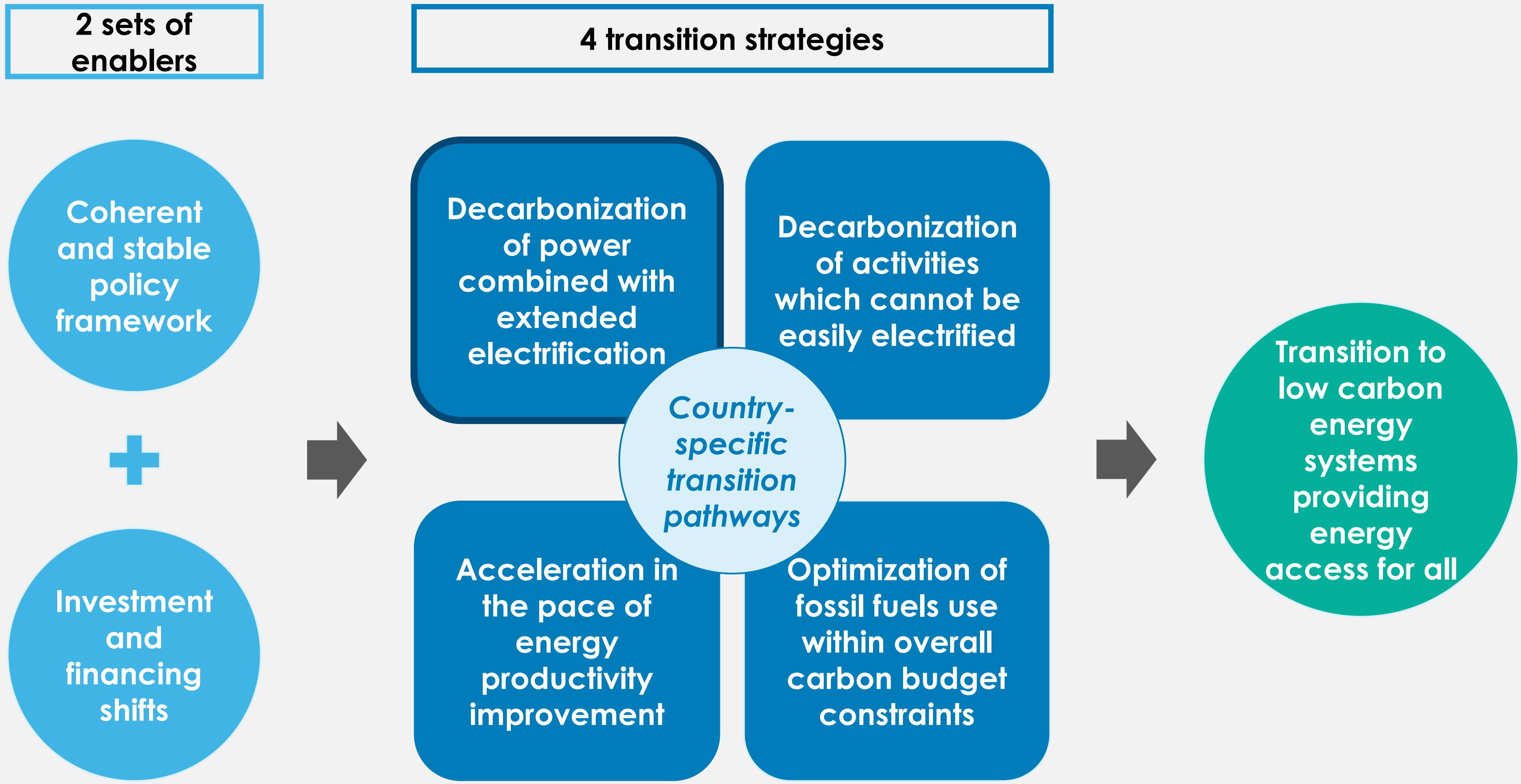
The paper has contributed to the ETC's report Better Energy, Greater Prosperity available on the ETC website.

Climate Policy Initiative have sole responsibility for the content and findings of this document, which should not be interpreted as recommendations made by the ETC.

Contact us at: info@energy-transitions.org
Follow us on: Twitter, LinkedIn and Facebook

This research paper supports the work of the ETC by analyzing flexibility challenges, costs and solutions in renewable-based power systems

The Energy Transitions Commission believes that accelerating energy transitions to low carbon energy systems providing energy access for all will require rapid but achievable progress along 4 dimensions. This research paper investigates how flexibility can facilitate the decarbonization of the power system.



Low-cost, low-carbon power systems:
How to develop competitive renewable-based power systems through flexibility

An analysis of flexibility challenges, costs and solutions in renewable-based power systems

Climate Policy Initiative analysis

January 2017

CLIMATE POLICY INITIATIVE

BRAZIL
CHINA
EUROPE
INDIA
INDONESIA
UNITED STATES

22 Long Acre
London, WC2E 9LY
United Kingdom
climatepolicyinitiative.org

Contents

While a low-carbon power system faces additional flexibility challenges, these can largely be met by existing technologies and costs are expected to fall significantly, supported by policy mechanisms

1. By 2030, the maximum total cost of a new power system based mainly on renewable energy is likely to be lower than that of a fossil fuel-based system

- The decline will be driven mainly by a continued decline in the cost of renewable energy generation

2. Low-carbon energy sources have greater flexibility requirements, driven by their variable nature and technical characteristics

- Developing cost-effective flexibility solutions is an important part of the overall low-carbon transition strategy

3. Future flexibility requirements are highly dependent on regional specifics, such as demand profile, transmission capacity, hydroelectric capacity and weather

- These needs will grow and evolve to meet very high and increasing levels of renewable energy
- In the near term, most systems are well positioned to accommodate significant increases in renewable energy
- In the long term, new policy, technology, infrastructure and market design will be needed

4. System flexibility can be achieved today with a range of existing technologies, and expected improvements in their cost-effectiveness could reduce the total cost of a renewable-based power system even further

- Deployment is lowering the cost of today's cutting-edge options like demand-side flexibility and battery energy storage; next-generation solutions are expected to be even more cost-effective

5. Policymakers can pursue ambitious low-carbon targets; to do so cost-effectively, they will require a portfolio approach and a transition framework working over a longer-term planning horizon

In the near future, the maximum total cost of a near-total-variable-renewable power system is likely to be lower than that of a fossil fuel-based system

By 2030, without a carbon price, a near-total-variable-renewable power system with flexibility provided by gas generation and lithium ion batteries would cost $69/MWh compared with $73/MWh for a gas-only system today.

With a carbon price at $50 a tonne, a near-total-variable-renewable power system, at $72/MWh, compares even more favorably to a gas-based system at $93/MWh.

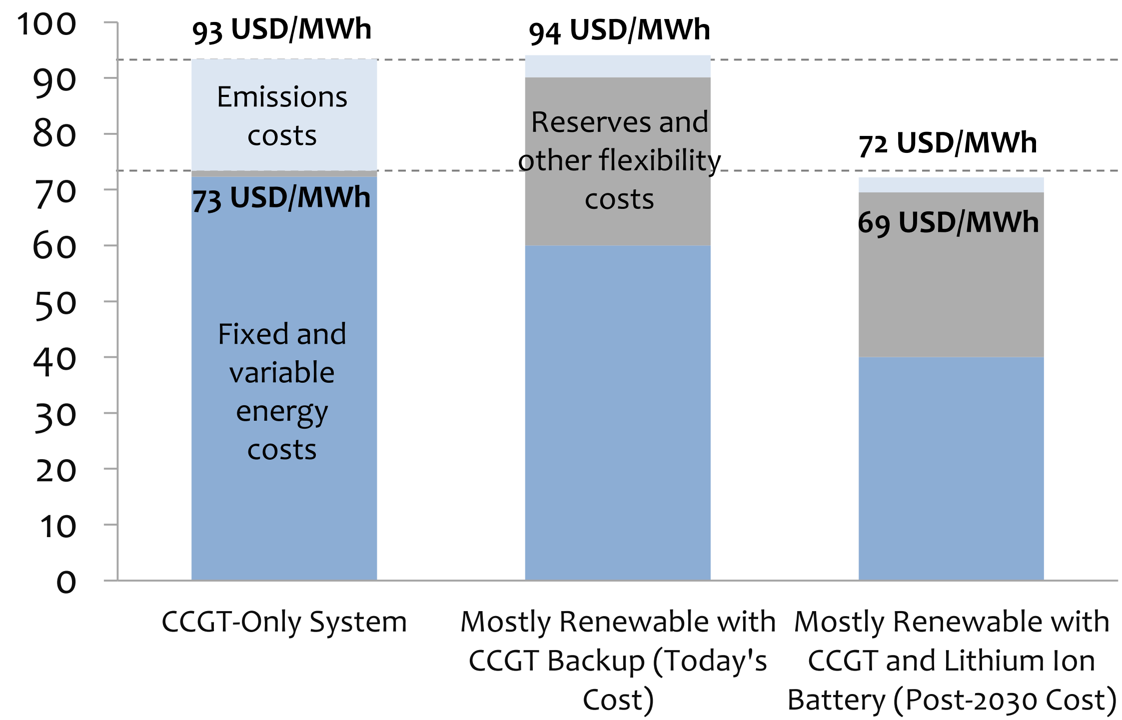
The significant decline in the cost of a renewable-based system with flexibility (from $94/MWh today to $72/MWh in 2030) is driven mainly by the continued decline in the cost of renewable energy production.

Between 2009 and 2015, the levelized cost of electricity from wind and solar fell by 60%-80%, and this decline is expected to continue as the industry scales and technologies improve.

The efficiency of these renewable resources is improving, driving down the cost of resources and creating opportunities to build a flexible, low-cost, low-carbon grid.

Note: This is a generic analysis based on the load/ resource profile of Germany. Regional variations would exist in both load profile and availability of flexibility options. However, for most load profiles, we would expect a portfolio of flexibility solutions to lead to similar or better costs of a renewable-based system.

Power generation and balancing cost (based on Germany load/resource profiles at 100% variable renewable energy)
USD/MWh, including $50/tonne CO2 carbon value



See detailed findings

Low-carbon energy sources have greater flexibility requirements, driven by their variable nature and technical characteristics

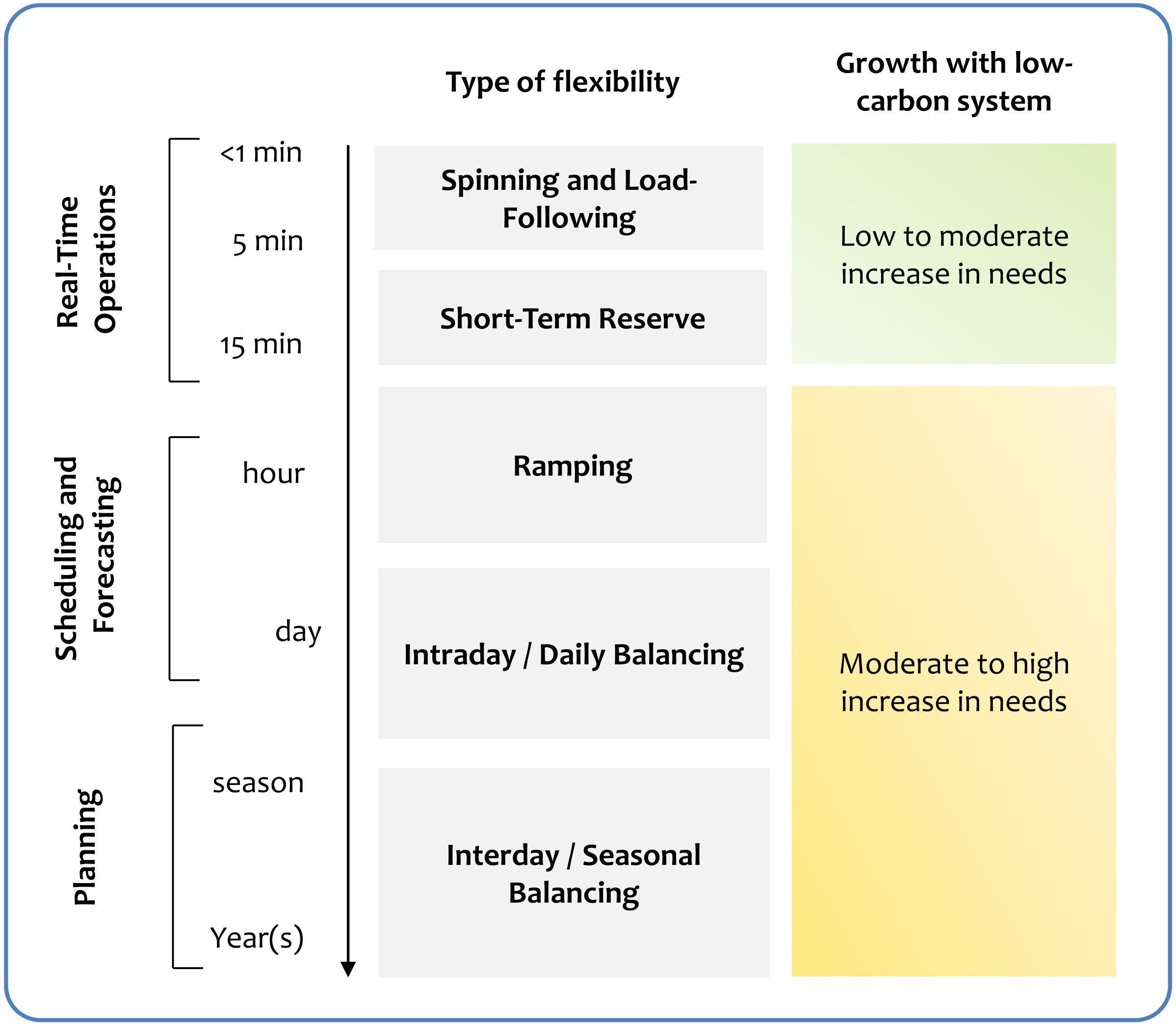
Power quality, security and reliability for a modern power system require the matching of supply and demand at every minute, hour, day and season at each location on the network, and these requirements are greater for a low-carbon system.

All power systems currently depend on flexible generation, flexible demand and in some cases energy storage to keep demand and supply in constant balance.

This need will grow with the increased integration of variable renewables, such as wind and solar, particularly when it comes to ramping and seasonal balancing.

Other low-carbon solutions, such as nuclear and fossil fuel generation with carbon capture and storage (CCS), are capital intensive and often technically constrained to deliver a constant supply of electricity. Other flexible resources are therefore needed to shift demand across days or seasons to optimise nuclear or fossil fuel generation with CCS.

Location also matters, as flexibility in where electricity is delivered to consumers or stored is essential in maintaining grid balance.



See detailed findings

3. Future flexibility requirements are highly dependent on regional specifics, including demand profile, transmission capacity, hydroelectric capacity and weather

We have analyzed four regions with ambitious renewable energy plans, but very different renewable supply mixes and demand profiles, as well as different economic and institutional contexts.

The power systems of all four regions have adequate flexibility to support the integration of 30%+ variable renewable energy. However, Maharashtra also faces a rapidly developing economy and growing electricity demand, which will require more electricity generation – this is an opportunity to develop more flexible systems from the start.

	California	**Germany**	**Maharashtra**	**Nordic Region**
Economic development	Advanced, diversified economy	Advanced, diversified economy	Emerging market still expanding energy access	Advanced, diversified economy
Renewable energy ambitions	High • 50% RE (ex. large hydro) by 2030	High • 50% RE by 2030	Medium • India-wide solar (100 GW) and wind (60 GW) missions by 2022, ~18% RE	High • Hydro-based • Varies by country, supporting carbon-neutrality by 2050
Hydro capacity	Medium	Medium	Low	High
Interconnections	Med/High • Southwestern coal, nuclear & solar / Northwestern hydro	High • Continental Europe and Nordic countries	Medium • Neighboring states and transmission companies	Medium/High • Continental Europe and future large expansions to UK and EU
Solar resource	High	Medium	High	Low
Demand profile	Summer peak driven by high AC load	Winter peak driven by heating load	Flat load profile, daily ramps driven by residential and commercial lighting and AC	Winter peak driven by heating load
Seasonal patterns	Wind and solar highest in spring / early summer	Wind peaks in winter driven by North Sea storms / Solar peaks in summer	Wind concentrated in May-Oct monsoon, solar consistent throughout the year	Wind output peaks in winter
Market structure	Regulated utilities with competitive wholesale market	Regulated transmission and distribution, competitive generation	Regulated retail with mix of regulated and competitive generation	Regulated transmission and distribution, competitive generation through Nord Pool
Existing plant capabilities	Flexible gas fleet	Significant lignite / coal generation low flexibility	Coal-based fleet	Hydro-based mix, with nuclear and thermal

See detailed findings

System flexibility can be achieved today with a range of existing technologies, and expected improvements in their cost-effectiveness could reduce the total cost of a renewable-based power system even further

Our analysis suggests that by 2030 the maximum cost of flexibility would be $30/MWh for a system where nearly all electricity is supplied by variable renewable energy.

Different technologies are best suited to providing different flexibility services.

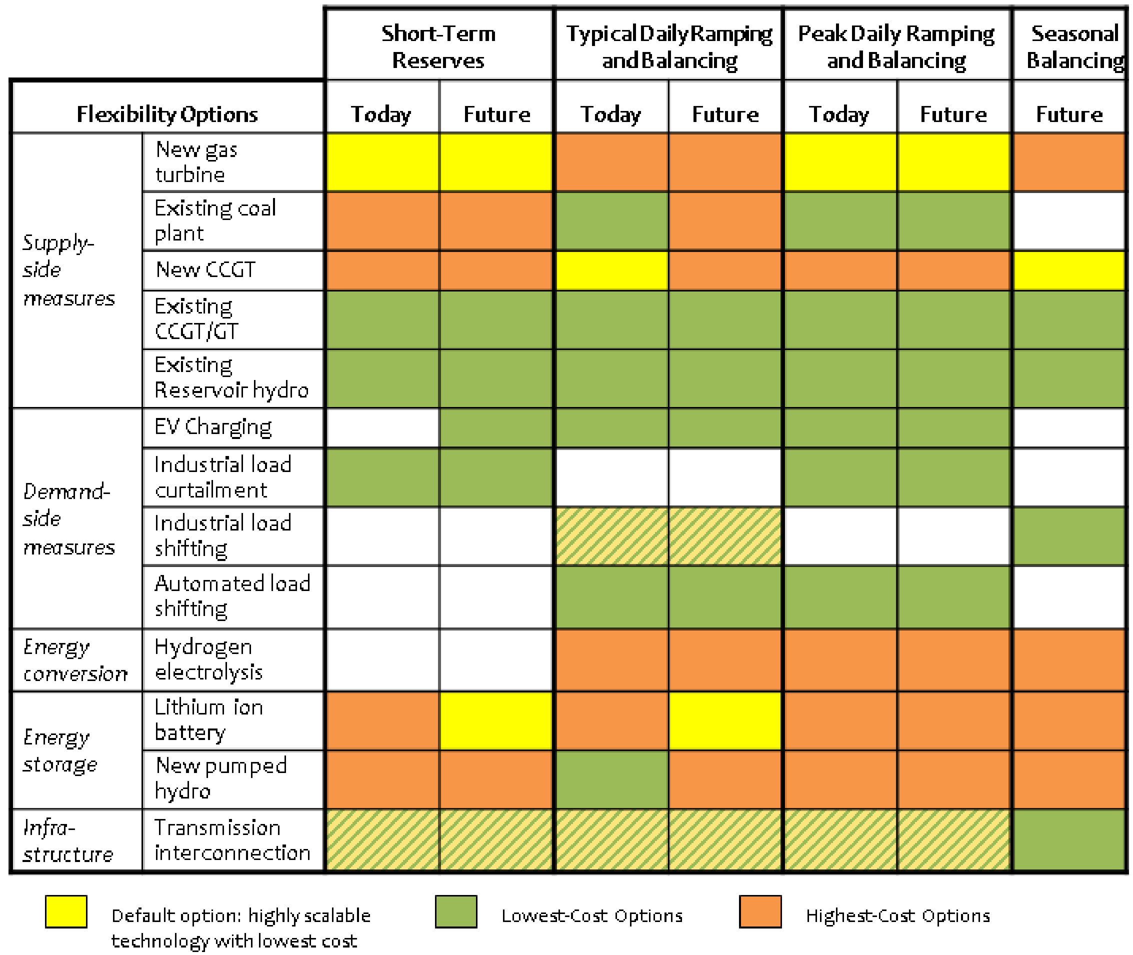
Existing power plants and demand-side flexibility are the lowest-cost sources of flexibility for today's power system.

However, batteries are expected to be competitive as a low-cost, highly scalable source of flexibility in the near future.

Electrification of transport and heating will increase the amount of demand that can be made flexible, provided the right policy and market signals are in place.

Even lower flexibility costs can be realized by optimizing resources to provide several types of flexibility from the same asset.

Cost competitiveness changes over time



See detailed findings

5. Policymakers can pursue ambitious low-carbon targets; to do so cost-effectively, they will require a portfolio approach and a transition framework working over a longer-term planning horizon

Key findings	What policymakers should think about
Renewable energy ambition *Solutions are available now in most power systems to accommodate high proportions of renewable energy at a reasonable cost*	• **Feel free to set ambitious renewable energy targets** to meet their low-carbon objectives. • **Focus on optimizing the costs of today's flexibility options**, while setting policies that will deliver increased flexibility capacity in time to meet targets for decarbonizing the power sector at the lowest possible cost.
Portfolio approach *No single technology, market mechanism, or flexibility resource will be able to meet all flexibility requirements across all regions*	• **Promote the development and cost reduction of several technologies and flexibility resources,** while creating markets and policy for cost-effective integration of these resources as they develop. • **Create solutions that can contribute to delivering the needed flexibility at a competitive cost including:** using existing generation capacity differently; increasing demand-side flexibility; increasing and optimizing new electrification; restructuring transmission and distribution; developing new roles for batteries; and building some new gas turbines as additional support.
Transition framework *New policy, market and regulatory mechanisms are needed to cost-effectively develop flexibility for a near-total-variable-renewable power system*	• **Focus planning and policy development on the transition path to a much higher variable-renewable power system**: markets need to be configured to get the best output, lowest cost and lowest risk from both renewable energy and the evolving flexibility resources. • **Design markets with long term signals for investment in the transition, including:** better signals to consumers; markets that address both the supply of energy and flexibility; mechanisms that balance sources of renewable energy to reduce flexibility needs; and processes and price signals to improve regional coordination.
Planning horizons *Longer-term planning horizons are needed to develop new flexibility solutions and avoid lock-in of long-term solutions that do not align with transition goals*	• **Create markets and policy that incentivize long-term innovation and balance this innovation against near-term objectives.** For example, there is a continued role for existing fossil fuel generation to ease the transition, while innovation policy and long-term planning is needed to access some of the lowest-cost future resources.

Contents

In the near future, the maximum total cost of a near-total-variable-renewable power system is likely to be lower than that of a fossil fuel-based system

By 2030, without a carbon price, a near-total-variable-renewable power system with flexibility provided by gas generation and lithium ion batteries would cost $69/MWh compared with $73/MWh for a gas-only system today.

With a carbon price at $50 a tonne, a near-total-variable-renewable power system, at $72/MWh, compares even more favorably to a gas-based system at $93/MWh.

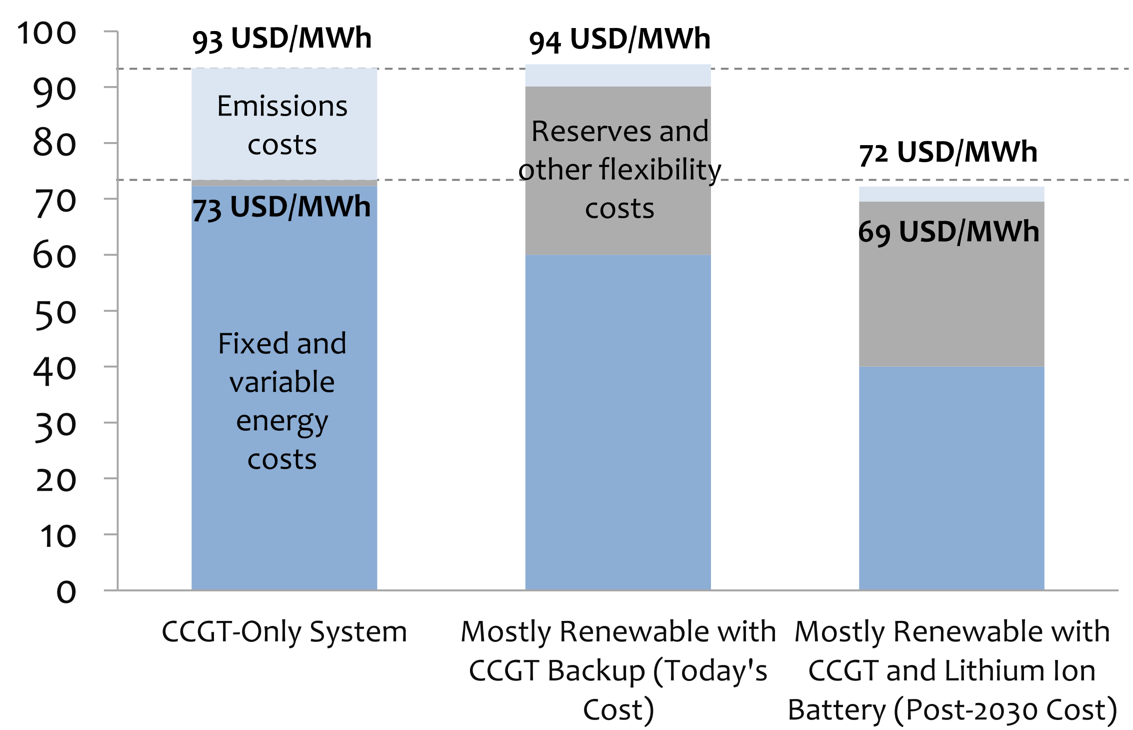
The significant decline in the cost of a renewable-based system with flexibility (from $94/MWh today to $72/MWh in 2030) is driven mainly by the continued decline in the cost of renewable energy production.

Between 2009 and 2015, the levelized cost of electricity from wind and solar fell by 60%-80%, and this decline is expected to continue as the industry scales and technologies improve.

The efficiency of these renewable resources is improving, driving down the cost of resources and creating opportunities to build a flexible, low-cost, low-carbon grid.

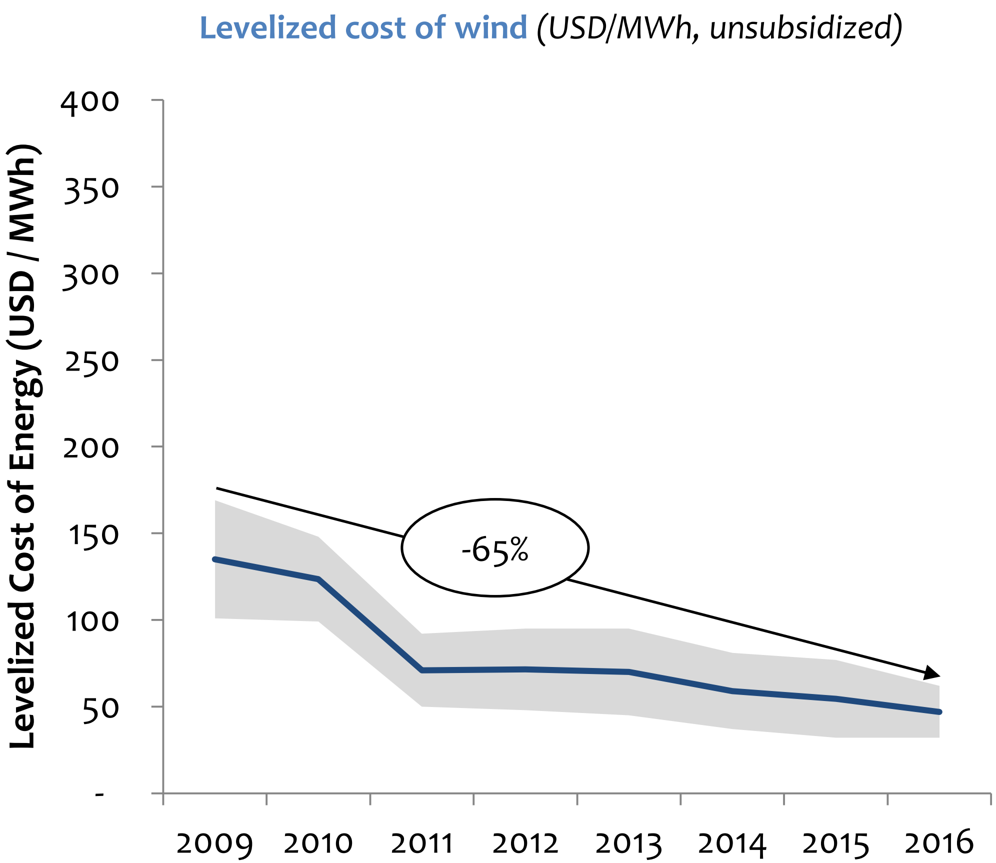
Note: This is a generic analysis based on the load/ resource profile of Germany. Regional variations would exist in both load profile and availability of flexibility options. However, for most load profiles, we would expect a portfolio of flexibility solutions to lead to similar or better costs of a renewable-based system.

Power generation and balancing cost (based on Germany load/resource profiles at 100% variable renewable energy)
USD/MWh, including $50/tonne CO2 carbon value

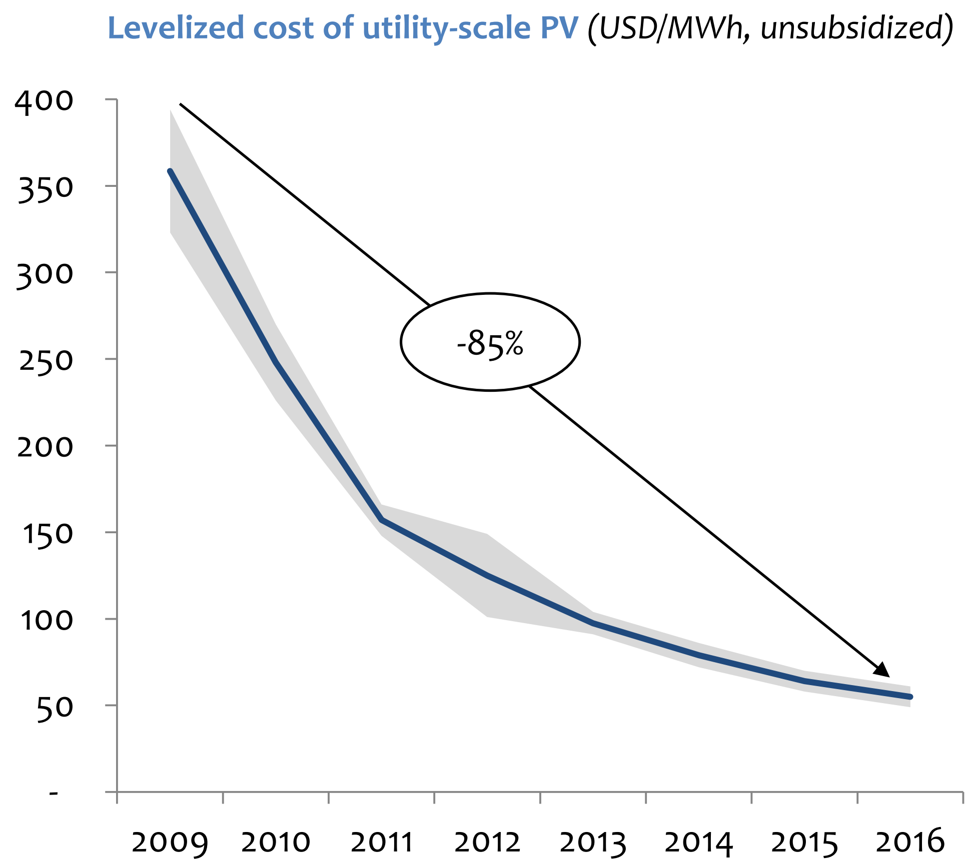


See note on methodology

Wind and solar costs have declined by 65-85% in recent years



Recent bid prices:
- 35 USD/MWh onshore (excl. tax credit) – USA, 2015
- 72.5 EUR/MWh offshore – Netherlands, July 2016
- 54.5 EUR/MWh offshore – Netherlands, Dec 2016



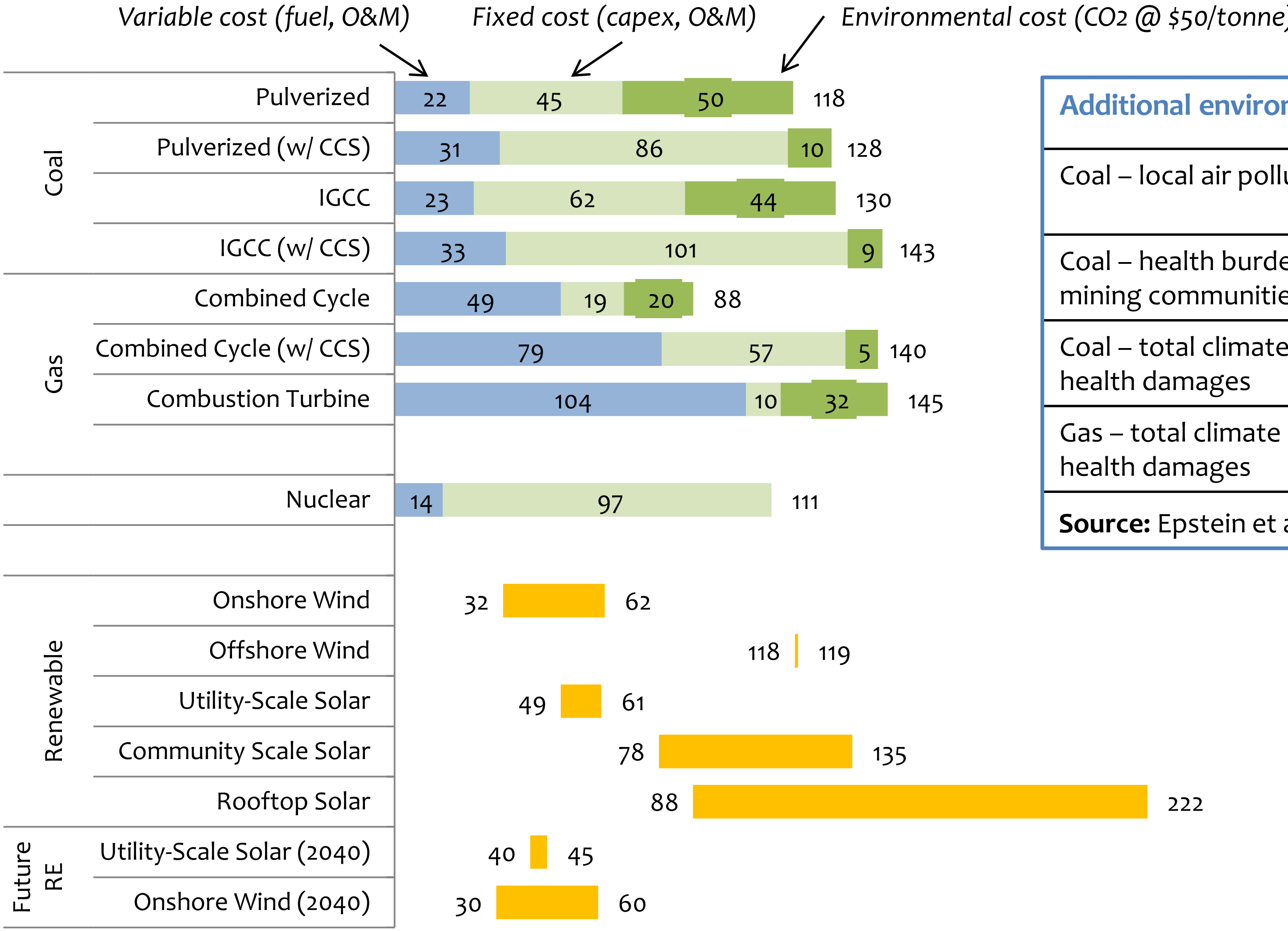
Recent bid prices:
- 29.9 USD/MWh – Dubai, May 2016
- 29.1 USD/MWh – Chile, August 2016
- 24 USD/MWh – Abu Dhabi, Sept 2016

NOTE: USA 2015 wind bid price adjusted for Production Tax Credit. According to LBNL's 2015 Wind Technologies Market Report, 2015 USA PPA prices are as low as ~20 USD/MWh after PTC, plus an adjustment of 15 USD/MWh levelised value of the PTC.

SOURCE: Lazard Levelized Cost of Energy 10.0 (2016), Greentech Media, Reuters, Lawrence Berkeley National Lab

Low-carbon electricity sources are becoming cost-competitive with fossil fuels, especially considering environmental and health externalities

Levelized cost of energy from fossil fuel, nuclear and renewable generation (USD/MWh)



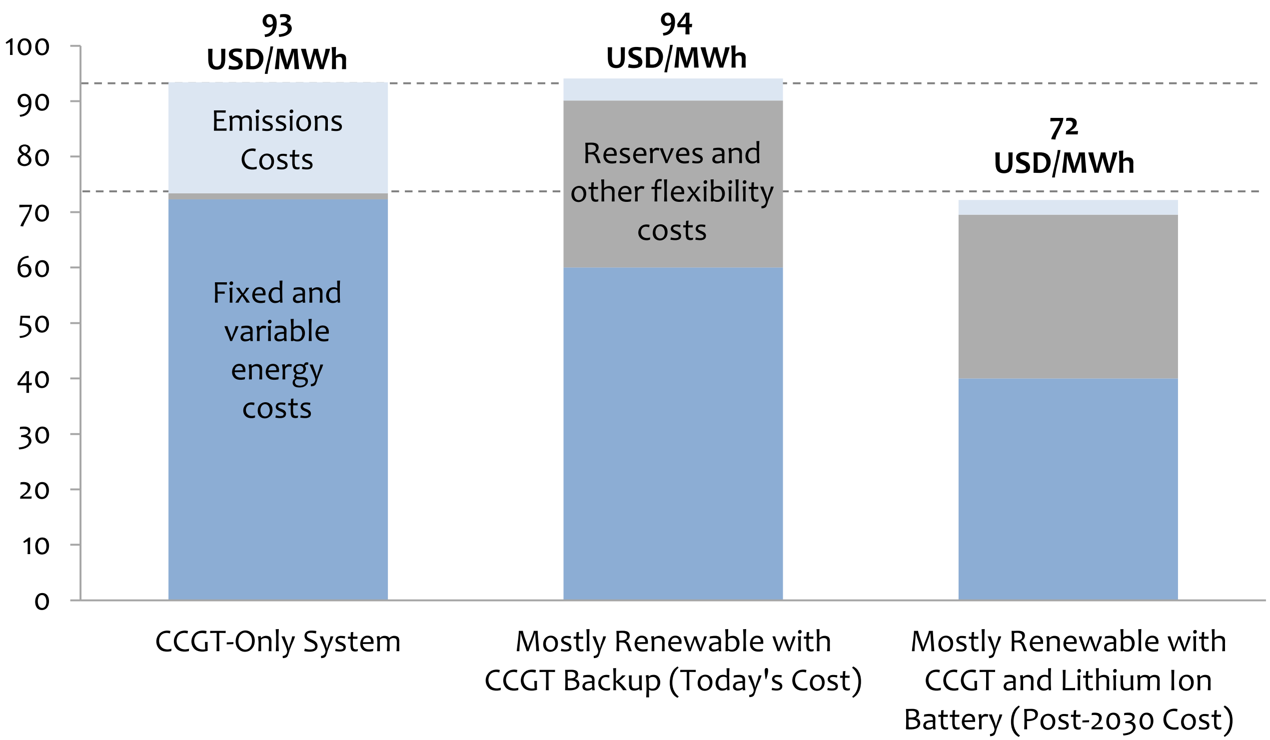
Additional environmental costs of fossil generation	
Coal – local air pollution	32-93 USD/MWh
Coal – health burden on mining communities	44 USD/MWh
Coal – total climate and health damages	140-340 USD/MWh
Gas – total climate and health damages	40-180 USD/MWh

Source: Epstein et al. (2011), Shindell (2015)

SOURCE: CPI analysis, Black and Veatch (2013), Lazard (2016), BNEF (2015), IRENA (2016), Agora/Fraunhofer (2015). Gas fuel cost assumed 4.70 USD/MMBtu, Coal at 2.00 USD/MMBtu, although fuel costs will vary by region. Costs for fossil and nuclear estimated at 85% capacity factor.

A new generation system, based on variable renewable sources with gas capacity and batteries providing flexibility, would be cheaper than a new fossil fuel-based system (1)

Power generation and balancing cost
(based on Germany load/resource profiles at 100% variable renewable energy)
USD/MWh, including $50/tonne CO2 carbon value



Analysis based on Germany's load and resource profiles at 100% variable renewable energy (64% wind, 34% solar and 2% run-of-river hydro, before curtailment).

Key assumptions:

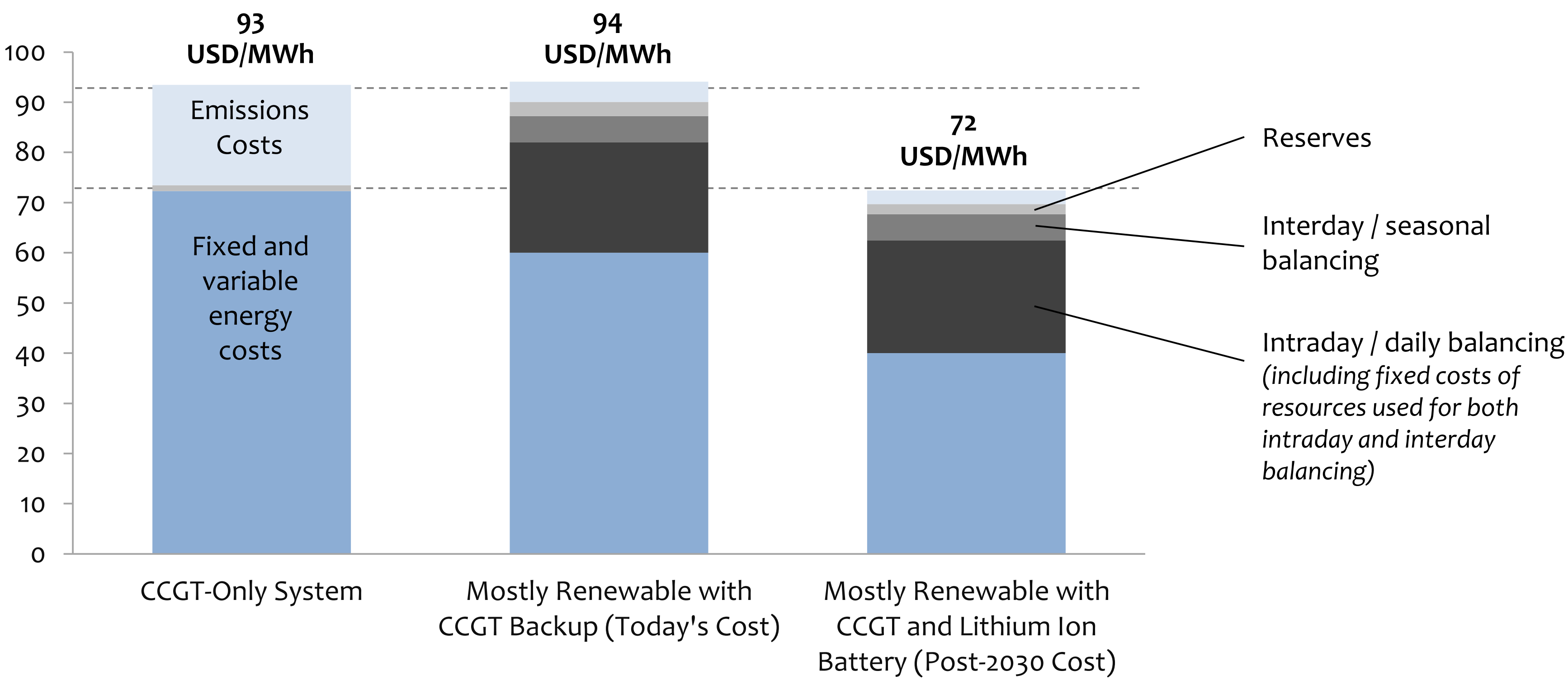
- *Variable RE costs:* $60/MWh today, $40/MWh post-2030
- *CCGT costs:* $50/MWh variable cost, $20/MWh emissions cost, and $140/kW-year fixed capital and O&M costs
- *Lithium ion battery costs:* $160/kW-year (based on $150/kWh capital cost for 6-hour battery plus fixed O&M), plus 8% round-trip losses at RE cost

Technology and resource costs are likely to vary from region to region, and there is some uncertainty in future technology cost projections. However, these estimates represent a central view of technology and resource costs.

SOURCE: CPI Analysis

A new generation system, based on variable renewable sources with gas capacity and batteries providing flexibility, would be cheaper than a new fossil fuel-based system (2)

Power generation and balancing cost
(based on Germany load/resource profiles at 100% variable renewable energy)
USD/MWh, including $50/tonne CO2 carbon value

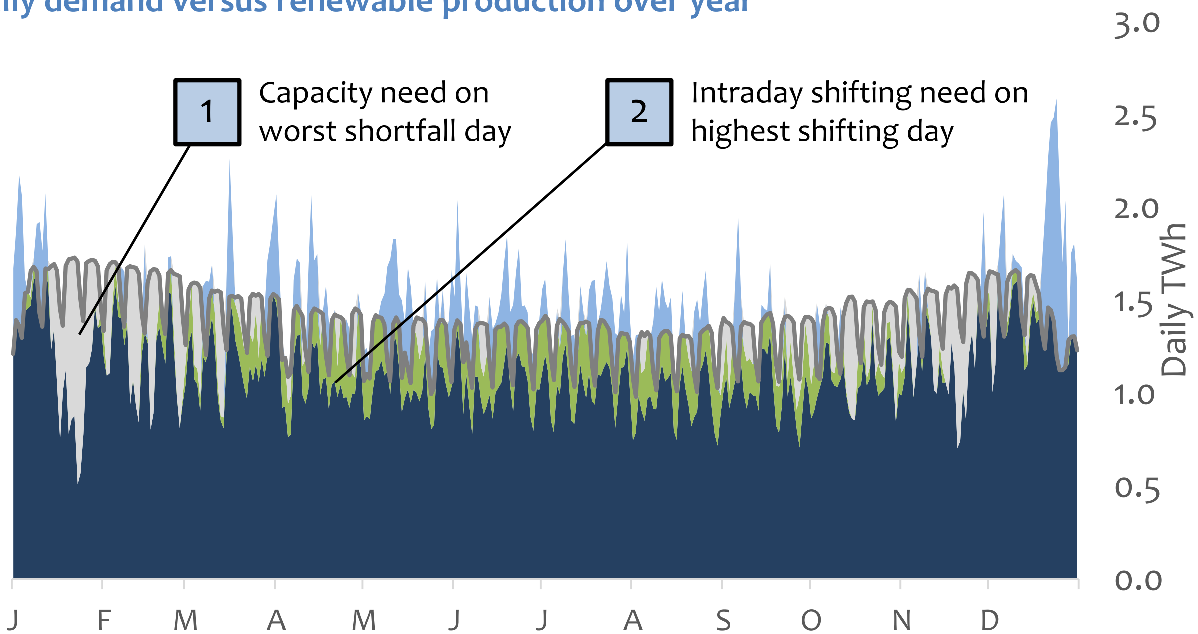


SOURCE: CPI Analysis – Same assumptions as previous slide

For this analysis, flexibility costs are based on intraday/daily and interday/seasonal flexibility needs created by a near-total-variable-renewable power system and on Germany's existing load shape (1)

In our calculations for the costs of a renewable-based system, flexibility needs are based on the demand profile of Germany, versus the current production profile of wind and solar in Germany scaled up to meet the total annual demand (excluding import/export). 505TWh were assumed to be met entirely with wind (64%), solar (34%) and run of river hydro (2%), before any shifting or curtailment. This profile sets the need for short term capacity, daily storage and load shift, and seasonal storage or shifting.

Daily demand versus renewable production over year



— Daily electricity demand (before shifting)
Renewable energy generation used in the same hour it is produced
Intraday shift – VRE used in same day, but a different hour
Daily shortfall – Daily shortfall of renewable energy output
Daily surplus – Excess energy production each date

Note: System is in energy balance, so total daily shortfall = total surplus. Both equal seasonal shifting

Total annual load shift

Total annual demand, renewable energy generation, intraday and interday shifting	**TWh (%)**
Renewable energy coincident with demand	403 (80%)
Intraday / daily shift of renewable energy	50 (10%)
Interday / seasonal shift of renewable energy*	53 (10%)
Total renewable energy generation	505 (100%)

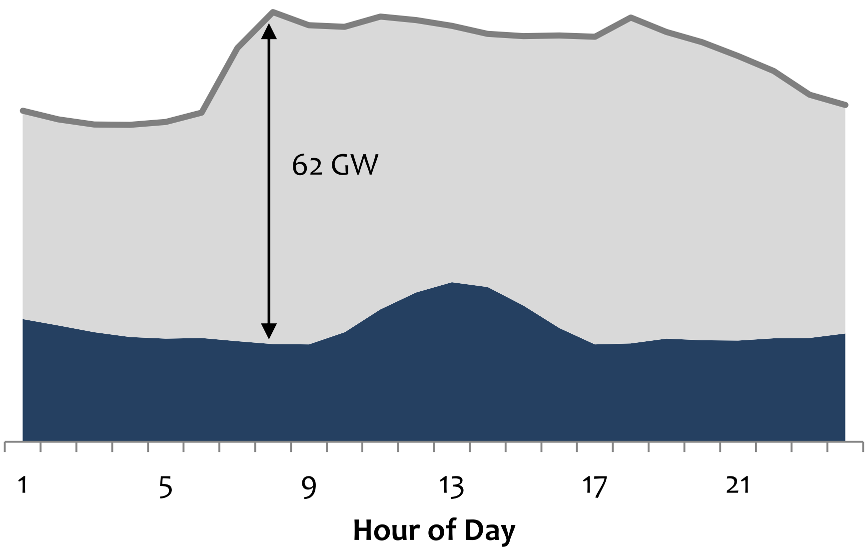
*Seasonal Shift is 53TWh based on sum of daily shortfall, or daily surplus

For this analysis, flexibility costs are based on intraday/daily and interday/seasonal flexibility needs created by a near-total-variable-renewable power system and on Germany's existing load shape (2)

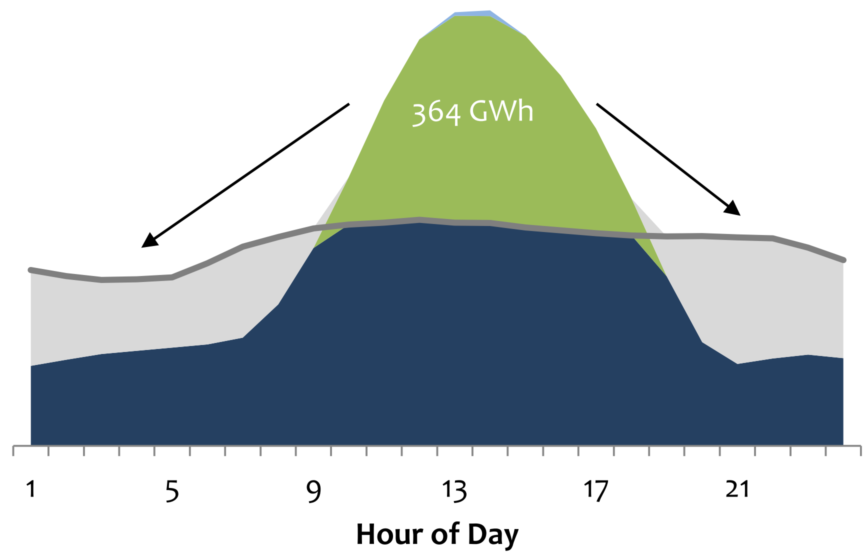
Backup peaking capacity is based on the largest difference between electricity demand and total renewable energy production, which in the model would have reached 62GW on a cold, windless January day.

Daily storage capacity is based on the peak daily storage needs for a mild, sunny, windy day in late April where 364GWh of daytime energy production would need to be shifted to the night.

1 Capacity need on worst shortfall day



2 Intraday shifting need on highest shifting day



Intraday/daily balancing needs could be met by a mixed system of gas and storage at a cost similar to that of gas turbines, i.e. $22/MWh, even without a carbon price

Intraday/daily balancing provided by:	**Gas only (with no carbon price)**	**A mix of gas and storage (with no carbon price)**
CCGT		
Capacity	62 GW	50 GW
Energy generated	50 TWh	17 TWh
Capacity cost per year	140 USD/kW-yr	140 USD/kW-yr
Variable cost	50 USD/MWh	50 USD/MWh
Total cost	11.2bn USD	7.8B USD
Lithium ion battery		
Capacity		21 GW x 136 GWh
Energy shifted	-	33 TWh
Capacity cost per year	-	160 USD/kW-yr
Variable cost (losses)	-	3.2 USD / MWh
Total cost	-	3.5B USD
Total	11.2B USD	11.3B USD
Cost per MWh shifted	225 USD/MWh	229 USD/MWh
Cost per MWh of total load (505 TWh)	**22.1 USD/MWh**	**22.5 USD/MWh**

Costs are similar for gas-only and mixed systems without a carbon price. However, with a carbon price, the mixed system will be a significantly less expensive option and would further reduce carbon emissions by 13 million tonnes per year.

Quantities are based on estimated system needs for a near-total-variable-renewable power system with Germany's demand and resource profiles.

Costs are based on expected technology costs by 2030. Technology and resource costs are likely to vary from region to region, and there is some uncertainty in future technology cost projections. However, these estimates represent a central view of technology and resource costs

NOTE: Excludes cost of curtailment to avoid double-counting with energy generation cost
SOURCE: CPI analysis

Interday/seasonal balancing needs could be met with existing CCGT capacity at a cost as low as $5/MWh, even without a carbon price

	CCGT to provide interday/seasonal balancing (with no carbon price)
CCGT	
Capacity	62GW
Energy generated	53TWh
Capacity cost per year	Counted under intraday/daily balancing
Variable cost	50 USD / MWh
Total cost	2.6B USD
Cost per MWh shifted	50 USD/MWh
Cost per MWh of total load (505TWh)	**5.2 USD/MWh**

NOTE: Excludes fixed costs of resources used for both intraday and interday balancing to avoid double-counting with intraday balancing costs
Excludes cost of curtailment of renewable energy to avoid double-counting with energy generation cost

SOURCE: CPI analysis

Contents

Low-carbon energy sources have greater flexibility requirements, driven by their variable nature and technical characteristics

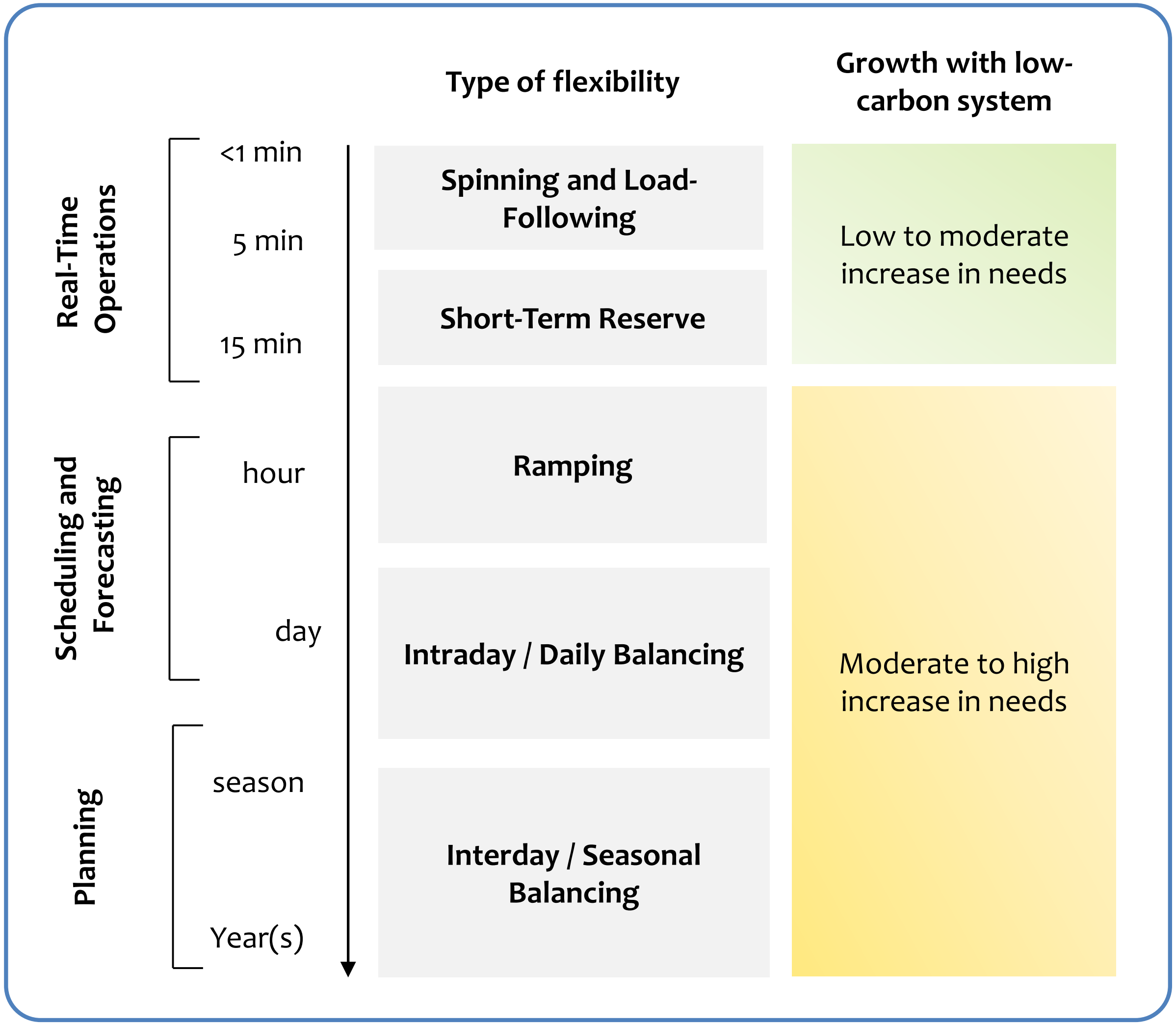
Power quality, security and reliability for a modern power system require the matching of supply and demand at every minute, hour, day and season at each location on the network, and these requirements are greater for a low-carbon system.

All power systems currently depend on flexible generation, flexible demand and in some cases energy storage to keep demand and supply in constant balance.

This need will grow with the increased integration of variable renewables, such as wind and solar, particularly when it comes to ramping and seasonal balancing.

Other low-carbon solutions, such as nuclear and fossil fuel generation with carbon capture and storage (CCS), are capital intensive and often technically constrained to deliver a constant supply of electricity. Other flexible resources are therefore needed to shift demand across days or seasons to optimise nuclear or fossil fuel generation with CCS.

Location also matters, as flexibility in where electricity is delivered to consumers or stored is essential in maintaining grid balance.



Power systems require multiple types of flexibility to manage variability and uncertainty

Timeframe	Timescale	Type of flexibility	Power system need
Real-Time Operations	<1 min, 5 min	**Spinning and load-following**	Accurately predicting load and generation, maintaining adequate reserves for voltage and frequency stability, contingencies, and real-time balancing
	15 min	**Short-term reserve**	
Scheduling and Forecasting	hour	**Ramping**	Meeting predicted but rapid changes in generation and load
	day	**Intraday / Daily balancing**	Addressing hours of generation surplus or shortfall
Planning	season	**Interday / Seasonal balancing**	Long-term capacity planning, addressing days, weeks, months or seasons of generation surplus or shortfall
	Year(s)		Managing long-term resource uncertainty

A low-carbon power system faces additional flexibility challenges (1)

Low-carbon power system transition options	Flexibility implications
Variable renewable energy (e.g. wind & solar)	**Need to shift energy from hours and seasons with excess production to periods of high demand** • Curtailing production instead will increase carbon and increase costs • By 2020 using curtailment to handle excess output in Germany could increase renewable energy costs by 5-30% (depending on policy)
Nuclear	**Baseload energy supply will cause excess production during periods of low demand if flexibility cannot shift supply or demand** • Increasing flexibility of nuclear is possible, but expensive • Lower utilization of high capital cost plant will drive cost increases
Fossil fuels with carbon capture and storage	**CCS is likely to add to flexibility requirements rather than resolve them** • Lower utilization of high capital cost plant will drive cost increases • Potential technical constraints: pulverized coal and lignite plants have long start-up times and slow ramp rates, so if CCS is a retrofit on these plants, those are likely to remain issues • IGCC coal plants perform similarly to a gas CCGT, so there the flexibility constraints are primarily economic
Extended electrification	**- Could increase flexibility needs without effective policy and flexibility solutions** • For example, electric vehicle charging could increase evening peak and ramp-up needs if users plug in cars when they get home **- Could also facilitate flexibility by creating more opportunities for demand management through greater electrification of sectors with shiftable loads**

A low-carbon power system faces additional flexibility challenges (2)

Increase in flexibility needed with growth of low-carbon power

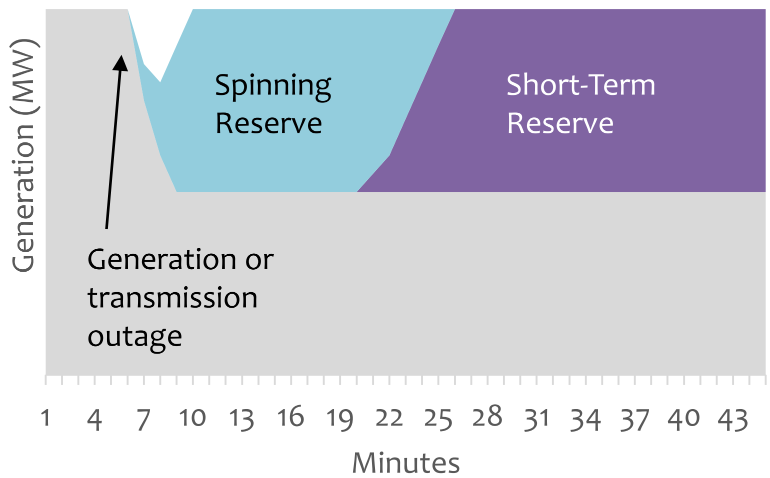
Phase	Timescale	Type of flexibility	Variable renewable energy	Nuclear	Fossil fuels with CCS
Real-Time Operations	<1 min, 5 min	Spinning and load-following	**Low to moderate** *Modest increases in forecast error with more variable generation*	**Low** *Low demand forecast errors*	**Low** *Low demand forecast errors*
Real-Time Operations	15 min	Short-term reserve			
Scheduling and Forecasting	hour	Ramping	**Moderate to high** *Daily patterns (e.g. sunset) lead to substantial ramping needs*	**Low to moderate** *Baseload nuclear has limited ramping capability*	**Low to moderate** *Baseload fossil with CCS has limited ramping capability*
Scheduling and Forecasting	day	Intraday /Daily balancing	**Moderate to high** *Misalignment between generation and load drives hourly over/under-production*	**Moderate to high** *Constant supply and variable demand creates need for daily energy shift*	**Moderate** *Following demand lowers capacity factor, and increases cost*
Planning	season, Year(s)	Interday / Seasonal balancing	**Moderate to high** *Dependent on resource mix, seasonality of renewable resource*	**Low to moderate** *Dependent on seasonality of demand and ability to operate plant seasonally*	**Low to moderate** *Following load lowers capacity factor, and increases cost substantially*

Primary focus of this analysis (Variable renewable energy)

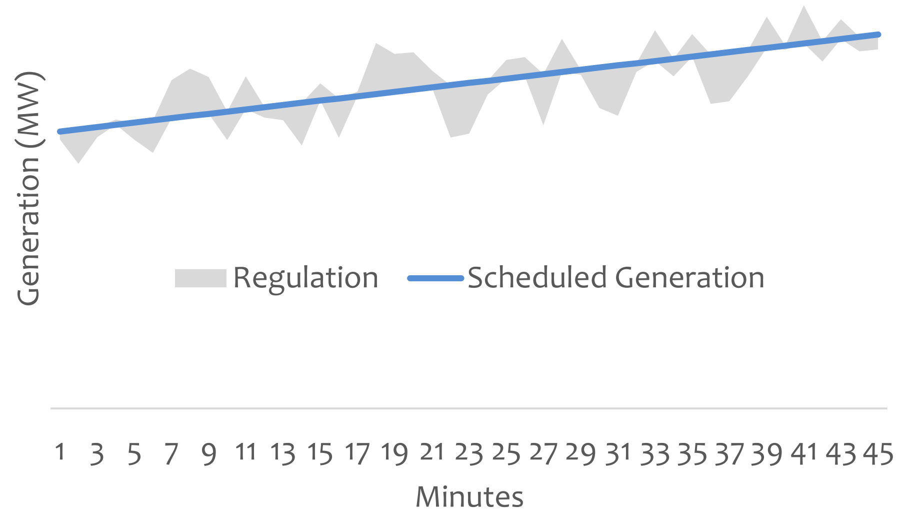
Spinning, load-following and short-term reserves: Renewables may increase generation forecast uncertainty, but mitigating solutions exist to limit this risk

Low to moderate

‘Contingency-based’ spinning and short-term reserves



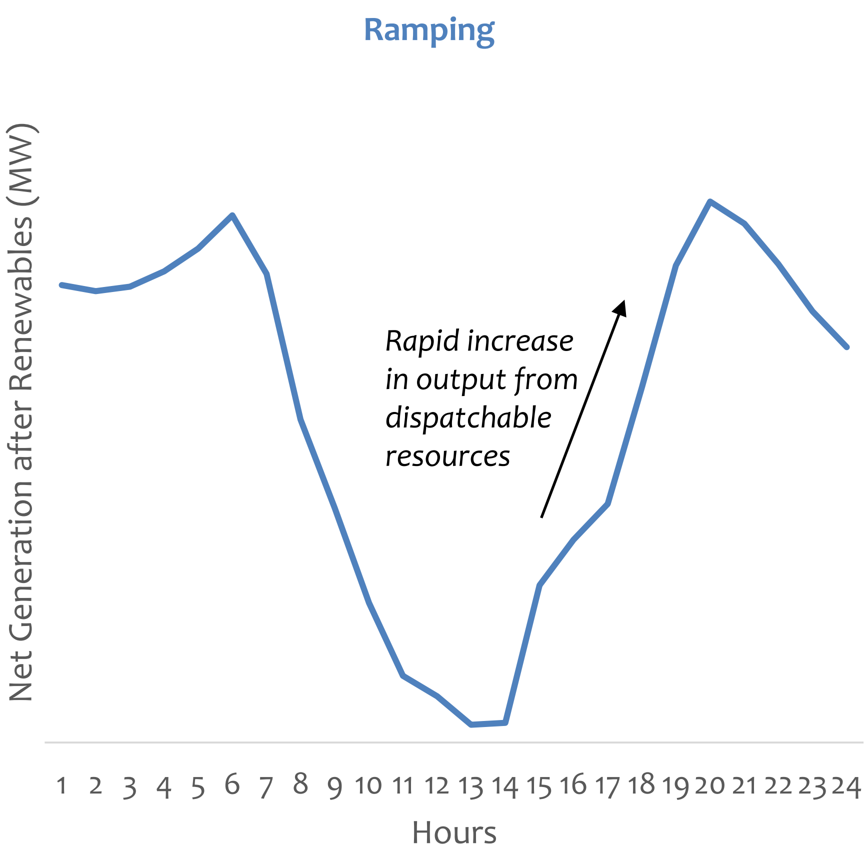
Load-following ‘regulation’ reserves



	‘Contingency-based’ spinning and short-term reserves	Load-following ‘regulation’ reserves
Power system need	• Generation that can come online quickly in case of unexpected generation / transmission outage • Typically less than 5% of peak load	• Rapid changes in output to account for differences between predicted and actual generation and load • Typically around 1% of peak load today, often provided by hydro and pumped storage • Often between 3-7% of renewable generation capacity to account for forecast uncertainty
Implications for renewable-based power system	• Increased renewables unlikely to change largest contingency • Often provided by excess headroom on operating generators, which could get pushed out of merit order by zero-marginal cost renewables	• Increased renewables may increase generation forecast uncertainty, although dynamic reserve requirements, improved forecasting, and lower delay from scheduling to delivery can lower requirement

Ramping: Daily patterns of renewable-based power generation will increase frequency and magnitude of ramping events

Moderate to high



Power system need

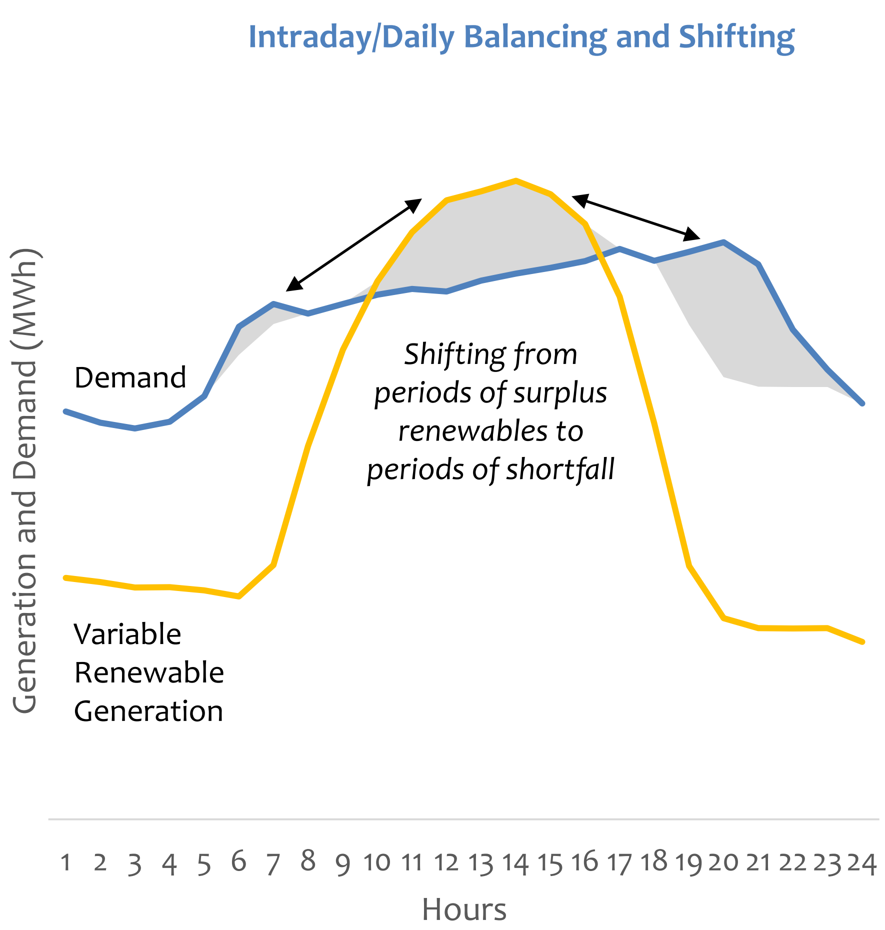
- Level of output can increase quickly as load increases or variable generation decreases, typically over 1-3 hours
- Generally, ramping needs can be predicted in advance, as opposed to unpredicted variations handled by regulating reserves
- Examples include ramping needed to accommodate drop-off of solar generation at sunset in solar-heavy systems

Implications for renewable-based power system

- Greater penetration of variable renewable energy will increase frequency and magnitude of ramping events
- Some thermal generation technologies (particularly coal and nuclear) cannot ramp production quickly, while others (natural gas turbines) can ramp to full production in a matter of minutes

Intraday / daily balancing: Renewables will increase misalignment between generation and load, increasing the need for shifting

Moderate to high



Power system need

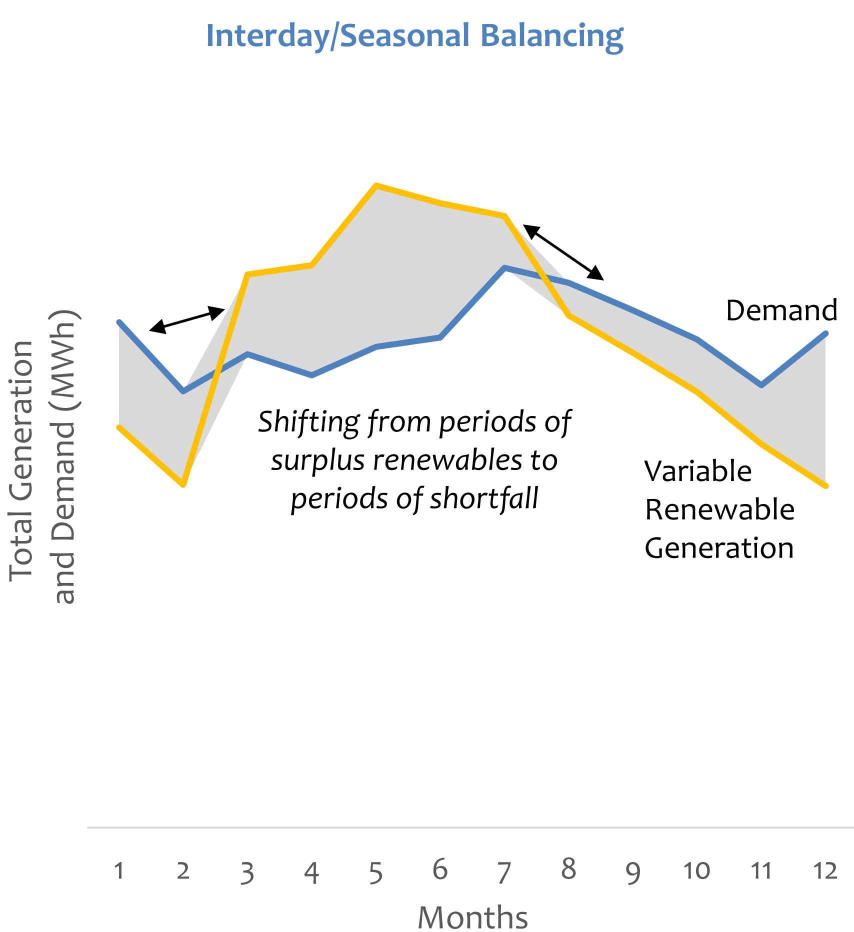
- Timing of variable renewable generation may not exactly match timing of electricity consumption
- Some electricity consumption may be time-shifted to periods of surplus renewable production or periods of low system demand
- Surplus electricity generation can be stored in batteries, pumped hydro storage, or other resources for later use

Implications for renewable-based power system

- Greater penetration of variable renewable energy will increase amount of surplus generation on some days and need for shifting
- Baseload thermal generation (nuclear, coal or gas) that remains online to serve other grid services (e.g. reserves) can increase the amount of surplus generation at times, increasing the amount of shifting needed

Interday / seasonal balancing: At high levels of renewable penetration, seasonal shifting needs may increase in response to seasonality of resource

Moderate to high



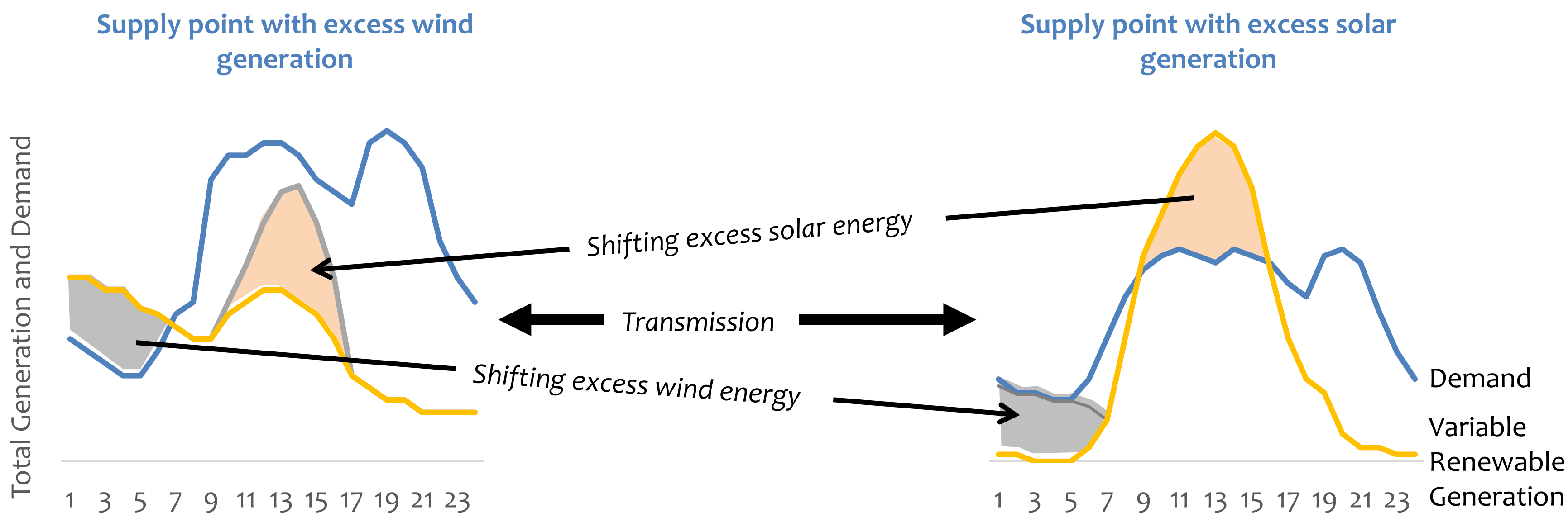
Power system need

- Both load and renewable energy generation have seasonal variation
- In addition, there is production uncertainty from year to year (e.g. drought years for hydro)

Implications for renewable-based power system

- At very high levels of renewable energy penetration, there will be months of surplus production and months of under-production, implying the need for long-term storage, long-term load shifting or balancing resources that operate only for several months per year

Locational flexibility: Renewables place a greater emphasis on optimizing transmission, distribution and the location of flexibility resources



Power system need

- Flexibility must be delivered to where it is needed as well as when
- Transmission and distribution can balance regional differences in electricity production and demand, but when differences become large transmission can become constrained and expanding the grid could become expensive
- Locating flexibility resources at strategic points in the grid can reduce the amount of flexibility that needs to be transported

---

Implications for renewable-based power system

- Distributed flexibility tools as well as those that can be located with renewable generation sources can have cost advantages
- Price signals need to offer locational differentiation to encourage flexibility to be developed in ways that minimize congestion, grid costs and losses

Contents

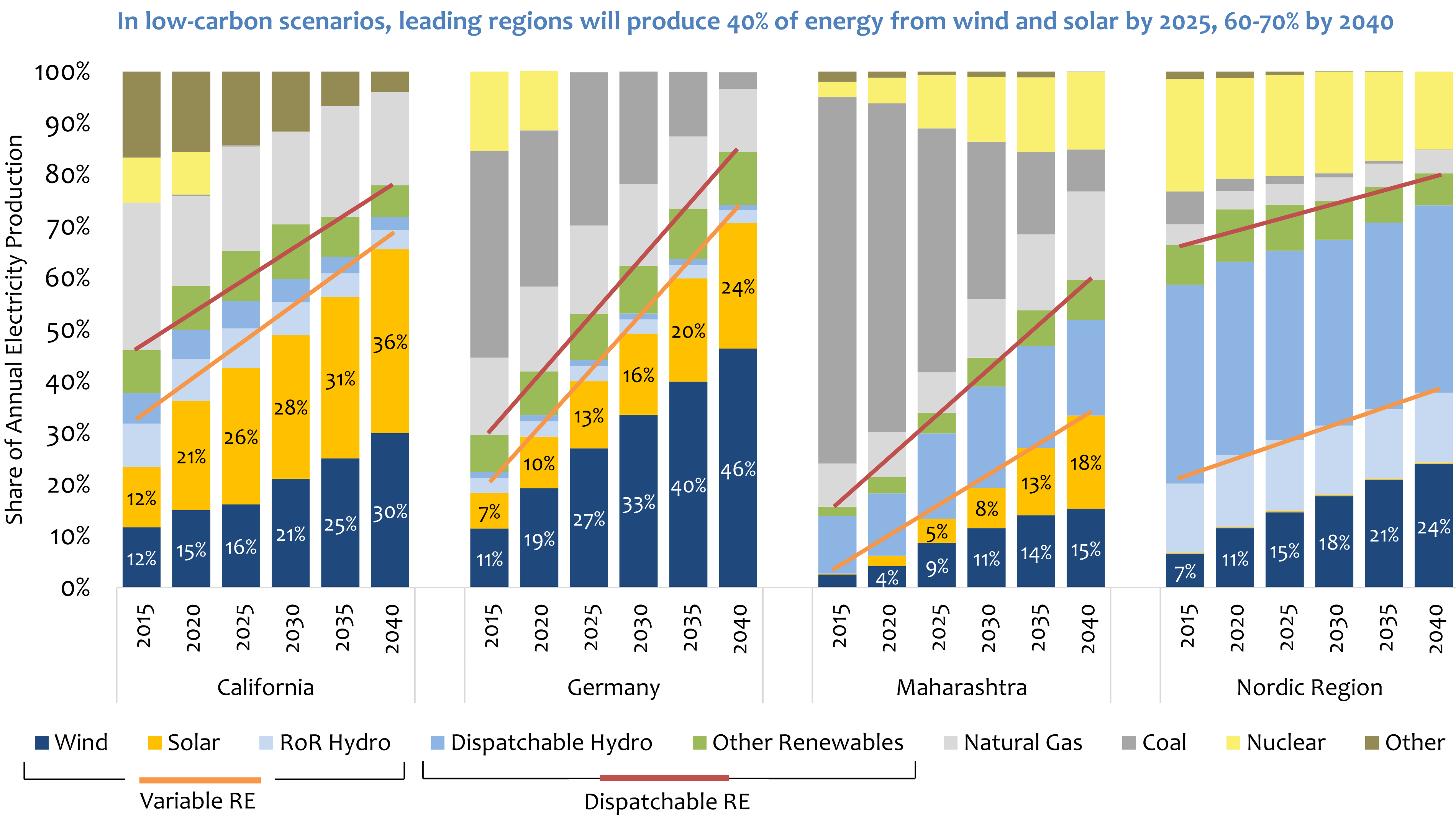
Future flexibility requirements are highly dependent on regional specifics, including demand profile, transmission capacity, hydroelectric capacity and weather

We have analyzed four regions with ambitious renewable energy plans, but very different renewable supply mixes and demand profiles, as well as different economic and institutional contexts.

The power systems of all four regions have adequate flexibility to support the integration of 30%+ variable renewable energy. However, Maharashtra also faces a rapidly developing economy and growing electricity demand, which will require more electricity generation – this is an opportunity to develop more flexible systems from the start.

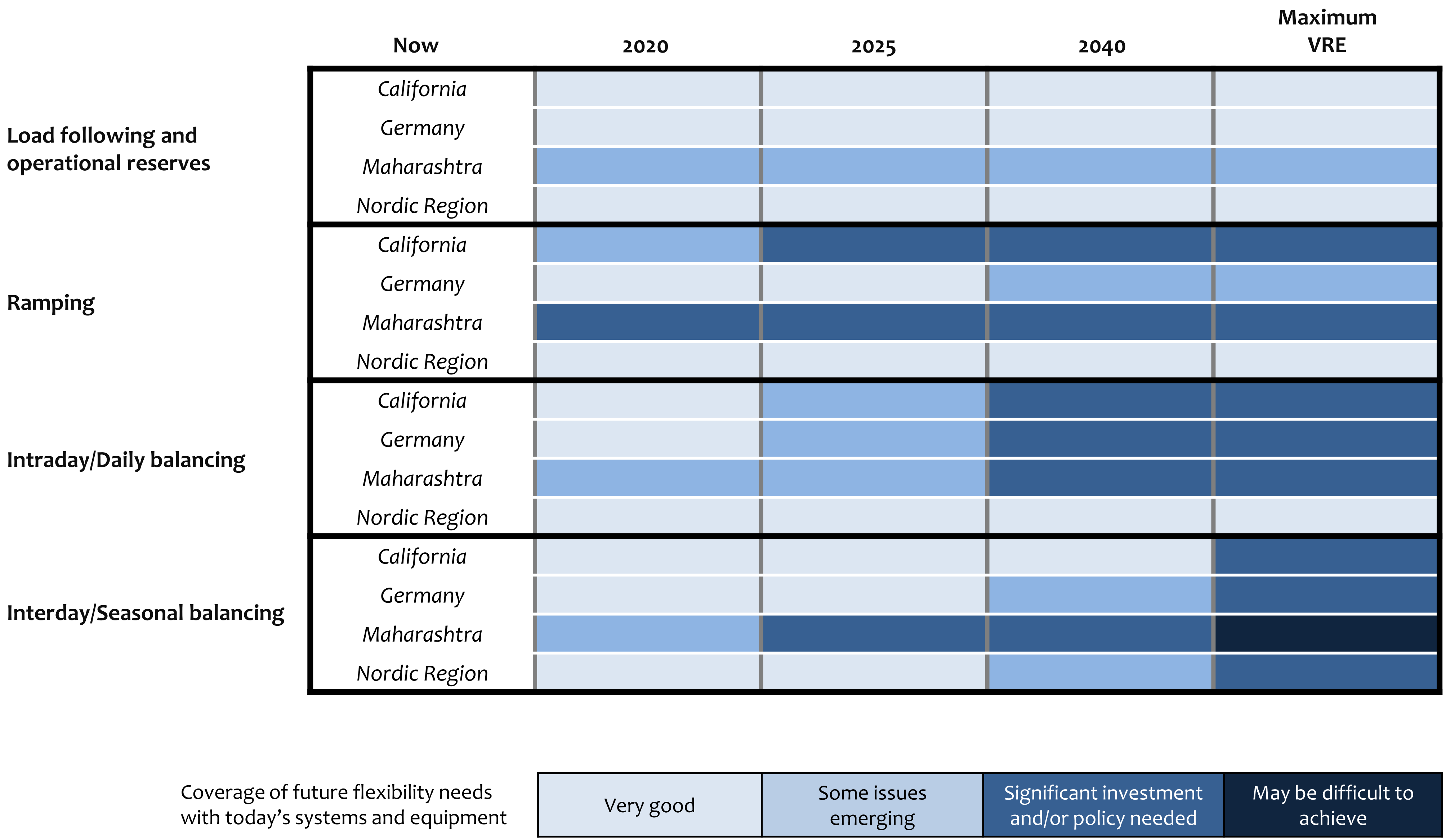
	California	**Germany**	**Maharashtra**	**Nordic Region**
Economic development	Advanced, diversified economy	Advanced, diversified economy	Emerging market still expanding energy access	Advanced, diversified economy
Renewable energy ambitions	High • 50% RE (ex. large hydro) by 2030	High • 50% RE by 2030	Medium • India-wide solar (100 GW) and wind (60 GW) missions by 2022, ~18% RE	High • Hydro-based • Varies by country, supporting carbon-neutrality by 2050
Hydro capacity	Medium	Medium	Low	High
Interconnections	Med/High • Southwestern coal, nuclear & solar / Northwestern hydro	High • Continental Europe and Nordic countries	Medium • Neighboring states and transmission companies	Medium/High • Continental Europe and future large expansions to UK and EU
Solar resource	High	Medium	High	Low
Demand profile	Summer peak driven by high AC load	Winter peak driven by heating load	Flat load profile, daily ramps driven by residential and commercial lighting and AC	Winter peak driven by heating load
Seasonal patterns	Wind and solar highest in spring / early summer	Wind peaks in winter driven by North Sea storms / Solar peaks in summer	Wind concentrated in May-Oct monsoon, solar consistent throughout the year	Wind output peaks in winter
Market structure	Regulated utilities with competitive wholesale market	Regulated transmission and distribution, competitive generation	Regulated retail with mix of regulated and competitive generation	Regulated transmission and distribution, competitive generation through Nord Pool
Existing plant capabilities	Flexible gas fleet	Significant lignite / coal generation low flexibility	Coal-based fleet	Hydro-based mix, with nuclear and thermal

To meet low-carbon objectives, all four regions analyzed will require over 50% of electricity produced by renewable energy by 2040, with California and Germany reaching 60-70% wind and solar by 2040



SOURCE: California – E3 Pathways Scenarios (2016) – "Other" primarily combined heat and power (CHP); Germany – Nitsch Szenario 2013 (2013); Maharashtra – India-wide projection from IEA Energy Technology Perspectives (2015); Nordic Region – IEA Nordic Energy Technology Perspectives, Carbon Neutral Scenario (2016)

Flexibility needs are well covered over the next 10 years in most regions, but intraday/daily and interday/ seasonal balancing will require more flexibility at very high level of renewable generation (I)



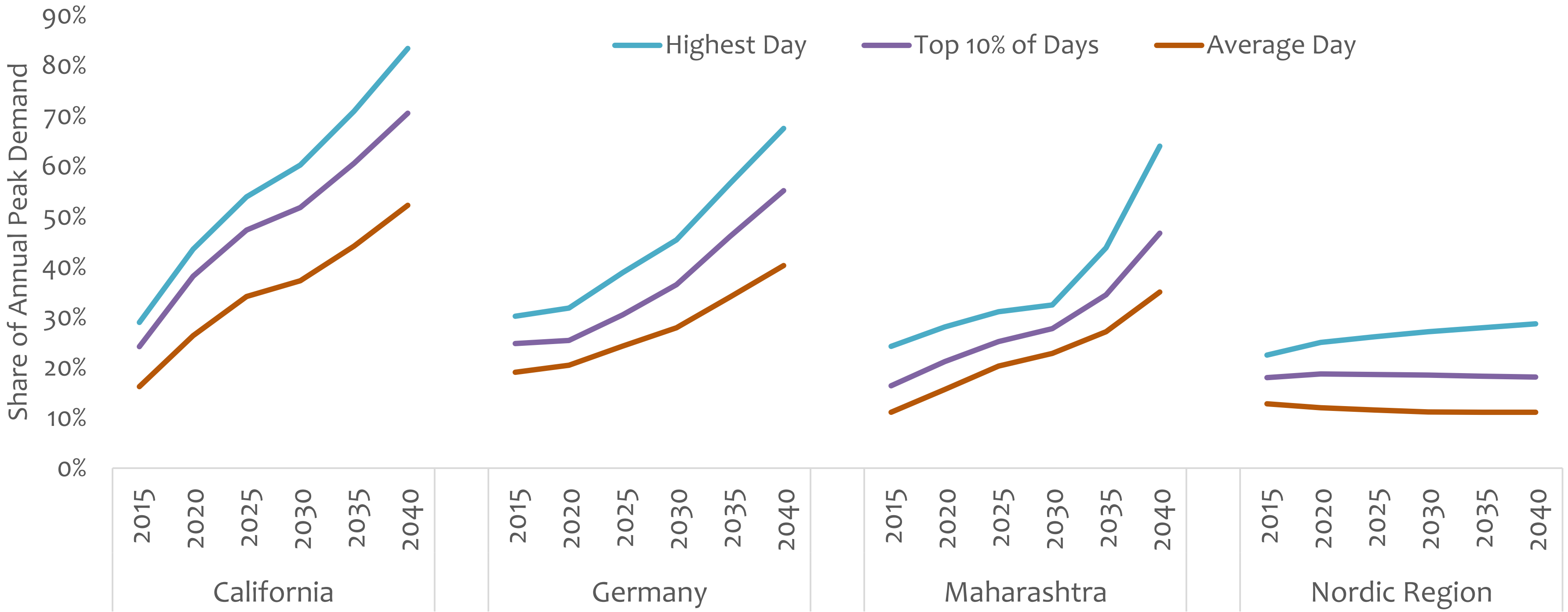
Flexibility needs are well covered over the next 10 years in most regions, but intraday/daily and interday/seasonal balancing will require more flexibility at very high level of renewable generation (II)

<table>
<tr><th>Region</th><th>Spinning/Load following (Primary/Secondary)</th><th>Short term (Tertiary) reserve</th><th>Ramping</th><th>Intraday / Daily Balancing</th><th>Interday / Seasonal Balancing</th></tr>
<tr><td>California</td><td rowspan="2">The needs for contingency and load following flexibility are unlikely to grow substantially due to low demand growth and now growth in largest plant size.
These markets appear well served now and into the distant future, but institutional and political issues do increase cost.</td><td rowspan="2">Uncertainty in solar and wind forecasts increasing standby backup needs.
Retirement of fossil fuel plants could eventually have as much impact as higher renewables.</td><td>Ramp-up needs growing substantially due to increased solar penetration. Uncertainty at sunset is an important issue.</td><td rowspan="2">Regulators and policymakers depending upon market mechanisms they have created.
Investors and technology developers do not see market signals to justify investment.
Current technology and policy available but could be very costly if not implemented strategically.
Renewable energy curtailment is a favorite mechanism, but can be a costly approach.</td><td rowspan="2">Long-term problem that will become more important with higher levels of renewable energy penetration.
Relatively little longer-term development, but well planned mix of wind and solar can contain shifting need.</td></tr>
<tr><td>Germany</td><td>Diversity of renewable resources and weather patterns lessen ramp up impact of wind and solar.</td></tr>
<tr><td>Maharashtra</td><td colspan="2">Rapidly growing demand, improved power quality and increased electrification leading to increasing demand for flexibility.</td><td>Ramp up needs growing fast as increasing consumer use of electricity pushing up evening ramp up.</td><td>Little focus on daily load shifting; often handled through customer curtailment.</td><td>Questions about how to deal with higher renewable penetrations with seasonal output variation.</td></tr>
<tr><td>Nordic region</td><td colspan="4">Abundant hydro resources create a significant surplus of flexibility resources.
Surplus flexibility may be absorbed through Swedish nuclear retirement and replacement with wind.
Electrification of heating, and district heating systems, provide additional, easy-to-access flexibility resources.
Key questions revolve more about whether it is cost-effective to export this excess flexibility.</td><td>Questions remain about what to do in case of a prolonged drought.</td></tr>
</table>

Ramping needs are growing over time in every region, driven by greater output fluctuation and growing loads at peak

Ramping needs in four regions of study in low-carbon scenarios

Highest, top 10% and average daily 3-hour ramp (% of annual peak demand), assuming no existing flexibility



Key drivers

California:
- Solar output declines at sunset, right as evening load peaks

Germany:
- Solar output declines at sunset
- Swings in wind output (e.g. storm fronts)

Maharashtra:
- Solar output declines at sunset
- Growing household and commercial load increases evening peak

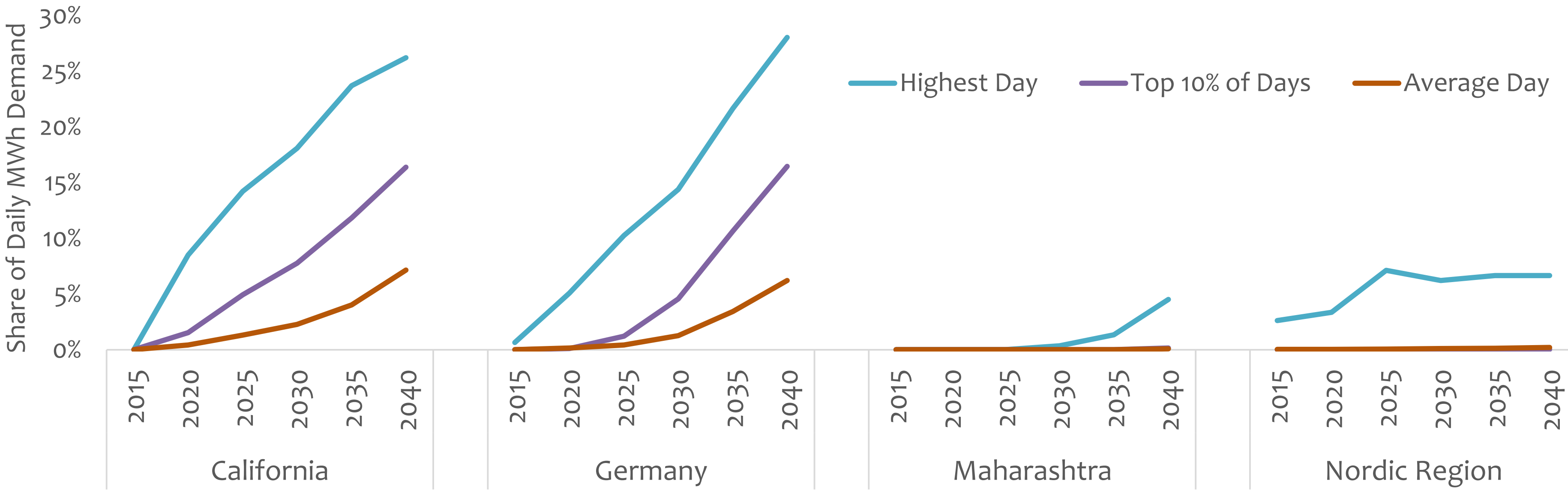
Nordic Region:
- Swings in wind output (e.g. storm fronts)

SOURCE: CPI Analysis – Assumes aggressive electrification of vehicle transport, heat and water heating, based on E3 analysis.

Intraday/daily balancing needs are highest in California and Germany, where the share of variable renewable energy is expected to be highest

Intraday/daily balancing needs in four regions of study in low carbon scenarios

Highest, top 10% and average daily energy shifting need (% of daily MWh demand), assuming no existing flexibility



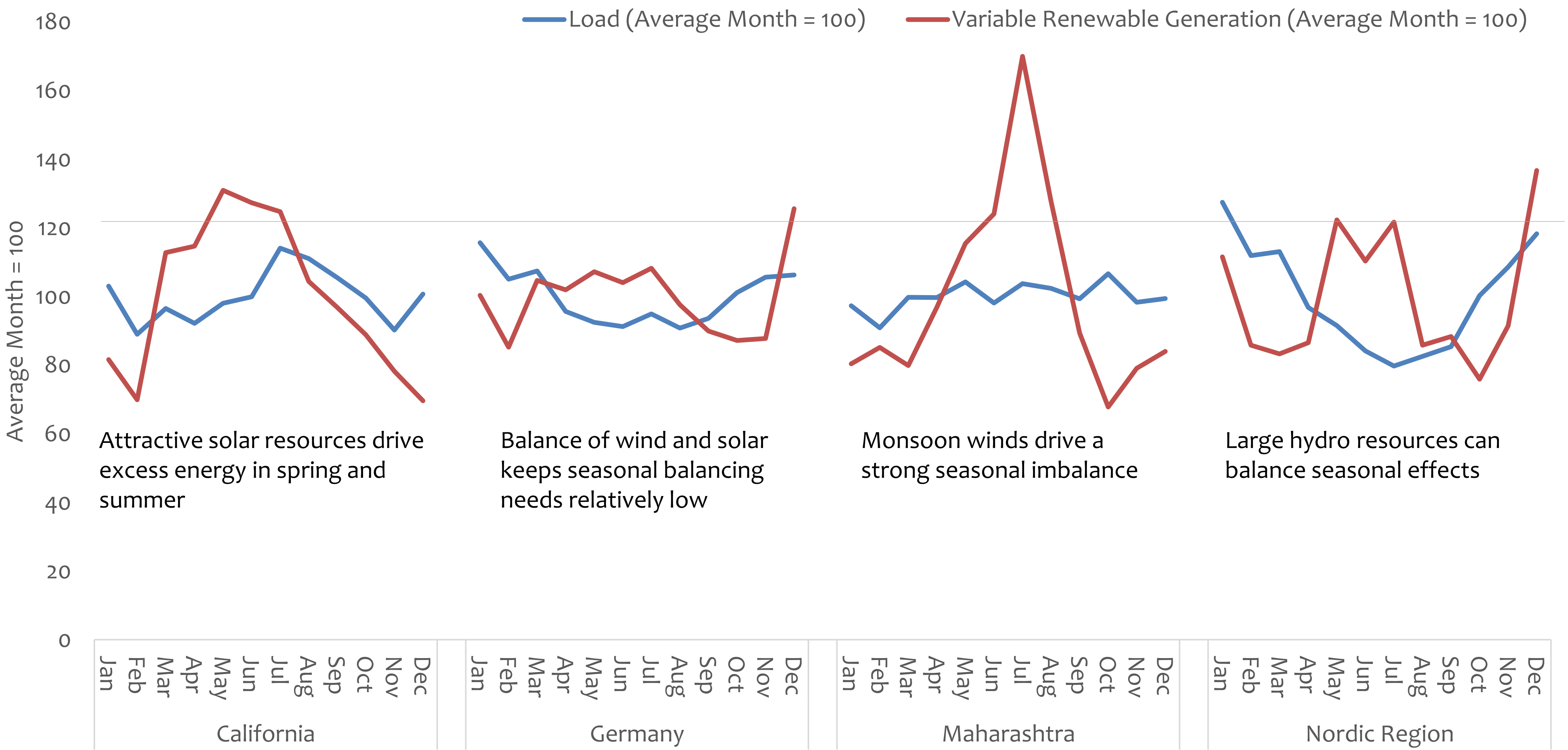
Key drivers				
	• Increasing number of hours and MWh of surplus production from wind and solar	• Increasing number of hours and MWh of surplus production from wind and solar	• Comparatively low share of wind and solar (vs. California and Germany) leads to few hours of surplus production	• Comparatively low share of wind, and virtually no solar (vs. California and Germany) lead to few hours of surplus production

SOURCE: CPI Analysis. Note that assumed energy mix includes expected coal and nuclear baseload share, operating at typical minimum generation levels, as non-dispatchable.

Differences in load and renewable energy generation patterns drive differences in interday/seasonal balancing needs

2040 demand and variable renewable generation relative to average month in four regions of study in low carbon scenarios

Index, average month = 100

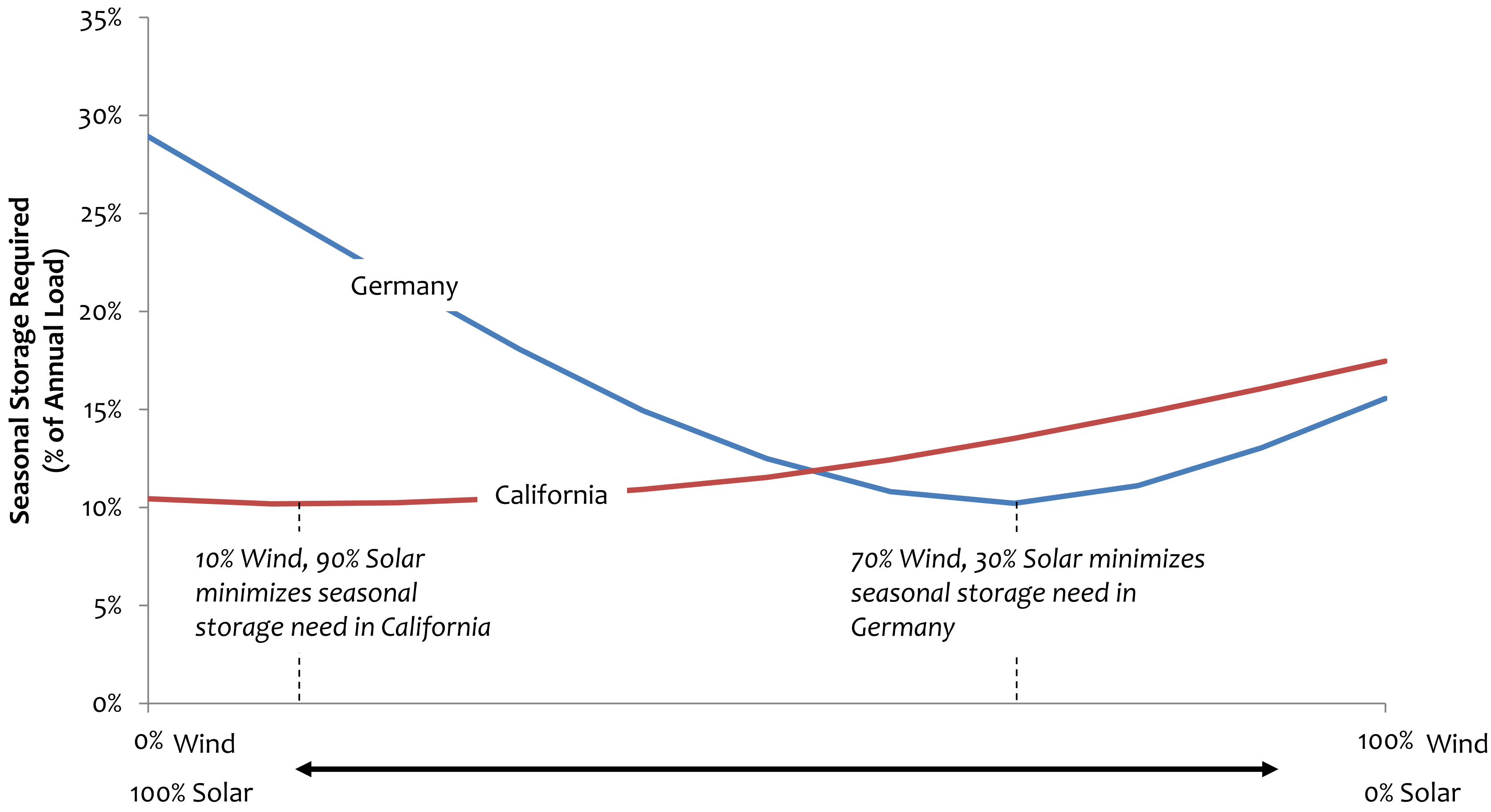


SOURCE: CPI Analysis

Optimizing the mix of renewable energy sources can significantly mitigate interday/seasonal energy shifting needs

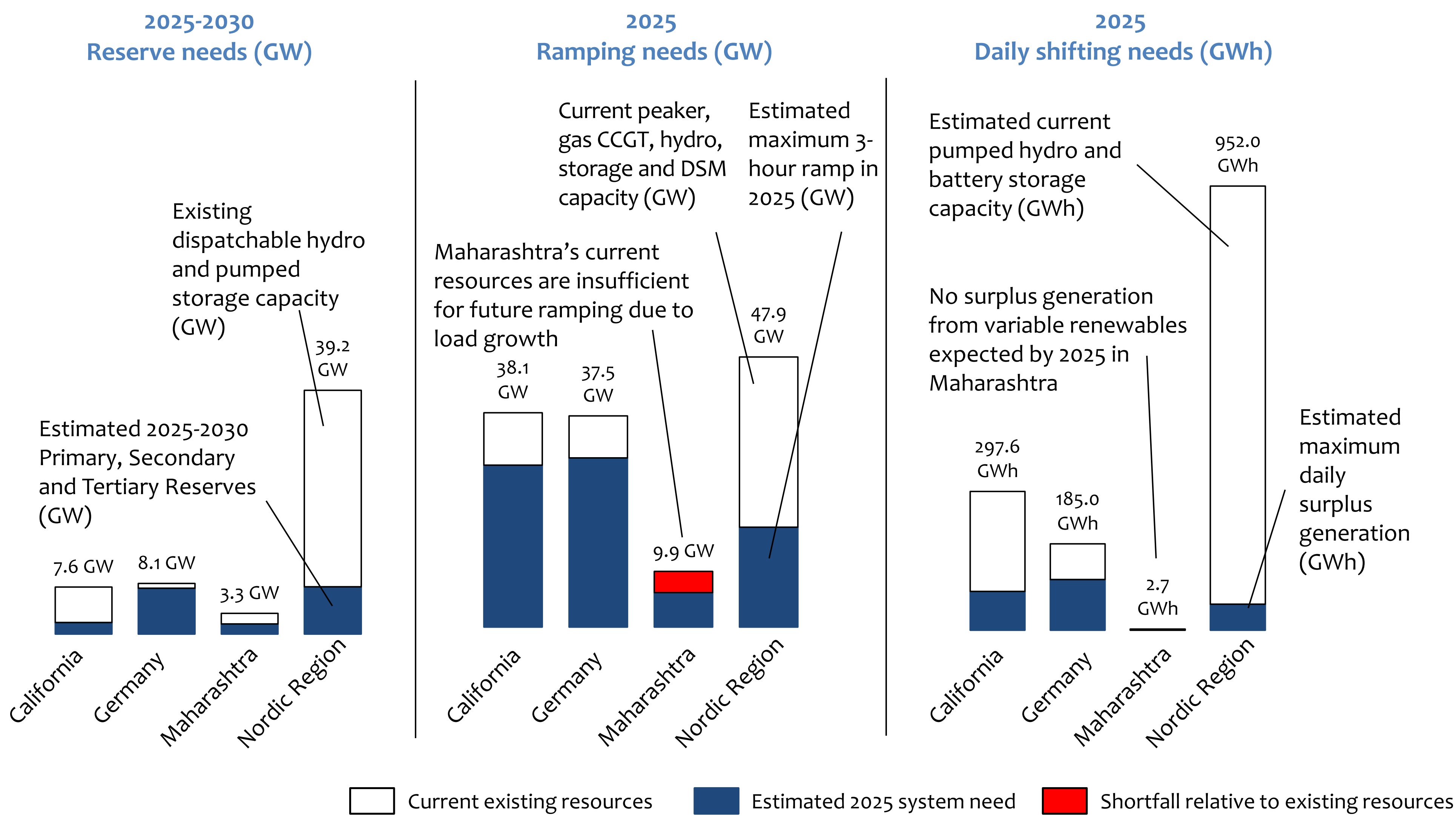
Cumulative interday/seasonal storage required for different shares of wind and solar

% of annual MWh



SOURCE: CPI Analysis – California and Germany chosen to illustrate how different regions with different resource profiles will have different optimal energy mixes.

Today's power systems have adequate resources to meet the flexibility needs by 2025, when some regions' systems will exceed 30% variable renewable energy



SOURCE: CPI Analysis – Based on California: 42% VRE / Germany: 40% VRE / Maharashtra: 14% VRE / Nordic Region: 15% VRE

Institutional issues, forecasting, interconnections and regional strategies all add complexity to regional flexibility needs

	California	Germany	Maharashtra	Nordic Region
Institutional issues	• Accessing flexibility from other States • Market designs, jurisdictions, and industry structure preventing lowest cost options • 10-year planning horizon	• Focus on near term overcapacity distorts the debate – Does 10-year planning horizon lock in fossil fuel power plants? • Multiple transmission operators reduce coordination and create conflicting signals	• Ancillary service markets being considered and developed, but delays caused by implementation issues and lack of telemetry infrastructure • Significant curtailment already occurs, but not necessarily organized	• Uncertainty around impact of Swedish nuclear retirement
Data and forecasting	• Lack of data on distributed PV additions and locations causing errors at sunset • Improved forecasting can significantly reduce costs	• Move to dynamic forecasting could meet spinning and short-term reserve needs at much higher levels of renewables	• Frameworks for forecasting connected and embedded generation are just in process of being developed	**Key questions:** • How best to use the Nordic Region's excess flexibility? • New interconnections to export flexibility value? • Build additional renewable energy to replace nuclear, but use up excess flexibility? • Should low-cost local flexibility options be developed to enhance export of flexibility? • Would hydro be competitive in export markets once transmission costs are included? • How to protect supply against future droughts?
Inter-connections	• Connections to other western States could be expanded, but institutional issues prevent full use of existing interconnection	• Potential to tap flexibility across Europe and from Nordics, but potential challenges integrating regional markets	• Rapid expansion of transmission networks, but cost issues	
Concerns / Strategy	• Pricing of use and access to distribution system • Day-ahead flexibility left to market signals, but these signals may be insufficient • 50% renewable penetration by 2030 • Procurement of storage in progress, generally focused on managing peak loads	• Constraints at local and transmission level in the North of the country • Nuclear retirement will increase system load shifting flexibility, but increase seasonal issues • Curtailment will increase markedly after 2023 without new flexibility	• Growing demand and increasing connection is driving up flexibility needs • Crucial concerns are meeting growing peak and then ramp-up • Demand response programmes being launched • Storage expensive	

Contents

System flexibility can be achieved today with a range of existing technologies, and expected improvements in their cost-effectiveness could reduce the total cost of a renewable-based power system even further

Our analysis suggests that by 2030 the maximum cost of flexibility would be $30/MWh for a system where nearly all electricity is supplied by variable renewable energy.

Different technologies are best suited to providing different flexibility services.

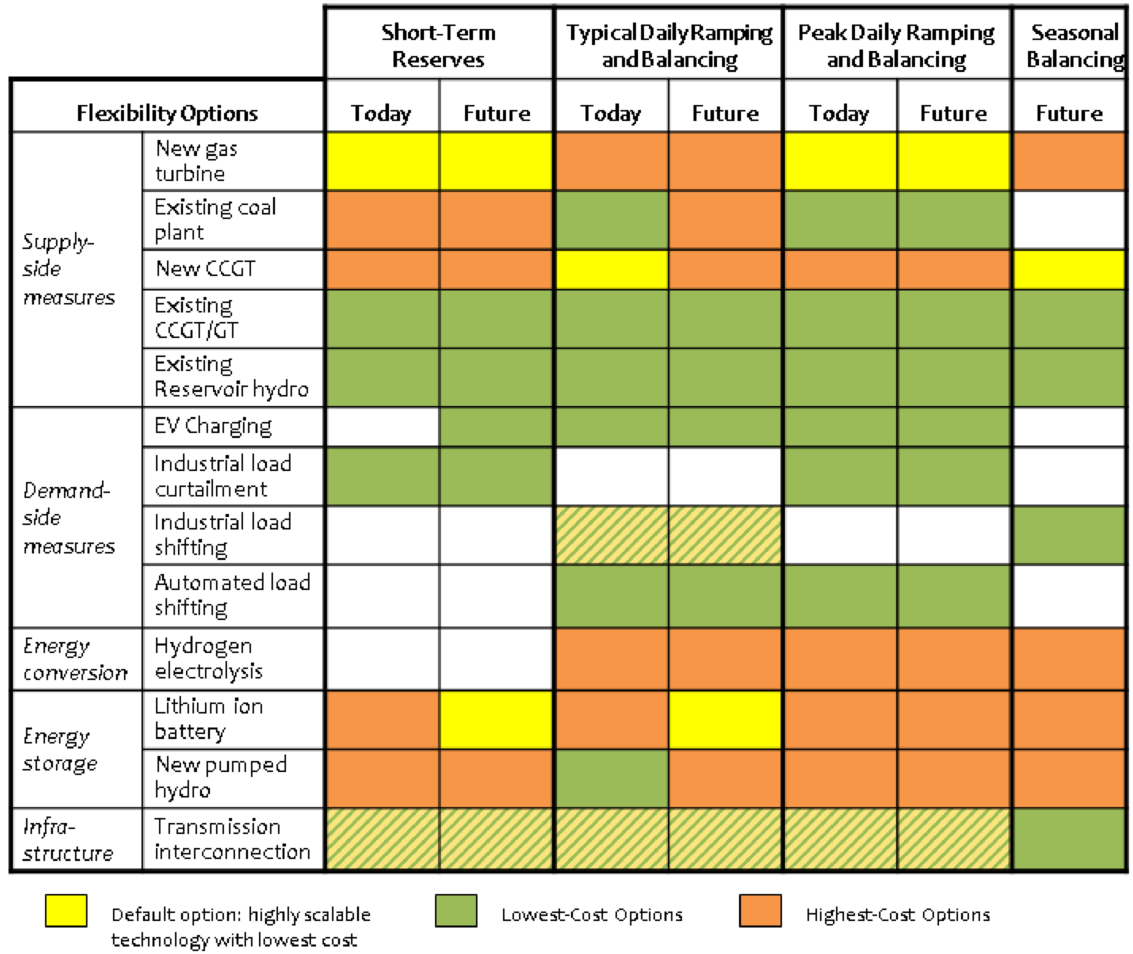
Existing power plants and demand-side flexibility are the lowest-cost sources of flexibility for today's power system.

However, batteries are expected to be competitive as a low-cost, highly scalable source of flexibility in the near future.

Electrification of transport and heating will increase the amount of demand that can be made flexible, provided the right policy and market signals are in place.

Even lower flexibility costs can be realized by optimizing resources to provide several types of flexibility from the same asset.

Cost competitiveness changes over time



Many technological and operational options exist to add system flexibility

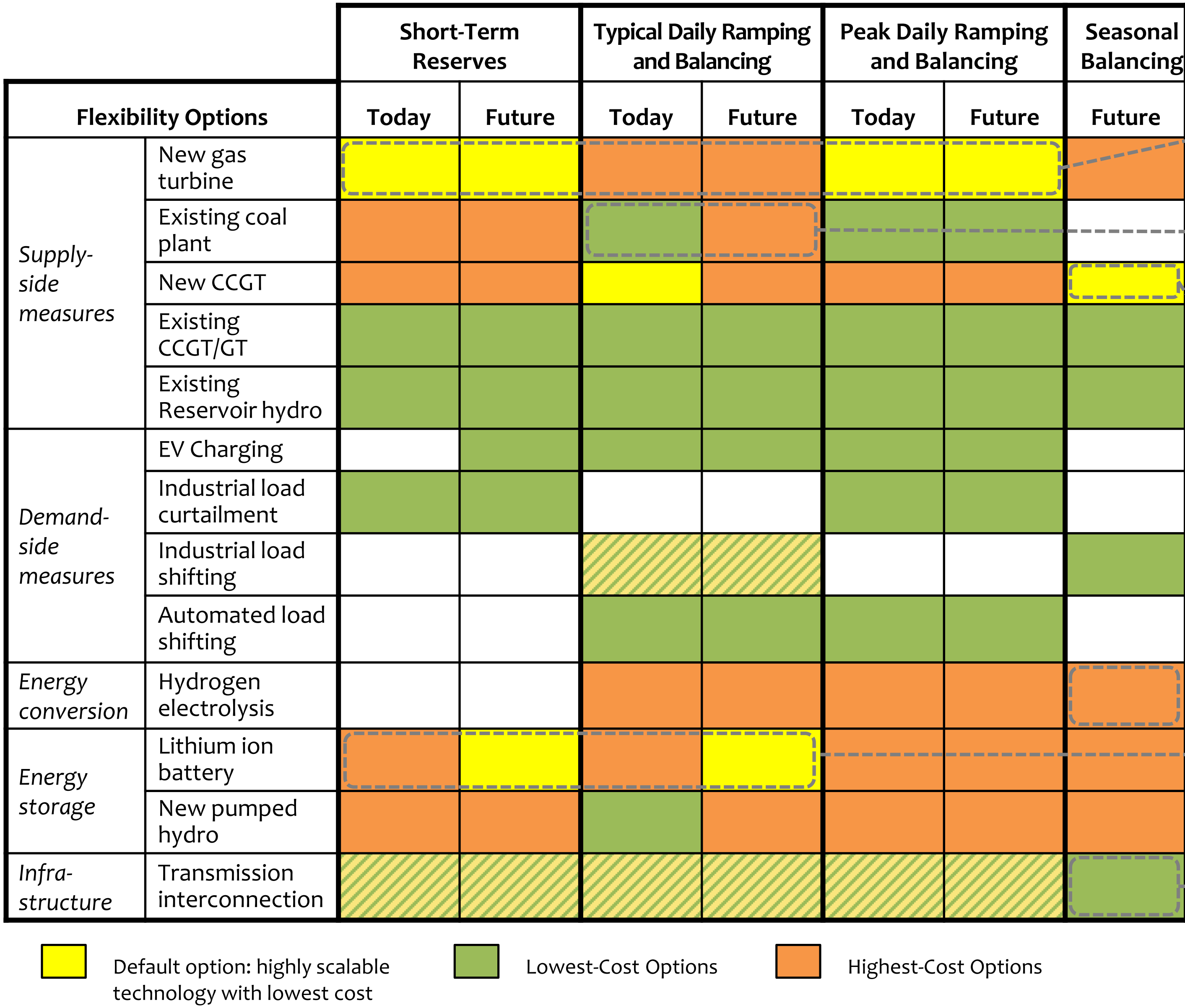
Supply-side measures	Demand-side measures	Conversion to other energy forms	Direct electricity storage	Infrastructure
Operating existing plants more flexibly • Coal • Gas • Storage hydro • Run-of-river hydro **Build new flexible plants** • Flexible gas • Hydro • Concentrated solar • Biomass • Tidal or wave power **Renewable curtailment** • Existing utility scale wind and solar • New utility scale wind and solar • Distributed solar curtailment • Improved forecasting **Delayed plant retirement** • Coal • Gas	**Industrial demand response** • Steel industry • Aluminum industry • Chemicals • Pulp and paper • Cement • Manufacturing **Commercial & residential demand response** • Heating • Cooling • Lighting • Water heating • Data centers • Refrigeration • Appliances & electronics **Water and waste** • Pumping • Desalination **Real time pricing** • By sector **Behavioral response** • By sector **Automation/direct control** • Consumer aggregation • Other by sector	**Heat and thermal inertia** • Storage heating • Storage cooling • CHP and district heating **Transport** • Light vehicle charging • Fleet LV charging • Bus and rail **Hydrogen production and similar** • Hydrogen production and storage • Synthetic fuels • Fertilizer **Other industrial products** • Production and storage of chemicals • Steel • Cement • Etc.	**Batteries** • Lithium ion • Lead acid • Zinc bromine flow • Other flow batteries • Lithium air • Solid state • Aqueous saltwater **Flywheels** **Supercapacitors** **Pumped storage hydro** • Pure pumped storage • Mixed pump-reservoir storage **Compressed air energy storage**	**Existing infrastructure** • Improved balancing and control **New transmission** • Intraregional reinforcement • Interconnection and regional expansion **Transmission smart grid technologies** • SCADA, etc. **New distribution** • Reinforcement • Active transmission elements (capacitors, management systems, etc.) **Distribution smart grid technologies** • Control systems and automation

These solutions can address different flexibility needs

Degree of technical fit: Low | Low-Med | Med-High | High

		Spinning/ Load following	Short-term reserve	Ramp-up capacity	Load shifting (day-night)	Interday/ Seasonal shifting	Location flexibility - Bulk	Location flexibility - Distrib.
Supply side measures	Operating existing fossil plant more flexibly	High	High	High	High	High	High	Low (light shading)
	Build new flexible plant	High	High	High	High	Low (light shading)	High	Low-Med
	Renewable energy curtailment	Low	Low	Low (light shading)	Low-Med	Low (light shading)	Low-Med	Low (light shading)
	Delayed plant retirement	Low	Low	Low	Low (light shading)	High	Low (light shading)	Low
Demand side measures	Industrial demand response	Low (light shading)	Med-High	Low	Med-High	Low (light shading)	Low (light shading)	Low
	Commercial/Residential demand response	Low	Low	Low-Med	High	Low-Med	Low-Med	Med-High
	Water and Waste	Low	Low	Low	High	Low-Med	Low (light shading)	Low (light shading)
	Real time pricing	Low	Low	Low-Med	High	Med-High	Med-High	Med-High
	Behavioral response	Low	Low-Med	Low-Med	High	Low (light shading)	Low (light shading)	Med-High
	Automation and direct control	Med-High	Med-High	Med-High	High	Low-Med	Med-High	High
Conversion to other forms of energy	Electric storage heating and cooling	Low	Low	Low-Med	High	Low (light shading)	Low	Low
	Transport (electric vehicle charging)	Low	Med-High	Med-High	High	Low	Low-Med	High
	Hydrogen production	Low	Low	Low-Med	Med-High	High	Low-Med	Low
	Other industrial products	Low	Low	Low	Med-High	Med-High	Low	Low
Direct electricity storage	Batteries, flywheels, supercapacitors	High	Med-High	Med-High	Med-High	Low	Med-High	Med-High
	Compressed air energy storage	High	High	High	High	Low	Low-Med	Low
	Pumped storage hydro	High	High	High	High	Low-Med	Low (light shading)	Low
Infra-structure	Existing transmission and expansion	Med-High	Med-High	High	High	Med-High	Med-High	Med-High
	New interconnectors	Low	Low	Med-High	High	Med-High	Low (light shading)	Low
	Distribution expansion	Low	Low	Low	Low	Low	Low (light shading)	High
	Smart grid technologies	Med-High	Med-High	Med-High	Med-High	Low	High	High

The cost-effectiveness of many flexibility options will evolve over time



Gas turbines are a default technology for many flexibility needs. The amount needed will depend on how much other flexibility is developed.

Existing power plants will have a role in daily balancing the system, but some may become relatively high cost in the future.

CCGTs are the marginal source of seasonal balancing (in the distant future) once all cheaper options are exhausted.

Almost all demand side options are in the money, if we can overcome traditional obstacles around incentives, pricing and customer management.

Hydrogen could work as baseload, but the economics do not support any flexibility option.

Lithium ion batteries can replace GTs as the default choice in some short-term needs.

Transmission will be case-specific, but has a lot of low-cost flexibility to contribute.

Flexibility cost curves help assess which flexibility options will be needed and will create value

Our analysis of flexibility cost differs by requirement:

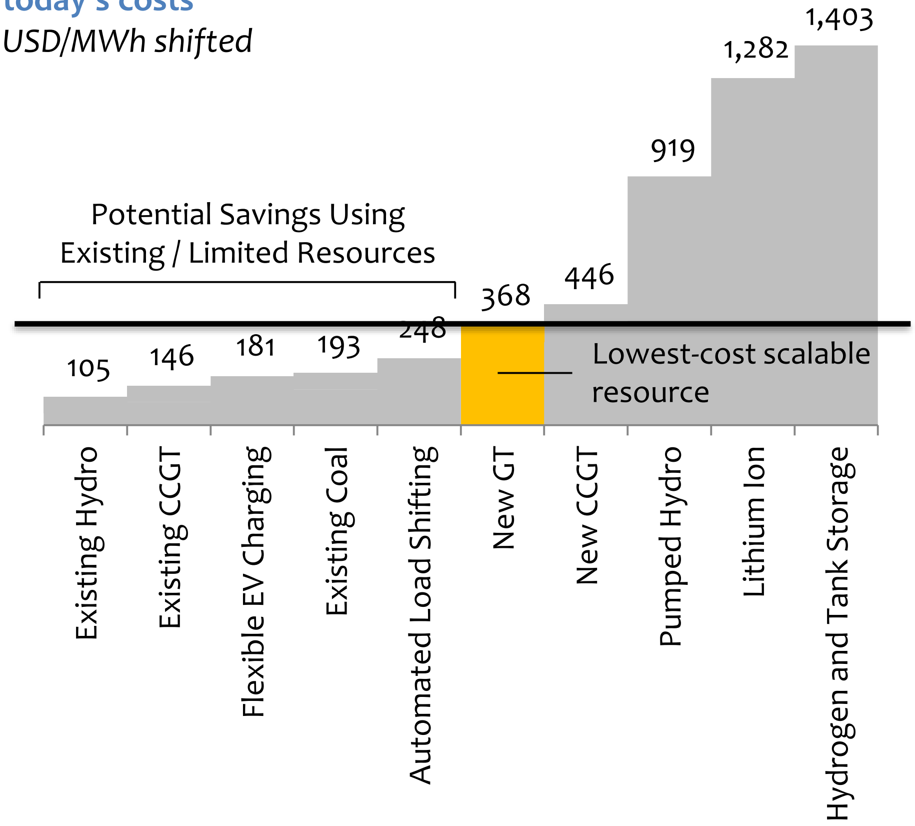
- For short-term (10-minute) reserves, the cost is to build and maintain capacity to sit in reserve.
- Intraday/daily and interday/seasonal shifting is the cost of moving energy from an excess period to a period of shortage, including fixed costs.
- Some flexibility technologies can shift energy, like batteries, others only produce energy, like gas turbines. For comparison, for those that only produce energy, we include the cost of energy that must be curtailed in the cost of shifting.
- For existing capacity, we include fuel, operating and maintenance costs, energy losses. For new capacity, we also include capital costs amortized over the life.

In the example on the right, the flexibility potential of the low-cost resources to the left of the gold column (from existing hydro through load shifting) is limited by existing capacity or consumer demand (load shifting**)**.

Of those technologies that are not limited by existing capacity or demand, a new gas turbine would be the cheapest way to meet a shifting need that has an impact for 5% of the year, or about an hour a day. $368/MWh includes $50/MWh of renewable energy curtailment. This is the "lowest-cost scalable resource", which would effectively be the default technology that sets a maximum cost for building new flexibility resources.

Example – Cost of peak day shift at 5% capacity factor: today's costs

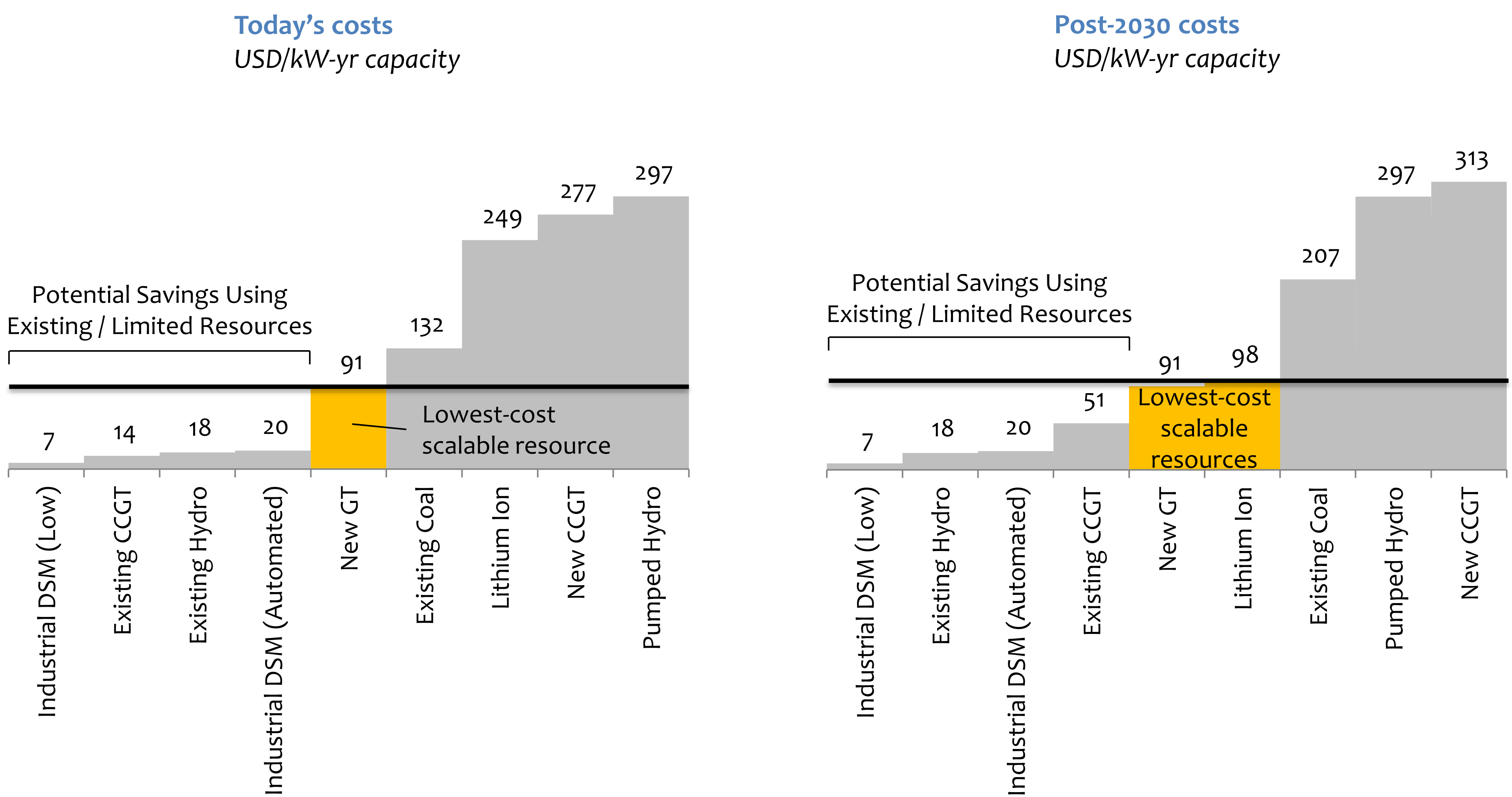
USD/MWh shifted



In this example, while a new gas turbine would set a theoretical market price, the marginal resource in a low-cost portfolio of hydro, existing capacity or demand management sufficient to meet requirements, could also set the price.

Short-term reserves: Existing hydro and demand-side flexibility are low-cost options to replace reserves currently provided by fossil fuel-based power plants

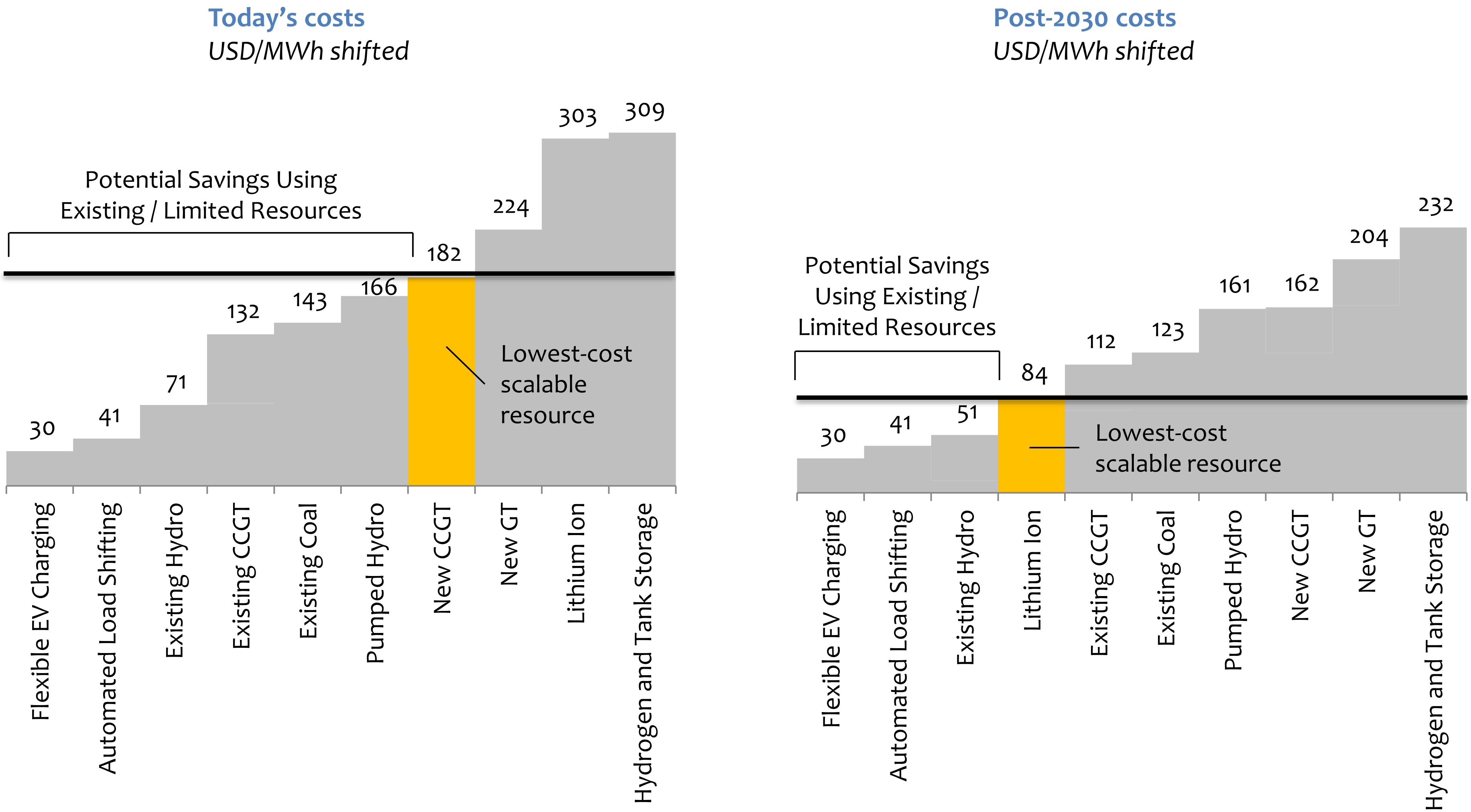
Cost of providing 10-minute reserve capacity



SOURCE: CPI analysis. Total fixed costs are allocated to plant capacity available within 10 minutes. "Unrecovered operating costs" based on operating time when variable renewables are on the margin - assumed to be negligible for today's cost, and 7% at minimum generation level in 2040, based on expected overgeneration. Includes $50/ton carbon price.

Intraday/daily balancing (typical day): Flexible loads and existing resources are the most cost-effective options today, but rapid declines in lithium ion batteries costs will yield a low-cost alternative

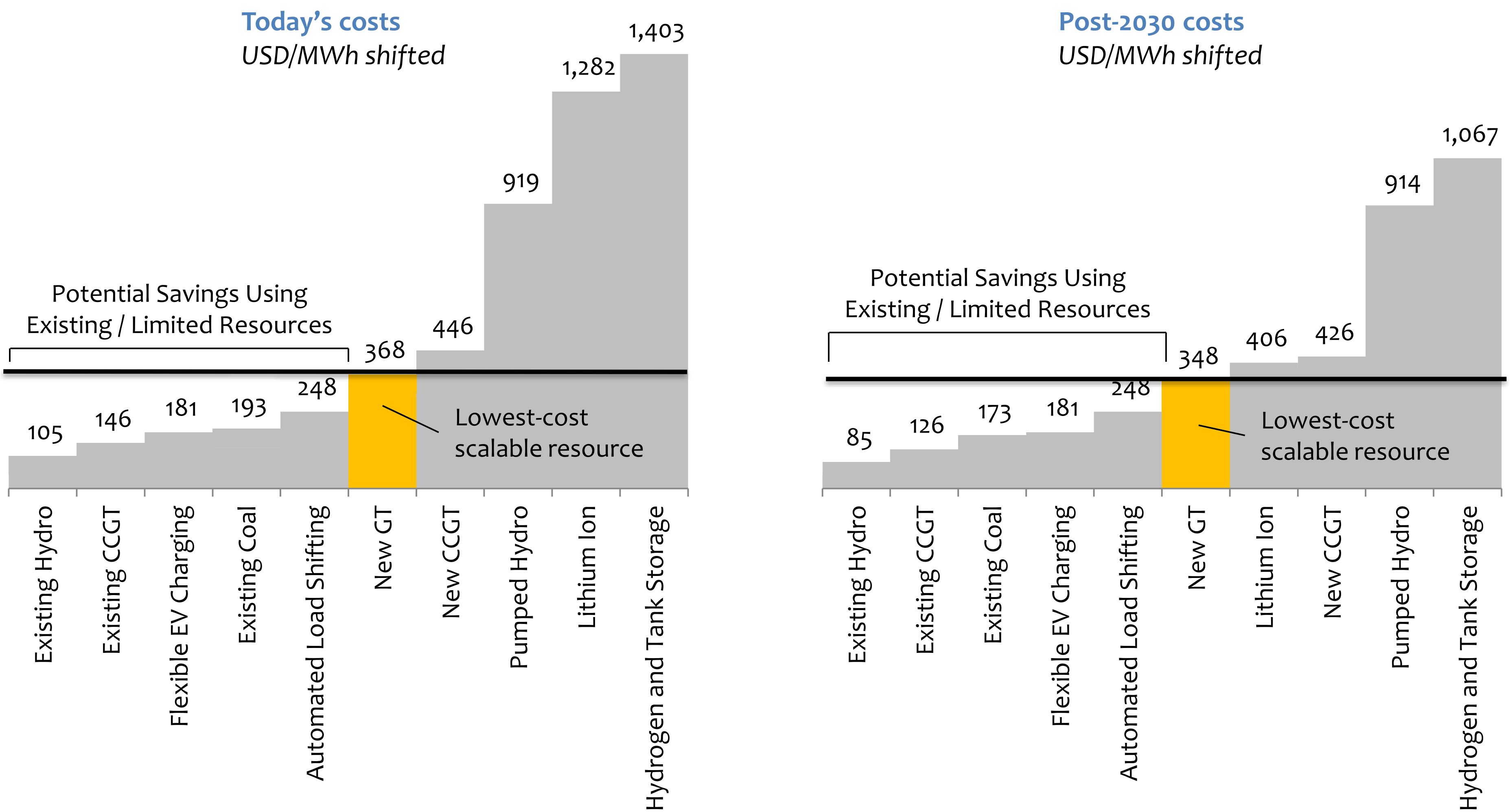
Cost of intraday shifting – 30% capacity factor



SOURCE: CPI analysis. Curtailment cost for renewable energy of $60/MWh for today's costs, $40/MWh for post-2030 costs. Shifting costs for storage technologies include losses valued at cost of curtailment of renewable energy. Includes $50/tonne carbon price.

Intraday/daily shifting (peak day): Peak intraday shifting needs may require gas generation by default, although cheaper shifting options exist

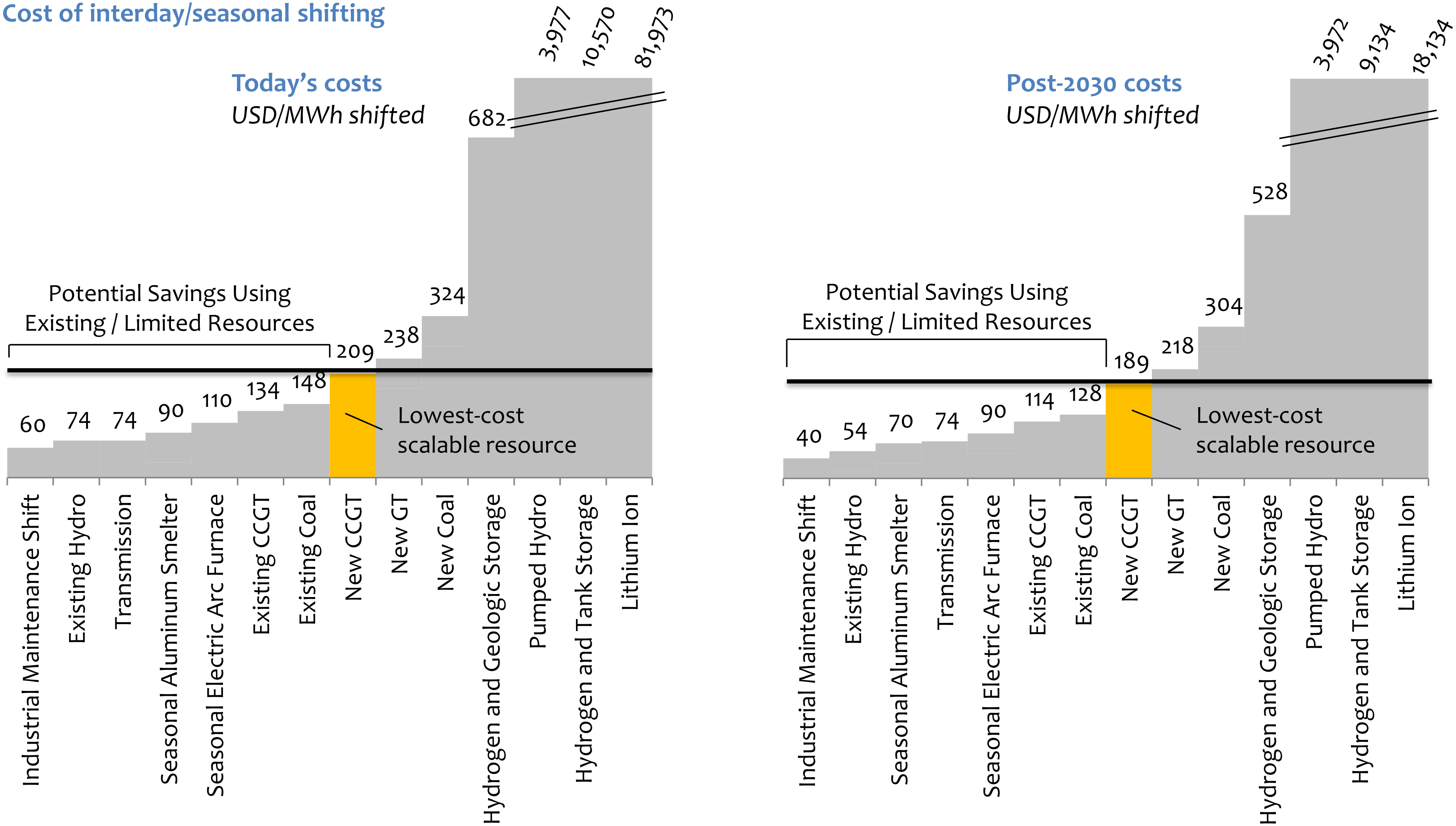
Cost of intraday shifting – 5% capacity factor



SOURCE: CPI analysis. Curtailment cost for renewable energy of \$60/MWh for today's costs, \$40/MWh for post-2030 costs. Shifting costs for storage technologies include losses valued at cost of curtailment of renewable energy. Includes \$50/tonne carbon price.

Interday/seasonal shifting: Seasonal storage requires 1-2 cycles of stored energy per year, leading to high costs for traditional storage technologies

Cost of interday/seasonal shifting



SOURCE: CPI Analysis. Curtailment cost for renewable energy of $60/MWh for today's costs, $40/MWh for post-2030 costs. Shifting costs for storage technologies include losses valued at cost of curtailment of renewable energy. Includes $50/tonne carbon price. Generation assumes 20% capacity factor. Storage assumes 1 cycle per year. Transmission assumes 40% utilization and interconnected flexibility resources.

Assets and technologies may serve more than one flexibility need, which will change the relative cost

The cost of any flexibility option can be shared between several flexibility needs.

Our analysis of the maximum system flexibility costs includes sharing of costs between different flexibility needs.

As an example, intraday/daily flexibility needs may require building new CCGTs.

Once these are built, they can be used to meet interday/seasonal flexibility; for instance, by using them to meet intraday/daily flexibility needs during seasons where there is a shortage of renewable energy, but using batteries during seasons with excess renewable energy.

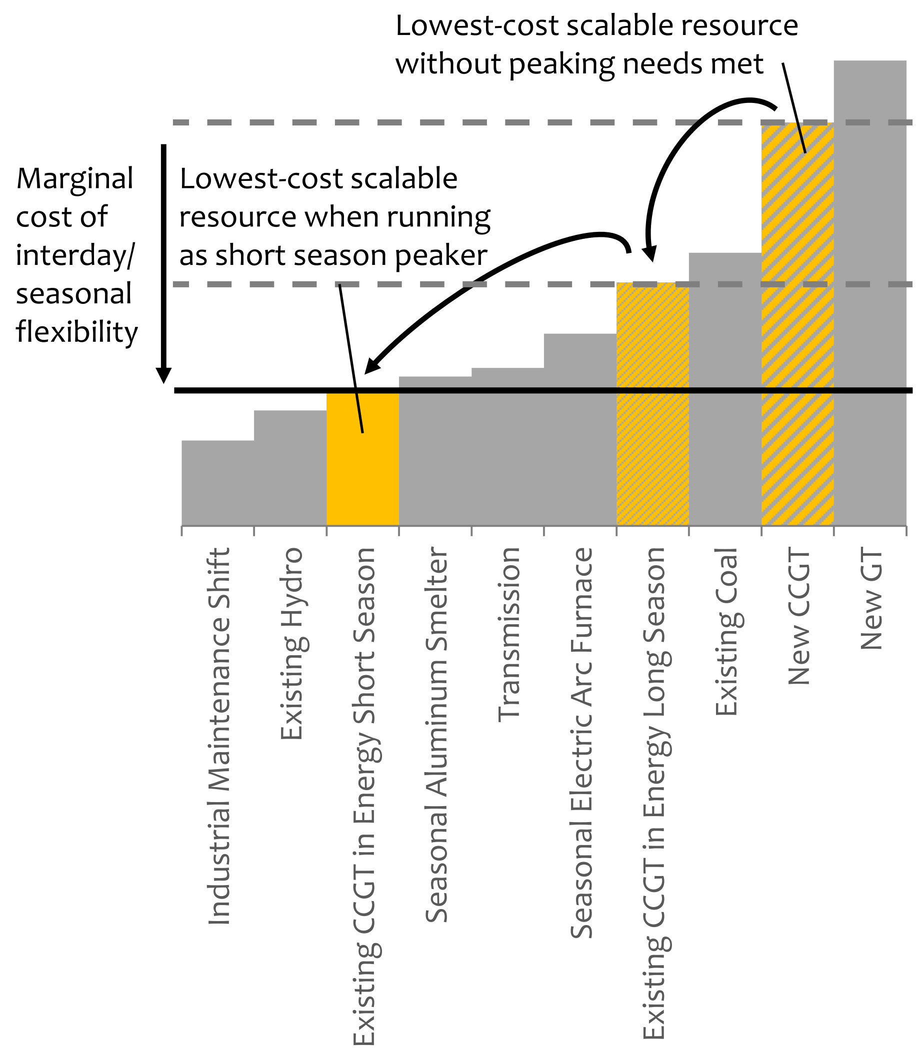
Since the capital cost is already accounted for in meeting intraday/daily balancing needs, interday/seasonal flexibility will only face the variable costs, as in an existing CCGT.

During short seasons, there will be no need to curtail renewable energy, as more energy is needed for the system, so costs for interday/seasonal balancing fall further.

Thus, sharing costs between flexibility options is likely to reduce total costs and may also lead to a different mix of flexibility options than meeting every need individually.

Cost of interday/seasonal shifting: Post-2030 costs when CCGTs are built for intraday load shifting

USD/MWh shifted

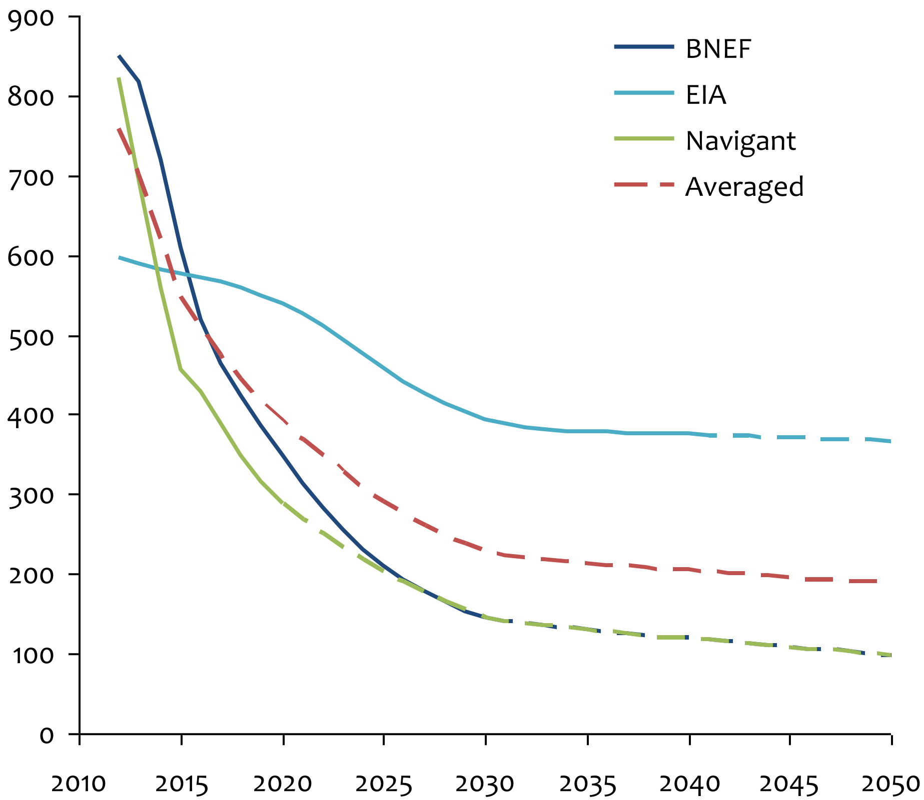


Illustrative example: A decline in cost of flexibility from lithium ion batteries will drive changes to optimum flexibility options while providing better locational flexibility

- A range of technologies currently exist to deliver the required system flexibility.
- But others are under development or are falling in cost through deployment to deliver future needs at lower cost.

Battery costs expected to decline rapidly

2012USD/kWh capacity



SOURCE: RMI, Economics of Grid Defection

Cost of intraday/daily shifting from lithium ion batteries

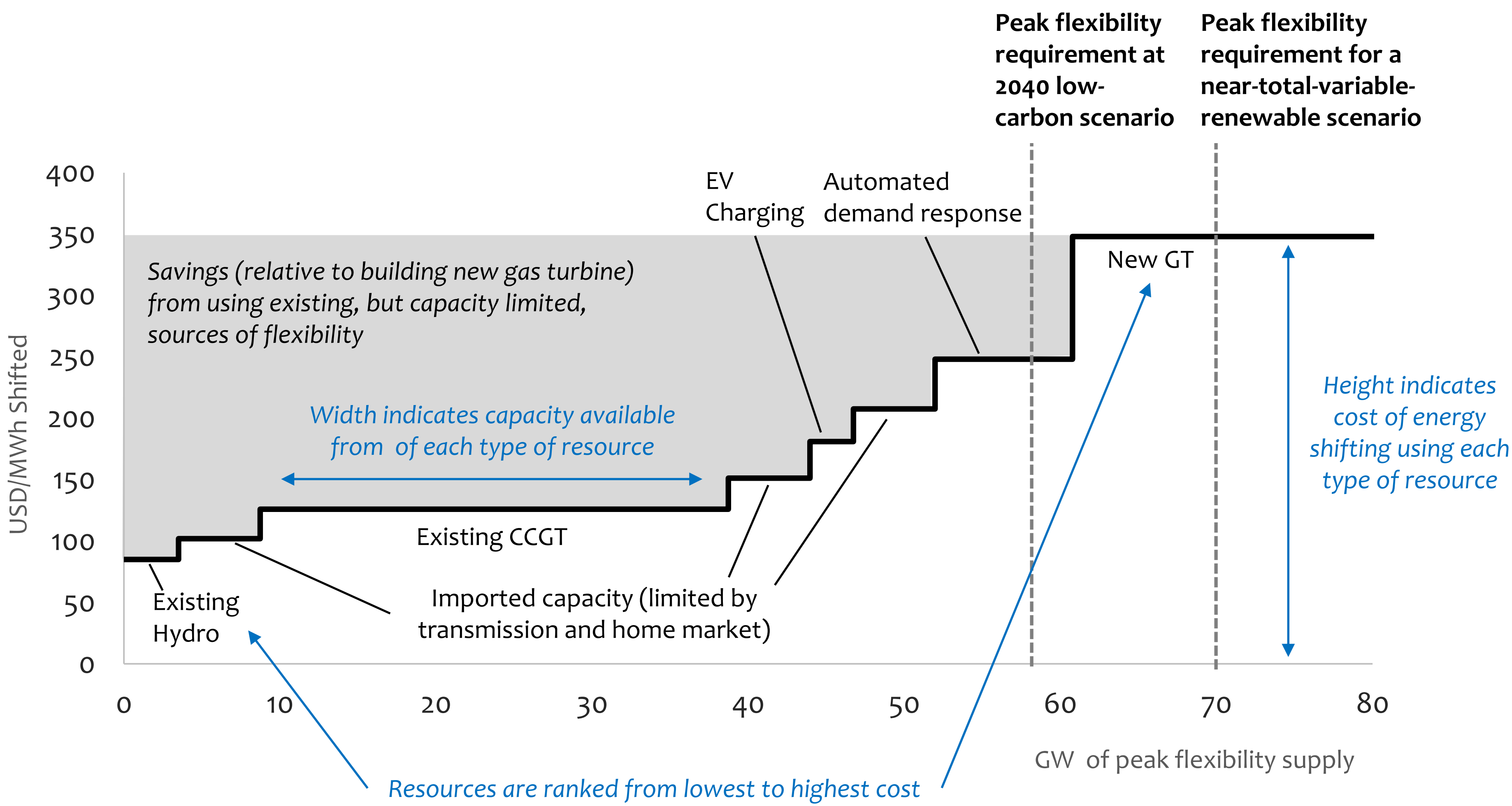
	Today	Post-2030
Up-Front Capital Cost	700 USD/kWh	150 USD/kWh
Hours of Storage	6	6
O&M	58 USD/kW-yr	58 USD/kW-yr
Max Cycle Life	5,000	10,000
Max Calendar Life	20 years	20 years
Discount Rate	10%	10%
Round-Trip Losses	8%	8%
Lifetime with Daily Cycling	~14 years	20 years
Discounted Annualized Fixed Costs	595 USD/kW-yr	162 USD/kW-yr
Annual MWh cycled per kW with Daily Cycling (after losses)	2.015	2.015
Cost per MWh cycled (excluding value of lost energy)	295 USD/MWh	81 USD/MWh

SOURCE: CPI Analysis, based on RMI, Lazard

Illustrative example: Using existing flexibility capacity, including existing plant, import capacity and demand management, could reduce flexibility cost in California by more than half

Using the lowest-cost peak intraday/daily shifting options

Illustrative cost and supply of California peak intraday/daily shifting options, 2040



SOURCE: CPI Analysis.

Contents

Policymakers can pursue ambitious low-carbon targets; to do so cost-effectively, they will require a portfolio approach and a transition framework working over a longer-term planning horizon

Key findings	What policymakers should think about
Renewable energy ambition *Solutions are available now in most power systems to accommodate high proportions of renewable energy at a reasonable cost*	• **Feel free to set ambitious renewable energy targets** to meet their low-carbon objectives. • **Focus on optimizing the costs of today's flexibility options**, while setting policies that will deliver increased flexibility capacity in time to meet targets for decarbonizing the power sector at the lowest possible cost.
Portfolio approach *No single technology, market mechanism, or flexibility resource will be able to meet all flexibility requirements across all regions*	• **Promote the development and cost reduction of several technologies and flexibility resources,** while creating markets and policy for cost-effective integration of these resources as they develop. • **Create solutions that can contribute to delivering the needed flexibility at a competitive cost including:** using existing generation capacity differently; increasing demand-side flexibility; increasing and optimizing new electrification; restructuring transmission and distribution; developing new roles for batteries; and building some new gas turbines as additional support.
Transition framework *New policy, market and regulatory mechanisms are needed to cost-effectively develop flexibility for a high-variable-renewable power system*	• **Focus planning and policy development on the transition path to a much higher variable-renewable power system**: markets need to be configured to get the best output, lowest cost and lowest risk from both renewable energy and the evolving flexibility resources. • **Design markets with long term signals for investment in the transition, including:** better signals to consumers; markets that address both the supply of energy and flexibility; mechanisms that balance sources of renewable energy to reduce flexibility needs; and processes and price signals to improve regional coordination.
Planning horizons *Longer-term planning horizons are needed to develop new flexibility solutions and avoid lock-in of long-term solutions that do not align with transition goals*	• **Create markets and policy that incentivize long-term innovation and balance this innovation against near-term objectives.** For example, there is a continued role for existing fossil fuel generation to ease the transition, while innovation policy and long-term planning is needed to access some of the lowest-cost future resources.

Portfolio approach: No single technology, market mechanism, or flexibility resource will be able to meet all flexibility requirements across all regions

Key findings	Recommendations	Policy levers
Existing generation, including fossil fuels and hydro, is a critical resource.	Operate and incentivize existing generation to support variable renewable energy, rather than forcing variable renewable energy to fit into existing supply incentive models.	**Market design**
Demand-side flexibility is an attractive and low-cost resource across all flexibility needs.	Develop better markets, market signals, increased awareness and technology to reach the full potential of demand-side flexibility across all types of consumers.	
Electrification of additional services can significantly increase consumer flexibility and add value beyond energy efficiency and decarbonization.	Implement well-structured demand-side signals to unlock the full value of extended electrification.	
Transmission and distribution can reduce total flexibility needs, enabling diversification, broadened access to low-cost resources and sharing of reserves.	Optimize transmission and distribution by supporting better locational energy pricing signals and policies to support efficient investment, while balancing with other flexibility options.	
Batteries will become increasingly cost-competitive, while reducing carbon emissions.	Support deployment of batteries to reduce costs, remove technical barriers to participation in electricity markets, enable financing through longer-term contracts, and improve integration as costs drop.	**Technology support**
Gas turbines provide a default source of flexibility across several types of needs.	Carefully balance new builds, existing plants and developing new flexibility options.	

Transition framework: New policy, market and regulatory mechanisms are needed to cost-effectively develop flexibility for a high-variable-renewable power system

Key findings	Recommendations	Policy levers
Electricity markets need to **provide better long-term and short-term signals to consumers**, who have been undervalued.	Develop short-term signals to encourage changed use patterns and long-term signals to encourage investment.	**Market design**
Markets must provide consumers and suppliers **better signals about where flexibility is needed.**	Implement location pricing and other tools to deliver incentives to consumers and suppliers for investment, operation and process change.	
Markets need to **develop signals addressing both core renewable energy supply and flexibility needs.**	Develop market signals that balance risks and rewards of offering low-carbon energy and flexibility solutions.	
A mix of renewable energy technologies with different generation profiles is likely to reduce flexibility requirements.	Design market signals and planning processes to optimize the mix of renewable energy types, minimize flexibility needs, and account for the value of supply diversification.	**System planning & market design**
Institutional coordination, between regions and value chain segments, can remove barriers to cost-effective management of flexibility.	Expand markets regionally and vertically.	

Planning horizons: Longer term planning horizons are needed during the transition to a low-carbon power system

Key findings	Recommendations	Policy levers
Current planning horizons may miss long-term flexibility resource opportunities, as these horizons are built around building the current set of supply-side flexibility options and thus may lock these options.	Encourage long-term planning to unlock low-cost options, focused on steady development of demand-side resources and new technology.	**System planning**
Continued fossil fuel generation is essential for a smooth transition, but in the long term, fossil fuel generation can be mostly replaced.	Avoid wasting valuable existing assets, but also guard against new assets that will either be stranded or lock in emissions.	
Industrial electrification may have significant long-term potential, but it is less explored than transport or buildings electrification, so the opportunity is not yet clear.	Assess how electrification will stack up against carbon capture, biofuels or other carbon abatement measures in the industry sector, and what further research is needed to clarify the opportunities.	**System planning and technology support**

Many examples of helpful policy directions across industry structure, market design, technology support and system planning can be emphasized in different regions

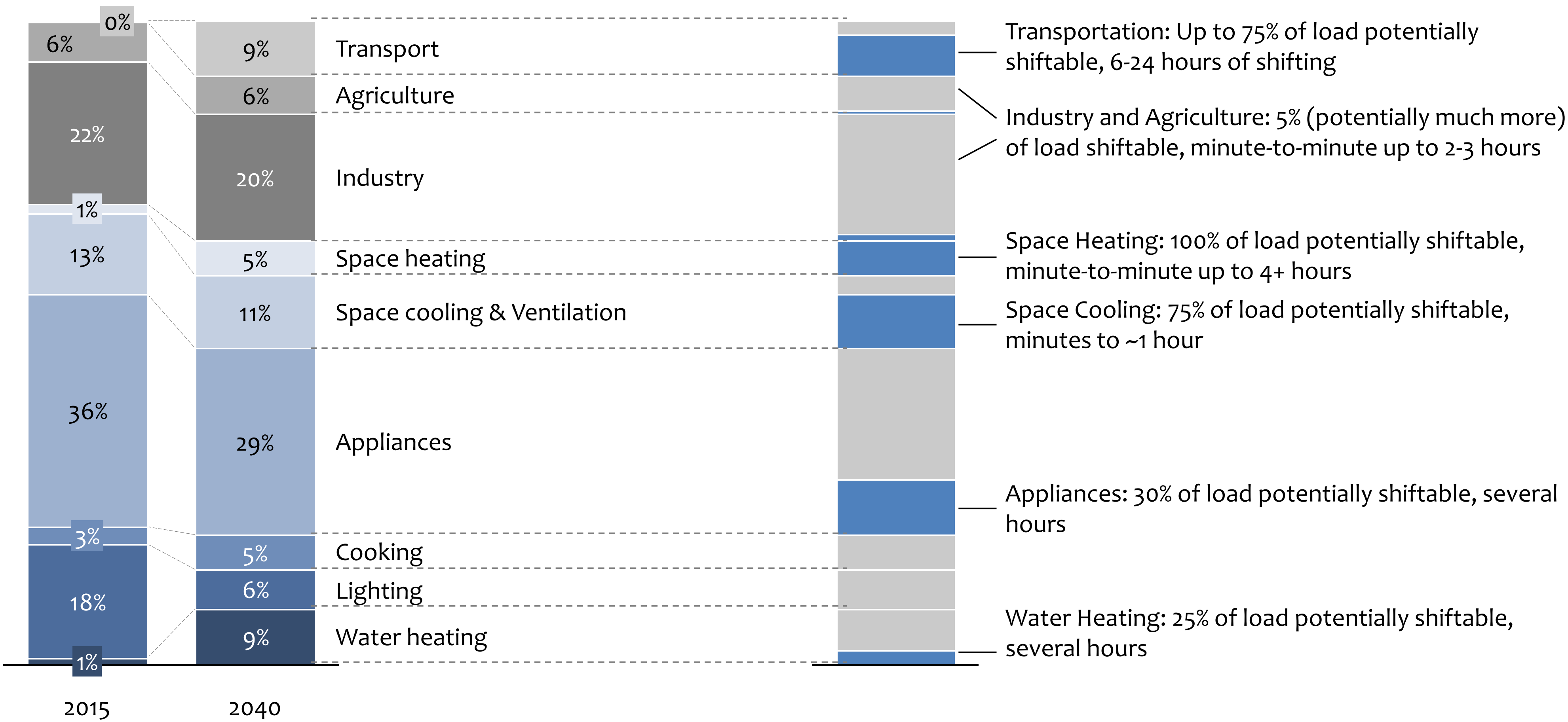
Policy lever	Key recommendations	Time horizon	Examples
Industry structure	Mitigate flexibility needs by integrating regional markets Unlock demand-side flexibility through coordination of distribution / transmission Develop new business models and corporate structures to respond to the new requirements of a flexible system	Next 10 years	• Nordic Region/Germany: Coupling of day-ahead markets in northwest Europe since 2014 enables efficient use of interconnectors between Nordic Region and continental Europe (implicit auctioning) • New York: Reforming the Energy Vision (REV)
Market design	Drive efficient operations and investment Develop appropriate market signals to encourage shifts/behavioral change Ensure technical adequacy at lowest cost Place operating risks with parties best placed to manage	Next 10 years	• California: Flexible Ramping Capacity, Demand Response Auction Mechanism • Maharashtra: Time of Day (ToD) tariff for large energy consumers
Technology support	Bring down the cost of multiple flexibility options in time to meet renewable ambitions Enable learning by doing and economies of scale Reduce perceived technology risk through demonstration	Long term	• Germany: 50MW/year "Innovation Auctions" in 2018-2020 included in latest Renewables Law to support technologies that provide flexibility • Maharashtra: On-site generation and microgrid incentives • California: 1.3GW Energy Storage Mandate
System planning	Identify long-term resource needs; balance with short-term constraints Prioritize investments and incentivize long-term innovation Set goals and procurement targets to minimize system costs Avoid lock-in	Long term	• California: Long-term procurement planning (typically 10-years) • Maharashtra/India: National energy planning is well developed but has short time horizon (12th Five-Year Plan 2012-2017)

Focus on demand-side flexibility: Demand management presents a particularly attractive low-cost flexibility solution, and can be supported by a number of mechanisms

	Supply & demand forecasting	Market design and flexibility service pricing	Consumer aggregators	Response and control technology	Metering data and analysis	Consumer infrastructure
Role	Provide advance information to flexibility suppliers and operators	Provide short term incentives to respond to flexibility needs and long term incentives to develop new response capacity	Aggregate market to consumers to reduce transaction costs and improve reach and scope	Enable aggregators to access flexibility potential of consumers and respond to market signals	Consumer end use metering to enable control, measurement and payment	Infrastructure that will allow consumers energy demand to be more flexible
Examples	• Renewable energy supply forecast • Weather and demand forecast	• 5-minute energy markets • Capacity markets • Long-term contracts for reserve • Long-term contracts for flexible supply • Annual flexibility auctions • Transmission rights	• Energy service companies • Utilities and municipalities • Consumer aggregators	• Automated control systems • Internet and broadband based communications • Integration and trading platforms and software	• Smart meters • End use meters • End use analysis software • Integration software	• Fast electric vehicle chargers to increase EV response • Building insulation to increase heat demand shifting • Appliance control systems for remote response
Current Status	Accuracy and advance timing steadily improving, substantially reducing short-term reserve costs	Many examples in place, but most do not yet provide optimum allocation of incentives	Many examples in development, but much greater potential once market design and price signals become more focused	Technology is available, but great potential to refine and expand as incentives and systems improve	Smart meter/end use meter roll out is underway in many geographies, room for improvement in the adoption and cost performance of end use metering	Build-out is ongoing, but lack of incentives means development is slow

Focus on demand-side flexibility: Greater electrification of sectors with shiftable loads can facilitate flexibility by creating more opportunities for demand management

Share of annual electricity demand by end use in California | **30% annual electricity demand could be shiftable by 2040**

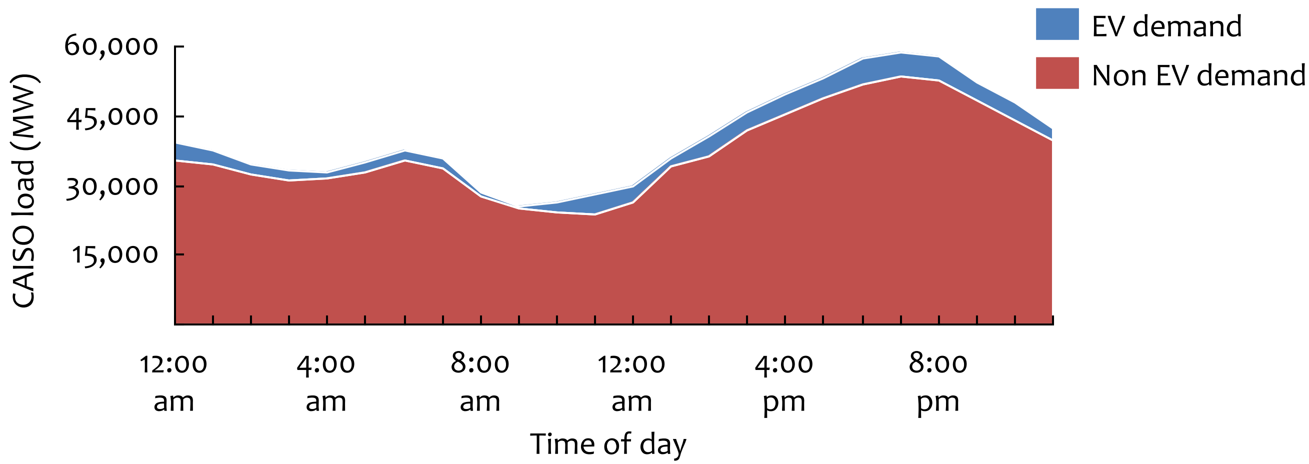


SOURCE: CPI analysis, based on E3 Pathways study

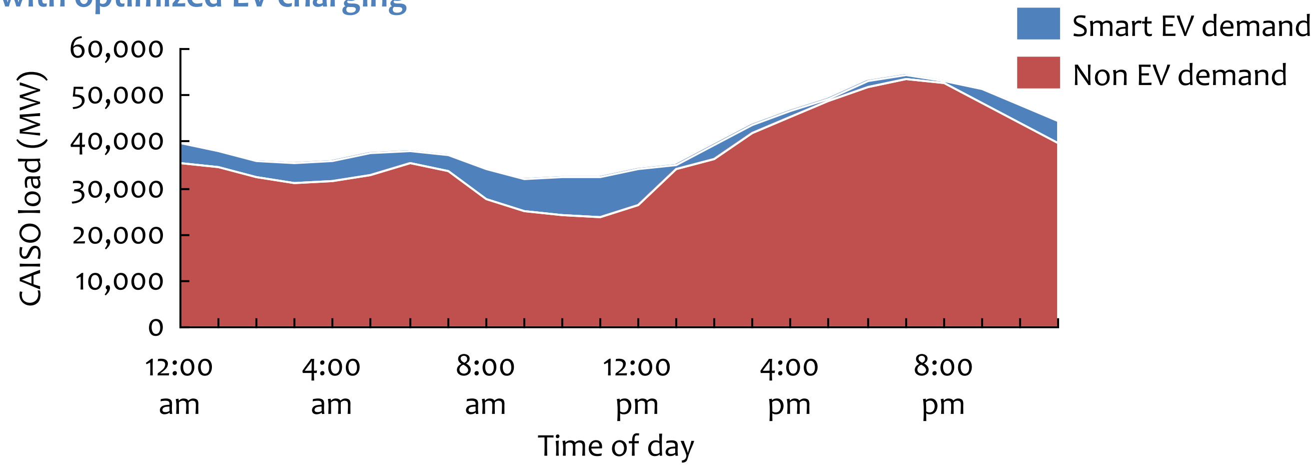
SOURCE: CPI analysis; Shiftable shares based on Birrer et. al. (2015), Oak Ridge National Lab (2013) and interviews with industry experts.

Focus on demand-side flexibility: The growth of electric vehicles could maximize demand-side opportunities or exacerbate flexibility needs if the incentives for charging are not set appropriately

Projected CAISO demand with 23% EV penetration and 2030 RE penetration goals with uncontrolled EV charging



Projected CAISO demand with 23% EV penetration and 2030 RE penetration goals with optimized EV charging



Rocky Mountain Institute analyzed the impact of a high penetration of electric vehicles on electricity demand profiles.

With uncontrolled electric vehicle charging, EV demand would add an additional 11% to peak electricity demand, while optimizing EV demand would only result in a 1.3% increase in peak electricity demand.

SOURCE: Rocky Mountain Institute, Electric Vehicles as Distributed Energy Resources 2016

Focus on transmission and distribution: While the role of T&D infrastructure varies by region, planning and policy can be used to optimize investment and use of T&D infrastructure

	Transmission infrastructure	Distribution infrastructure
Compensation	• Locational marginal pricing to quantify value of grid constraints • Policies and instruments that enable and reduce the risk related to investments in transmission capacity • Regulated return on investment for projects with broad social benefit but marginal project economics	• Traditionally thought of as a natural monopoly compensated through a regulated return on investment (typically through retail rates) • Distributed generation and flexibility resources could offset need for distribution upgrades, if given appropriate market signals (e.g. tariffs for flexible load or battery energy storage, value of solar tariffs, or locational distribution pricing)
Planning	• Transmission and interconnection planning needs to account for expected mix and location of electricity generators • Scenario analysis is useful to identify projects that have value across a range of possible future scenarios • Cost and value of new transmission should be compared with other options (e.g.,changing the location of generation, utilizing flexibility resources to reduce transmission infrastructure need)	• Distribution planning increasingly faced with integration of distributed generation and flexibility resources – needs to be used to identify distribution upgrades that have the most value in range of scenarios • Distributed generation and flexibility can also be used to defer or avoid investment in new distribution capacity – cost and value of new distribution should be compared with alternatives
Barriers	• Regional coordination challenges • Local resistance to transmission projects	• Regulatory models for distribution favor utility investment over use of third-party capital for investment in distributed energy resources • Limited information flow between resources and network operators • Utilizing distributed energy resources to offset distribution investments requires managing a large number of "endpoints," increasing operational complexity

Annex – Methodology

Methodology: Steps used to evaluate the maximum cost of a generic near-total-variable-renewable power system with default flexibility options

- Hourly resource and demand profiles for one region (Germany) were used to develop parameters (capacity, reserves, energy shifting needs) for generic cost analysis. The demand profile was modified to account for expected transport and heating electrification through 2030.
- While resource and demand profiles vary by region, regional differences do not make for substantial differences in total costs – roughly +/- 5% in cost variation.
- Variable renewables were scaled to meet 100% of the energy needs over the year before energy shifting to meet demand profile (64% wind, 34% solar and 2% run-of-river hydro) – after curtailing /shifting energy to meet hourly demand, this system meets 86% of energy needs from variable renewables.
- Cost of default, widely available flexibility technologies – gas combined cycle plants (CCGTs) and lithium ion batteries – were applied to the characteristics of the system to calculate maximum total system cost.
- Since demand-side flexibility, existing hydro, interconnection and other options are highly region-dependent, these low-cost options were excluded from this "maximum cost" case.
- Central estimates of future flexibility resource costs were used – notably, gas fuel price forecast comes from IEA's World Energy Outlook for US in 2020, and a carbon price of 50 USD/tonne is assumed in the case with a carbon price.
- Technology and resource costs are also likely to vary by region; this analysis uses central estimates.