Note: The following is a redacted version of the original report published May 22, 2024

Overcoming Gridlock

Powering Our Future

Citi Research Contributors

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May 2024

See Appendix A-1 for Analyst Certification, Important Disclosures and Research Analyst Affiliations.

Executive Summary

The power grid is arguably the backbone of modern society, and we're now at a critical convergence of the demand ramp-up of an increasingly electrified economy — driven by the rise of electric vehicles, data centers, artificial intelligence (AI), and other technological advances — and an aging power grid that requires significant improvement, especially in incorporating more renewable but intermittent energy, such as solar and wind. This once-in-a-century dynamic of supply-and-demand shocks will require construction of many more power lines. In this report, we discuss obstacles to grid modernization and explore potential hardware and software solutions, including much greater use of long duration energy storage; wider application of demand response; integrating decentralized energy systems (e.g., microgrids) and flexible generation; and adopting automation and AI.

Electricity demand is rising, and so is the need for supply. Things that we use are increasingly electrified, but the supply of electricity, particularly renewables, is generally located farther away from demand centers than before. (Yes, rooftop solar panels do provide electricity to homes, yet they are insufficient to power cities and factories.)

In addition, a significant bottleneck to the global expansion of data centers — facilities that organizations use to house their computer systems and related components — is the availability of power, and the grid is part of that bottleneck. The rapid expansion of data centers, coupled with the broad trend of rising electric vehicle (EV) penetration, are lifting power demand far beyond prior expectations. In developed countries, power demand has been nearly flat for years, but demand is surging as the digital economy develops at a breakneck pace, thereby catching some utilities off guard.

However, the grid, much of which was built decades ago for very different patterns of power supply and demand, has to undergo significant improvements. The most obvious improvements include building more power lines, improving other infrastructure and enhancing grid flexibility (Figure 1).

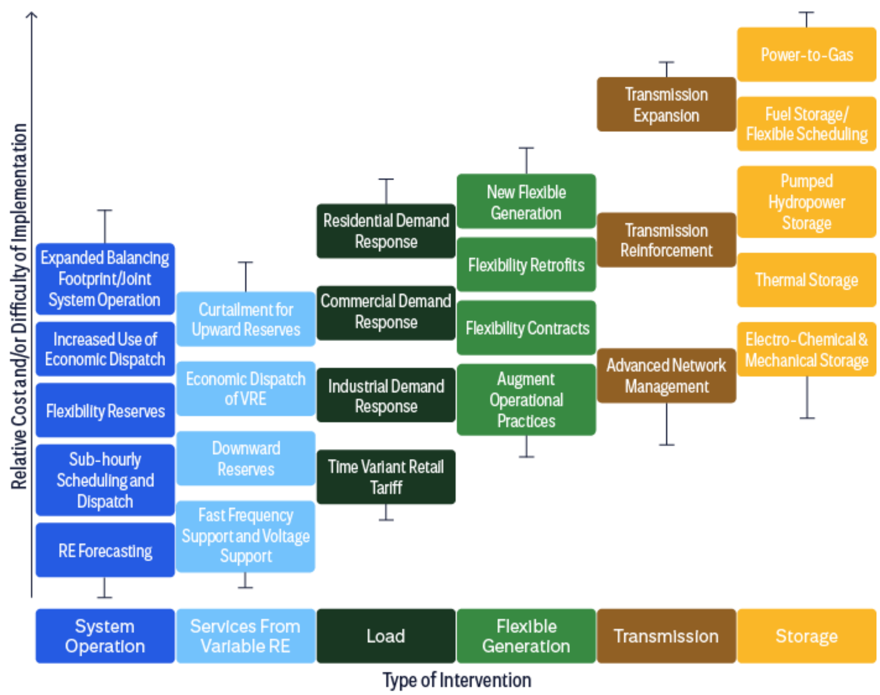
Many obstacles stand in the way of grid modernization, such as high upfront costs, regulatory and permitting challenges and lack of coordinated planning. Upgrading the power grid also requires significant investments in technology and workforce training. Even if costs are manageable, regulatory challenges abound, as grid improvements often face extensive permitting and regulatory processes. Incumbent utilities and other stakeholders, including local communities, also could rightfully question grid expansion efforts due to concerns about disruptions to existing business models, potential losses of revenue or property value, and impacts on health and safety. There is also a lack of coordinated planning, given the fragmented nature of the power sector, with multiple stakeholders and jurisdictions.

Resolving these obstacles requires government support, more private sector participation, and more innovative solutions beyond building more power lines. Governments need to have supportive policies and incentives to speed up grid modernization, such as grants, tax credits and simpler permitting processes. Facilitating public-private partnerships helps to share risks and leverage resources, as investors and project developers have different investment horizons and risk appetites. Yet, amid vast Energy Transition opportunities, what are the right ones?

This report is about finding and evaluating these solutions, both hardware- and software-based ones: The solution and opportunity set goes well beyond building power lines and the use of more batteries to facilitate the renewable buildout.

Opportunities include much greater use of long duration energy storage (LDES), wider application of demand response, integrating decentralized energy systems (e.g., microgrids) and flexible generation, and adopting automation and artificial intelligence (AI). AI could be transformational — in forecasting weather, predicting renewable energy generation and optimizing the grid — through innovations such as the typhoon predictions presented by NVIDIA. However, no amount of investment would succeed without regulatory enhancements, increased support from governments, as well as mechanisms that mobilize more financing and development from the private sector.

Figure 1. The flexibility supply curve for integrating renewables into power systems



Source: Citi Research, J. Cochran et al. Flexibility in 21st Century Power Systems, 21st Century Power Partnership; NREL Technical Report NREL/TP-6A20-61721, 2014, Updated

This report benefits greatly from our conversations with the US National Renewable Energy Laboratory and the Long Duration Energy Storage Council, as well as from analyses on the macro landscape from our own Commodities Strategy team and on regional grid outlooks from our Utilities teams in Equity Research.

Anthony Yuen
Head of Energy Strategy
Commodities Research

Guest Contributors — Q&A

Thinking Strategically about the Power Grid

__Douglas J. Arent, Ph.D.,__ is Executive Director of Strategic Public and Private Partnerships at the US Department of Energy's National Renewable Energy Laboratory (NREL).

Dr. Arent has worked in research on energy and sustainability for more than 30 years, publishing extensively on topics including clean energy, renewable energy, power systems, natural gas, and the intersection of science and public policy.

In addition to his NREL responsibilities, Dr. Arent is a distinguished fellow of the World Economic Forum and a senior visiting fellow at the Center for Strategic and International Studies. He is a member of the Keystone Energy Board and the Global Advisory Board for the Yale Emerging Climate Leaders Fellowship. Dr. Arent also is an external fellow at the Columbia University School of International and Public Affairs' Center on Global Energy Policy and the Andlinger Center for Energy and the Environment at Princeton University. He is the editor-in-chief of Renewable Energy Focus and is on the editorial board for the journal Renewable and Sustainable Energy Reviews.

Dr. Arent has a doctorate from Princeton University, a Masters of Business Administration from Regis University, and a Bachelor of Science from Harvey Mudd College in California.

__Jaquelin Cochran, Ph.D.,__ is the director of the Grid Planning and Analysis Center at the National Renewable Energy Laboratory, where she has worked for 13 years. Dr. Cochran's work has focused on the evolution of the power grid with high deployment of renewable energy. She recently led the Los Angeles 100% Renewable Energy Study and a portfolio of analyses about India's power system. Before joining NREL, Dr. Cochran was an Assistant Professor of Natural Resource Management with KIMEP University in Almaty, Kazakhstan. She also served as a Peace Corps volunteer for two years with the Polish Foundation for Energy Efficiency (FEWE) in Krakow. She holds a Ph.D. and M.A. from the Energy & Resources Group at the University of California at Berkeley, and a B.A. from Pomona College.

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Power grids are critical. Can you elaborate on the importance of stepping back and thinking strategically about them?

The potential scale, speed and scope of today's power sector transformation is unprecedented, raising strategic considerations for power grid infrastructure. The power grid of the past that was built upon the paradigm of bulk large-scale generation facilities, bulk high-voltage transmission and one-way power flow to distribution utilities is no longer the only paradigm at play. As well articulated in many prior publications, the grid is transforming to become much more heterogeneous, integrating both bulk resources, as well as distributed energy resources, and particularly at the distribution edge, multi-way power flow that may trickle up through and into high-voltage grids. The latter, for example, may be critical for spatial and temporal balancing of power systems that incorporate significant amounts of renewable energy over large geographic jurisdictions, as well as resource adequacy that is critical for providing electricity during critical events such as cyberattacks, heat waves, and winter storms.

Additionally, a strong power grid could unleash new opportunities to decarbonize transportation and industry and support new economic opportunities. The International Energy Agency illustrates the global scale and scope of need in their recent analyses, such as their Net Zero Report and their report on transmission grids. Deeper analyses for specific countries lay out the potential scale and benefits of macro grid expansion, but also some of the strategic considerations of managing permitting challenges, long lead times, remuneration mechanisms, and the trade-off with expanding lower voltage connected distributed energy resources. See, for example, NREL's Seams Study or 2035 decarbonization scenarios or Princeton's Net Zero Americas study. Likewise, there are multiple other studies for Southeast Asia, Brazil, Europe, etc. Each of these lays out the strategic considerations for grid expansion, and the importance of taking a mindful approach.

How big is the market likely to be for power grids?

These net zero analyses and the G20 political commitments to triple renewables in the next ten years — and by as much as an order of magnitude by 2050 — have particular implications for the power grid. By 2040, global grid expansion needs and associated investments are estimated to be 80 million kilometers at a cost of $600 billion/annum, over double today's budget, according to the IEA. This represents both an enormous opportunity and an enormous challenge. Equipment supply is significantly limited, permitting times are notoriously long; on the flipside, entrepreneurs are seeing new opportunities for investment in manufacturing facilities, and strategic alignment with power development and delivery business opportunities. For example, the early efforts of DESERTEC, in which there was consideration of tapping the large renewable potential from the Middle East and North Africa (MENA) for Europe, has engendered bespoke commercial opportunities. Similarly, projects that link transmission to large renewable generation locations are being considered in other regions, such as Central and Latin America, or in the United States and certainly across Southeast Asia.

Can you explain why it makes sense to develop long-distance transmission projects?

These interregional high voltage direct current (HVDC) concepts not only offer an opportunity to tap and deliver low-cost generation to locations that lack those clean energy resources, but also offer, through appropriate technology selection, better grid reliability. Greater regional interconnectivity leverages, of course, one of the fundamental principles that large balancing areas aggregate and smooth out the variability of renewable resources over large geographic areas. Further, larger balancing areas also tend to more efficiently use assets, lower overall capital requirements, and lower overall costs. These principles have been borne out in multiple studies and markets across the world, including the United States, Asia, Latin America, or between Africa and Europe. Additionally, the ability of HVDC systems and advanced components to offer services beyond just power delivery is of increased interest.

The idea of leveraging greater regional interconnectivity in order to more efficiently use assets makes sense. Still, the DESERTEC project seems to have stalled partly because of high costs[1]. What are the other options that are on the table if we want to decarbonize the power systems?

Other strategies include improved operations, shorter (5–15 minute) market structures (vs blocks, or allocated dispatch), improved forecasting for load and supply (taking advantage of AI/ML and "big data"), storage —

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[1] Euractiv, *"Desertec abandons Sahara solar power export dream"* (2013)

both relatively short duration of 4–6 hours, and long duration that may be days to seasonal — incentivizing and realizing services from renewables, and enabling flexibility (of all grid connected assets). These strategic options are laid out in the graphic below, in which load management (shifting, classic energy efficiency and more advanced hybrid integrated solutions with DERs, distributed batteries, managed EV charging) also come into play.

However, the enormous opportunities highlighted previously are not without strategic trade-offs. For example, studies have shown that under constrained transmission expansion, or under new power system investment paradigms, such as the New York REV program, that creative distributed solutions that incorporate generation, smart management, and location specific solutions, may offer bankable and more value-added services and capabilities than solely generation and transmission expansion. These alternative solutions will be location and temporally specific. For example, a hybrid system combined with smart load management may relieve congestion in a given area and provide bankable returns at lower costs than additional generation and transmission. With smart load management and distributed energy resources, including generation, storage and smart management, these solutions offset the need for generation and transmission expansion.

Further, particularly in Europe and America, reconductoring offers likely an unappreciated opportunity. Here, the strategic opportunity is to take advantage of existing rights of way and upgrade the transmission capacity along those rights of ways. Additional considerations consider leveraging existing right of way authorities, such as highway systems, or pipelines or railways in order to expedite transmission permitting.

As noted above, non-wires alternatives represent the need and desire to increasingly enable, procure, and remunerate flexibility. More critically, one sees that increasingly flexibility management at the distribution level can decrease the need for additional peak capacity, increase asset optimization and utilization, and therefore reduce the need for both bulk generation and transmission expansion. Clearly there is a strategic trade-off, one in which traditional solutions are weighed against a complex set of changes that employ emerging technologies and business practices.

Other critical elements of transmission build out, particularly over land, are both environmental concerns and social and equity justice concerns. Many large transmission projects receive considerable opposition from en-route local stakeholders who do not receive direct benefit and bear the impact of reduced land values, land/forest clearing, construction, and ongoing environmental impacts. There are, of course, many different approaches to address this, one of the most discussed of which is the ability to serve the area with inexpensive power to support manufacturing, economic productivity, and development.

In short, transmission grids, along with power generation, smart management solutions and creative business models are in a new paradigm of rapid and expansive growth. Recognizing both the opportunities and the challenges that this growth brings demands careful attention, ambitious, inclusive, and transparent planning processes, expedited permitting, and stable enabling policy environments to attract the many trillions of dollars needed for the clean energy transition.

Spotlight on Long Duration Energy Storage

Julia Souder *is the CEO of the Long Duration Energy Storage Council, an executive-led global nonprofit organization with more than 60 members operating in 20 countries, Julia leads strategic planning and market and policy development activities to rapidly deploy and scale long duration energy storage to support the clean energy transition worldwide. Most recently, Julia served as the Executive Director of the Long Duration Energy Storage Association of California (LDESAC). Previously she founded and was president of a strategic consulting company, JAS Energies, which focused on bringing inclusive, diverse, and equitable transitions and policies into fruition. She provided a deep understanding of challenges facing the US electricity sector in reducing carbon emissions, building renewable energy projects, creating markets, and implementing a clean energy vision. Previously, Julia was a Director at the Natural Resources Defense Council (NRDC), focused on market and energy policy creation and implementation, creating coalitions and interpreted real-time grid operations and transmission planning. Julia's prior roles include senior positions at Clean Line Energy Partners, North American Electric Reliability Corporation (NERC), and the U.S. Department of Energy (DOE).*

Alex Campbell *is the Director of Policy and Partnerships for the LDES Council, where he focuses on the intersection of long duration energy storage policy initiatives and working with LDES Council partners to implement storage targets, shared goals, and advocate for policies impacting the acceleration of the diverse family of LDES technologies. Through this work, Alex covers Europe and a broader global footprint. He previously served as the Head of Research & Policy at the International Hydropower Association (IHA) and before that he was Head of Contracts for Difference (CfD) Policy, the UK Government's flagship renewable electricity deployment scheme. His previous experience included leading the UK's engagement with multi-national civil nuclear bodies at the UN, OECD and G7, designing a major component of the regulatory framework for smart meters in Britain and developing policy to support the rollout of onshore wind whilst at RenewableUK.*

He holds an MSc in Climate Change and an MA in International Political Economy.

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Why do we need Long Duration Energy Storage? There are batteries already. Aren't batteries enough?

The huge and ongoing increase in the deployment of variable sources of renewable power like solar photovoltaic (PV) and wind will place significant strain on power grids worldwide. Long Duration Energy Storage technologies (LDES) will play a crucial role in helping create the system flexibility and stability required to safely deliver net zero while keeping the lights on, costs down and maintaining energy security. Deploying up to 8 TW of LDES capacity across power and heat by 2040 could save the global economy up to US$540 billion annually vs. other routes to net zero and avoid gigatonnes of carbon emissions by displacing fossil fuels.

The intermittency of solar and wind power, their inability to match power demand, and increased shares of geographically concentrated wind and solar power in the generation mix would lead to more frequent periods of power surplus and shortage. In the case of prolonged periods without sufficient sun or wind, these imbalance periods may last days or even weeks.

These challenges are solvable by introducing flexibility into the power sector, in particular by uncoupling the use of energy from when it is generated. This can be done across a number of different time spans: (i) intraday flexibility of less than 12 continuous hours; (ii) multiday and multiweek flexibility from 12 hours to weeks; and (iii) seasonal flexibility.

There is no single solution to all the challenges raised by decarbonising and expanding the global power system. On many grids and energy systems a range of options will be available, and the most cost-effective mix will depend on the specific circumstances of that grid. However, only LDES is able to provide the full range of services necessary to meet net zero and maintain energy security (Figure 2).

Figure 2. Summary of existing and emerging flexibility solutions for different flexibility duration needs

Solution | Partial Solution

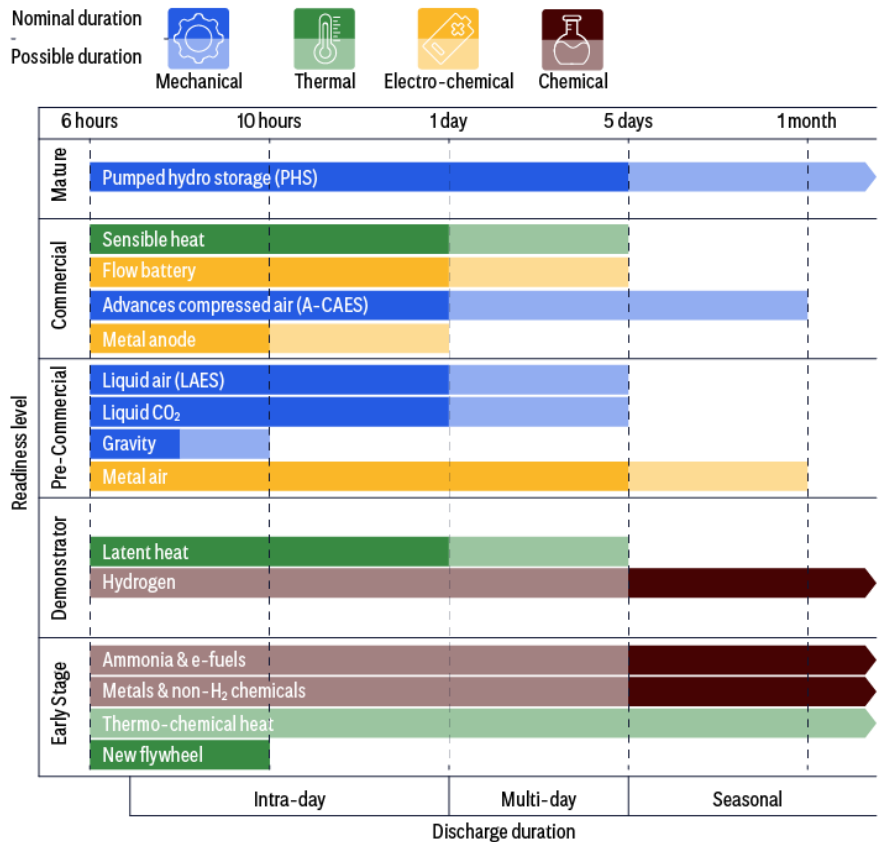
Flexibility Duration	Power System Challenge	Dis-patchable Generation	Grid Rein-forcement	Curtailment or Feed-In Management	Li-ion Batteries	LDES	Demand-Side Response
Intraday	Intermittent Daily Generation	Solution		Solution	Solution	Solution	Solution
	Reduced Grid Stability	Solution			Solution	Solution	Partial Solution
Multiday, Multiweek	Multi-Day Imbalances	Solution	Partial Solution	Partial Solution	Partial Solution	Solution	
	Grid Congestion	Partial Solution	Solution	Solution	Partial Solution	Solution	
Seasonal Duration	Seasonal Imbalances	Solution	Solution			Solution	
	Extreme Weather Events	Solution				Solution	

Source: LDES Council

What are different types of LDES?

LDES encompasses a range of technologies that can take electrical energy — typically generated by renewable sources — and then store it in various forms for prolonged periods at a competitive cost and at scale. These technologies can then discharge electrical energy or heat when needed — over hours, days, or even weeks — to fulfil long-duration system flexibility needs beyond short-duration solutions such as Li-ion batteries (Figure 3).

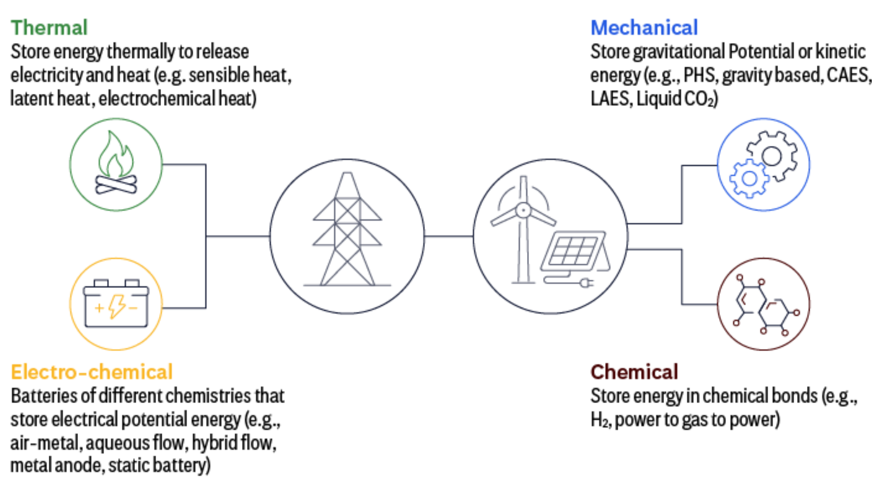
Figure 3. Readiness level and discharge duration for select power LDES technologies



Source: LDES Council

LDES technologies can be broadly categorized in four families: mechanical, thermal, electrochemical, and chemical storage (Figure 4).

Figure 4. The various LDES technologies are at different levels of maturity and market readiness.



Source: LDES Council

How large could the impacts be by deploying LDES?

Deploying LDES technologies at scale would bring major benefits to the global economy. Analysis by the LDES Council found that the lowest-cost pathway to net zero could see up to 3 TW of power LDES generation capacity and 5 TW of thermal (heat) LDES installed by 2040, with energy storage capacity of up to 140 TWh (power) and 80 TWh (heat), with an investment requirement of up to USD 3.6 trillion.

Such deployment could enable energy system savings of up to USD 540 billion annually, with avoid carbon emissions of over 2 gigatonnes in the power sector and each gigawatt of heat generation capacity could reduce about 1 megatonne (Mt) CO_2/year when replacing natural gas heat sources and roughly 2 $MtCO_2$/year when replacing coal.

However, securing these benefits requires action now.

LDES technologies, like many other forms of low carbon infrastructure, tend to have higher upfront costs (CAPEX) relative to their ongoing costs (OPEX) compared to fossil fuel alternatives. Therefore, policy intervention is needed to drive investment.

There are three notable types of policy support that can drive action towards net zero: long term market signals, revenue mechanisms and direct technology support. All have been deployed in various forms to support investment in a very wide range of low carbon infrastructure beyond LDES.

Overcoming Gridlock: Powering Our Future

Anthony Yuen
Maggie Lin

Commodities Strategy

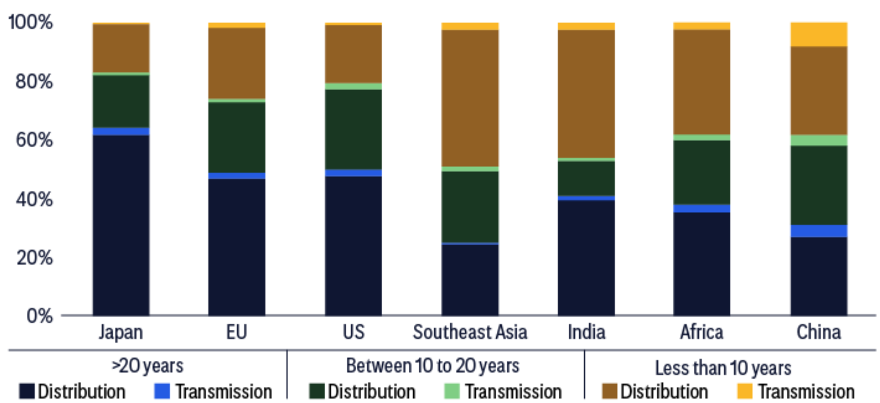
(1) What Are the Current Challenges? Transmission and the Broader Grid Expansion

(a) Current problems and growth prospects of transmission and distribution grids

The power grid has many well-known problems, including (i) an aging infrastructure, (ii) grid congestion and curtailment particularly of renewables, as well as (iii) permitting and construction delays even though the power system needs more transmission and distribution lines. However, solving these problems is not easy.

(i) **Aging Infrastructure:** Many existing grids are aging, posing safety and reliability risks. Some were built decades ago, particularly those in advanced economies (Figure 5).

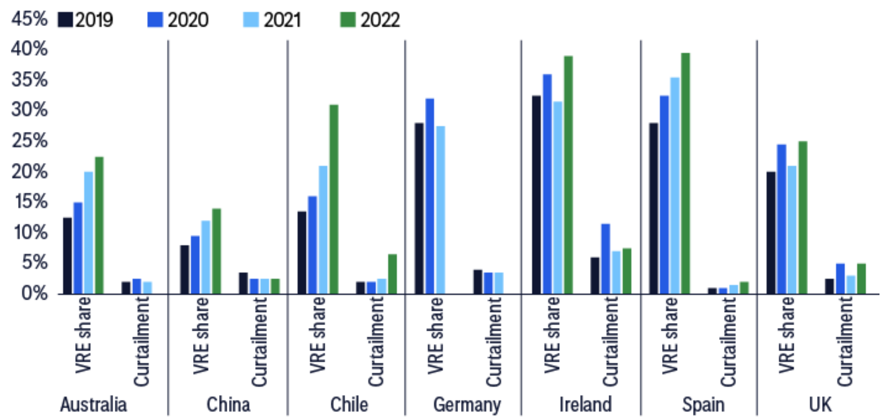
Figure 5. Share of grid length by age in various countries/regions in 2021



Source: Citi Research, IEA

(ii) **Grid congestion and generation curtailments:** This problem is compounded by the increasing integration of renewable energy resources, placing additional strains on existing infrastructure (Figure 6). Extreme temperatures and the resulting demand surges and swings put greater stress on the grid. Weather conditions themselves also affect the integrity of the grid, as seen in damages through more powerful storms, etc.

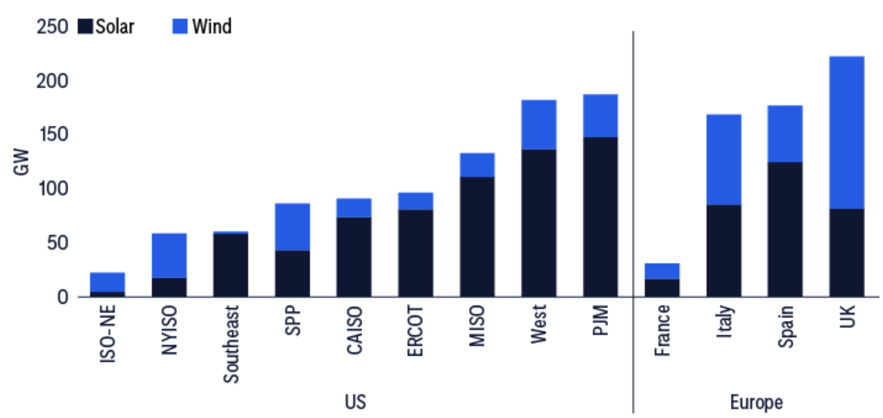
Figure 6. Annual technical curtailments (for network or system and not economic reasons) of variable renewables (VRE) in 2022, by country



Source: Citi Research, IEA

(iii) **Much-needed grid expansion against permitting and construction delays:** Besides aforementioned problems, the International Energy Agency (IEA) suggests that the organic growth of electricity supply and demand would require a doubling in the length of the power grid between now and 2050. Permitting and construction time is also substantial. Delays in grid development hinder the connection of new wind and solar projects, leading to increased system operation costs and renewable curtailment, thereby maintaining the reliance of fossil fuel fired power generation (Figure 7). A reason for the delays is the long permitting and construction process in many places globally. Cybersecurity is also becoming a key risk, particularly amid the increased digitalization of grid operations.

Figure 7. Grid interconnection queues for wind and solar projects in US (by regional bulk electric power systems) and Europe



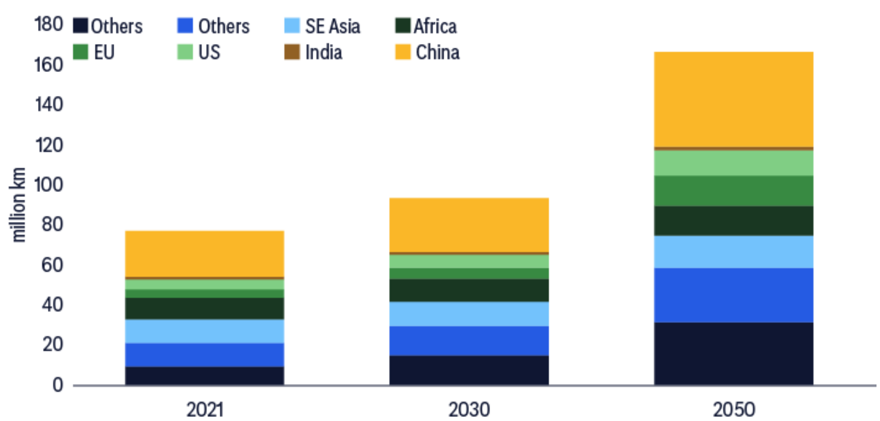
Source: Citi Research, BNEF

While all regions need to improve on their transmission and distribution grids, there are differences in emphasis between developed markets and developing markets. Developed markets, such as North America and Europe, would tend to focus on modernizing and upgrading existing infrastructure, and expediting project completions through permitting reforms and local engagements, given rather established regulatory processes. Developing markets, such as Africa and parts of Asia, would emphasize rapid expansions and financing of grid infrastructure to increase electricity access and the accompanied growth of power supply. As seen in graphs earlier, many developed markets have high renewable energy curtailment rates, as the current structure and age of their power grids are bottlenecks. In developing markets, the age of the power grid tends to be much younger. They just need to build more.

(b) How much to build? Relationship between grid length, power demand and macro conditions

Expanding the grid goes beyond simply adding power lines, but also replacing aging infrastructure. Indeed, the IEA projects that replacements and additions of transmission and distribution lines could add up to 80 million km of lines over the next 20 years. This would be longer than the total length of the grid in 2021. Over the past three decades, the global electricity grid length has almost doubled. Over 90% of this expansion has occurred in distribution grids, essential for providing the last mile of electricity access. Transmission lines constitute the rest. Even in developing markets, despite the relative younger age of power lines, the IEA expects more than half of the grid lengths in place in 2021 could be replaced by 2050, as many lines approach their supposed operating age limits. By 2040, two-thirds of the global total line length are projected to be newly built, underling significant growth in the sector. In its Announced Pledges Scenario, the IEA expects the length of transmission lines to grow from 5.3 million km in 2021 to 12.7 million km in 2050, and the length of distribution lines from 71.7 million km to 153.7 million km (Figure 8). Bloomberg New Energy Finance (BNEF) also expects 11–16 million km for transmission lines and 105–136 million km for distribution lines by 2050.

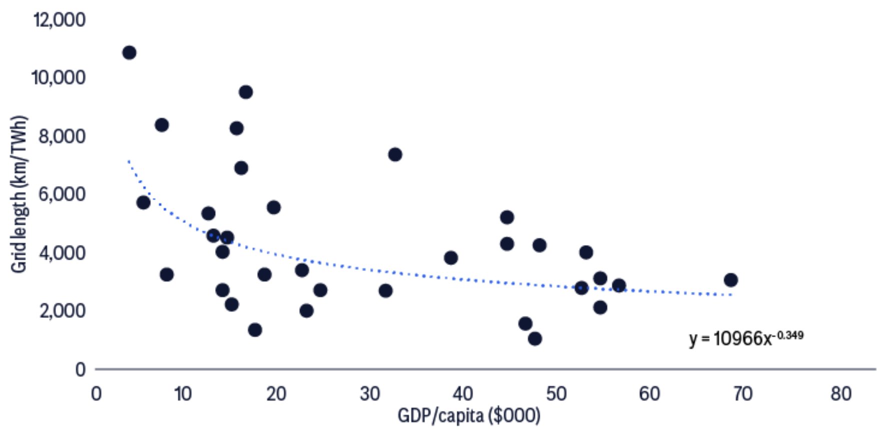
Figure 8. Global length of transmission and distribution lines projected by IEA in the Announced Pledges Scenario



Source: Citi Research, IEA

In general, there is some general relationship between GDP per capita and grid length. The incremental grid expansions per unit of electricity demand growth get smaller as the overall electricity demand grows for a region (i.e., diminishing marginal expansion of the grid needed) (Figure 9). If the size of the electricity demand growth were the same in developed vs. developing countries, then the amount of grid expansion needed would be greater in developing countries. Note that electricity demand growth is highly correlated with economic growth. Not only is the grid typically more established in developed markets, but existing consumers in developed countries are also incrementally raising their level of consumption, such as through increased electrification of transport or heating. Conversely, in lower-income economies, with the grid less developed, grid expansion is often necessary to meet the growing electricity demand resulting from economic development and population growth.

Figure 9. Transmission and distribution grid length per unit of electricity demand vs. GDP per capita



Source: Citi Research, IEA

The above relationships between grid length and GDP per capita are helpful in gauging how many more lines to build. Nonetheless, more complete analyses at the micro level are quite involved, due to the need to estimate power demand and supply growth, geographical distributions of demand and supply, types of power lines needed — transmission or distribution — as well as the physics of power flow. That's why advances in computing hardware and software, such as through AI, to be discussed later in this report, are important to expedite and optimize grid analysis done by grid system operators and regulators. Part of the delay in permitting is simply the time needed to run these comprehensive analyses.

(c) Data centers as the latest driver of the upcoming power demand surge — the chips have to go somewhere

Michael Rollins

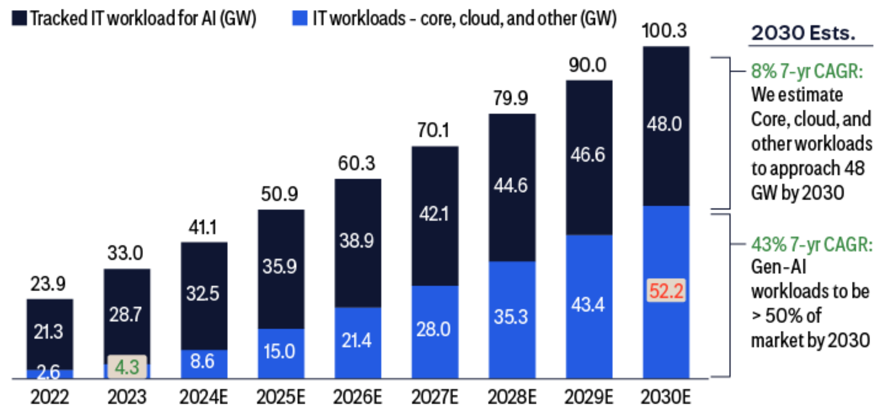
Telecommunications
Equity Research

The expected surge in power demand for data centers, many of which are located near cities or key hubs of existing data centers, adds to demand for power as well as transmission and distribution lines.

Our conclusion is the potential demand for IT Load should expand at a compound annual growth rate (CAGR) of 17% from ~33 gigawatts (GW) for the global markets we were able to track to ~100 GW by 2030. Starting with the idea that the chips for AI have to go somewhere, we collaborated with Citi Research analysts across multiple sectors to establish a new global industry model for data center power demand. We then triangulated those forecasts with the power needed to run the AI chips using the chip sales forecasts and share expectations from Citi Research's Semiconductors team.

When we consider the absorption of annual bookings demand, AI chip power requirements will represent over 70% of annual demand for power over this forecast horizon. The current cloud and core workloads in data centers only need to grow at a much slower rate of 8% over this same timeframe to support our industry forecasts. We forecast AI workloads are likely to reach over 50% of the demand for data center IT load by 2030 (Figure 10).

Figure 10. Globally tracked data center demand (annual)



Source: Citi Research, datacenterHawk (DCH), FactSet, Cogent Communications

When considering the power needed from utilities to enable these workloads, data centers need additional power beyond the IT infrastructure's IT load to keep the facility at a suitable temperature. The incremental amount of power needed to cool the facility and support its overhead is expressed as a multiple of the IT load, referred to as Power Usage Effectiveness or PUE. We apply a PUE that incorporates greater efficiency each year by an average of ~200 basis points over the next seven years. **Global data center *peak* utility power demand can rise at a 15% CAGR from almost 50 GW in 2023 to over 130 GW in 2030.**

So far, we have been describing peak demand from workloads and data centers, and recognize consumption has a lower average utilization rate. **Based on our discussions with data center firms, the average utilization rate could range from 50% to 70%.** We expect book-to-bill and bill-to-fill lags to drive down average power utilization for utilities in 2024 and 2025, then expect a recovery to an average of 65% over the longer term given anticipated utilization for the purpose-built nature for these workloads. Hence, the incremental generation needed in the early years may not be as robust as the annual incremental demand for power over the longer term.

One key risk to future data center demand forecasts is a potential capacity glut if AI demand does not fully materialize. However, the breadth of corporate interest in data analytics and generative AI capabilities to drive operating outcomes (better sales, cost efficiencies) is encouraging.

(d) The availability and costs of metals as additional considerations, with copper in focus

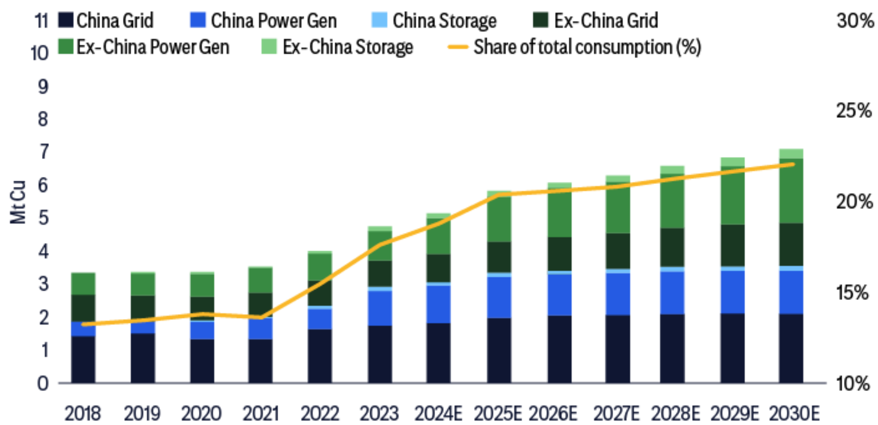
Tom Mulqueen
Maximilian Layton

Commodities Strategy

Power grid investments from now to 2030 could make up nearly half of copper demand growth. The expansion of electrical grid infrastructure is essential to facilitating both decarbonisation and growing global electricity requirements. This includes accommodating renewables capacity additions and adapting transmission and distribution networks to generational shifts in how and where the world consumes power. Key trends here include the transition to EVs and rising demand for electricity from AI data centres. The copper required annually for renewable capacity additions and associated grid investment can rise 2.4 million tonnes (Mt), at a 6% CAGR from 2023 to 2030, to 7.1 Mt — or to 22% of a 32 Mt copper market. This represents just under half (~45%) of all the global copper demand growth of ~5.3 Mt we expect by the end of the decade.

In our base case, annual copper demand from power grids, storage, and generation climbs 2.4 Mt from 2023 to 2030 (6% CAGR), to 7.1 Mt (Figure 11). We see these sectors rising from 18% to 22% of global copper consumption and contributing an average 1.2% per annum (pa) to global copper demand growth through the end of the decade. Our base case forecasts that consumption in power generation additions (primarily solar and wind) will climb ~1.3 Mt to ~3.2 Mt over this period, demand from grid networks by ~0.9 Mt to ~3.5 Mt, and by ~0.2 Mt to ~0.4Mt for battery energy storage. We see a further ~0.2 Mt of growth in annual copper consumption to ~0.3 Mt (not included in the above totals) from EV charging infrastructure.

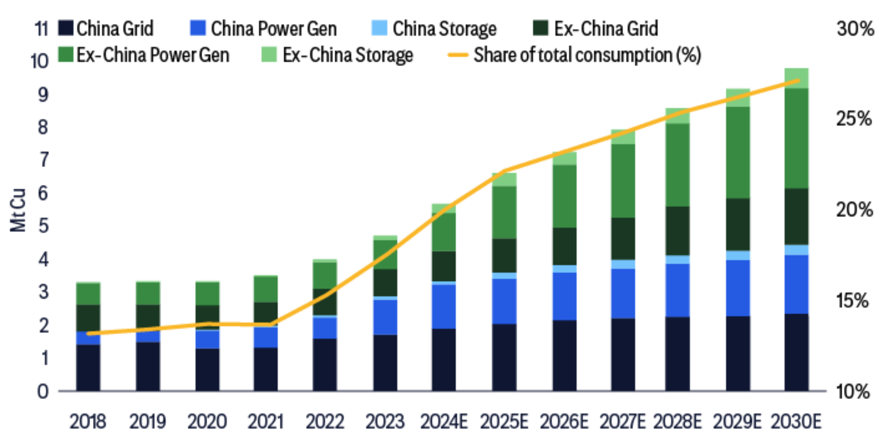
Figure 11. Base-case end-use copper demand for power grid, storage, and generation to climb by 2.4 Mt from 4.7 Mt in 2023 to 7.1 Mt by 2030



Source: Citi Research, IWCC, Bloomberg

In our bull-case scenario, annual copper demand from the same segments climbs 5.1 Mt between 2023 and 2030 (11% CAGR), to 9.9 Mt, or to 27% of global copper consumption (Figure 12). Our bull case envisages a renewables rollout aligned with the COP28 global renewables capacity tripling goal. Here copper in power generation additions climbs ~2.9 Mt to ~4.9Mt from 2023 to 2030, grid demand by ~1.5 Mt to ~4.1 Mt, and by ~0.7 Mt to ~0.9 Mt in battery energy storage. Bull-case contributions to global copper consumption growth from these segments would double from our base case to average 2.4% pa through 2030.

Figure 12. Bull-case copper demand across power grid, storage, and generation to climb 5.1 Mt from 4.7 Mt in 2023 to 9.9 Mt by 2030



Source: Citi Research, IWCC, Bloomberg

According to the IEA, grid investment (excluding renewables generation) needs to almost double to more than $600 billion by 2030 to meet global climate targets. Our bull-case grid demand scenario is broadly consistent with this doubling of spend and of copper demand by the end of the decade, though we take a more conservative approach in our base case. The IEA highlights how grid investment has declined ex-China in recent years. Spending by advanced economies needs to accelerate to accommodate the accelerating pace of renewable energy additions.

The incremental copper demand implications of data centre power requirements in broader power infrastructure are hard to isolate and quantify, but as a key driver of future electricity demand growth it adds confidence to our broader power-related copper demand forecasts. We expect pressure on blue-chip companies behind data centre expansions to demonstrate they are sourcing power for these sites sustainably. As an example, Microsoft plans for its data centres to be carbon neutral by 2030 and has announced it would purchase 9.5 GW of solar panels through 2032 to help meet this goal (19-Apr, Data Centre Dynamics)

Demand for other metals will also benefit from accelerating investment in global power infrastructure. Aluminium demand is positively exposed due its widespread usage in ultra-high voltage (UHV) overhead transmission lines, as a substitute for copper wiring and cabling in areas like renewable installations, and in support structures such as solar panel mounts. Lithium in batteries and tin and silver in solar panels are also key.

Anthony Yuen
Maggie Lin

Commodities Strategy

Conclusion

Given these challenges, modernizing and strengthening the grid also goes beyond simply building more power lines. It involves other strategies that integrate both hardware and software improvements. The next sections explore options beyond constructing power lines:

- **The hardware side includes flexible generation as well as energy storage — both short and long duration energy storage (LDES).** Developing new energy storage technologies will be key to integrating variable renewable energy sources.

- **The software side includes much greater use of optimization, automation and artificial intelligence**. Implementing advanced control and monitoring systems is necessary to maintain grid stability and reliability, as renewable energy sources become a larger share of the energy mix.

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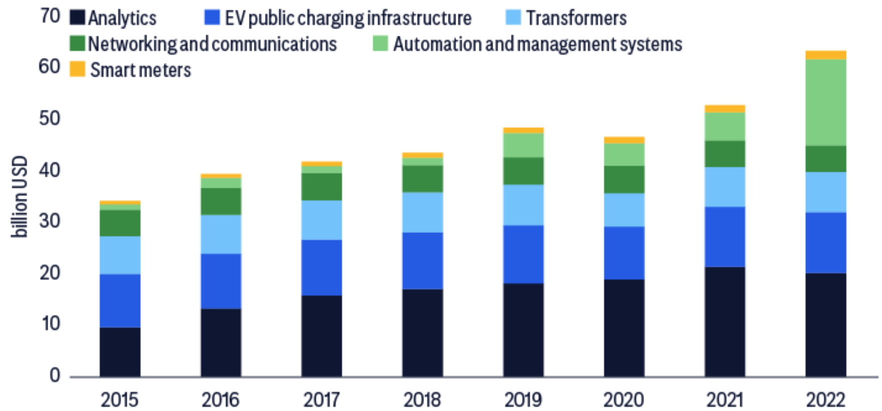
Commodities Strategy

(2) Transforming System Operation: Optimization, Automation, Artificial Intelligence

Optimization, automation, artificial intelligence (AI) and other grid-enhancing technologies, including both hardware and software solutions, could improve grid operation and reduce costs (Figure 13).

Figure 13. Digital-related investment in grid technologies, 2015–2022



Source: Citi Research, IEA

Regulatory support is generally strong for implementing grid enhancing technologies. Allison Clements of the US Federal Energy Regulatory Commission (FERC) was quoted as saying: "[they] are modest investments, they are going to save customers money...and the impacts are significant."[2] For example, Commissioner Clements cites improvements done by PPL Electric Utilities in Pennsylvania. For two 230-kilovolt transmissions lines, instead of spending $50 million for rebuilding or reconductoring, PPL put in sensors that costs less than $300,000. The savings on congestion comes out to be around $20 million annually.

Advances in grid management include the shift towards (i) dynamic line ratings (DLR), (ii) advanced power electronics, (iii) dynamic topology optimization and (iv) the wider use of optimization and artificial intelligence. These advances could help to facilitate a more resilient, reliable and sustainable electric network. Besides sensors, drones and satellites, along with the data analytics involved, could more effectively monitor grid conditions and adjust operation accordingly, rather than having no monitoring or using expensive helicopter observations.

(a) Dynamic Line Ratings (DLR)

Unlike static ratings, DLRs adjust in real-time the power line capacity based on environmental conditions, thereby offering greater transmission capacity and efficiency (Figure 14). This adaptability can provide significant congestion relief and cost savings, particularly on days with favorable weather conditions for renewable energy generation.

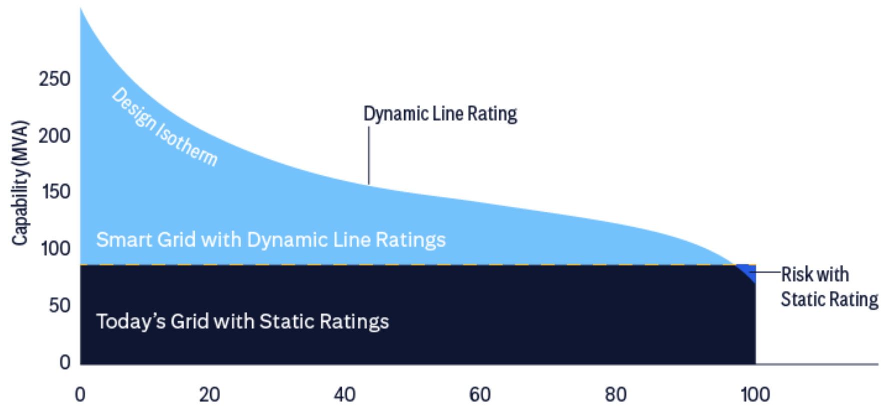
DLR incorporates various hardware and software to achieve more real-time adjustments in line ratings. It includes a number of sensors monitoring conditions of the transmission line, a communication system that sends real-time information to the control room, an analytics engine that processes information about the line and weather, and an energy management system (EMS) that allows for human or automated decisions.

It makes sense to adopt DLR. Challenges include implementation costs, data accuracy, and the need for operational knowledge. Independent System Operators (ISOs) have to adopt DLR while regulations need to provide the right incentives, so that transmission owners and operators

[2] https://www.utilitydive.com/news/transmission-grid-enhancing-technologies-gets-utilities-naruc-ferc-clements/699686/ (Nov 14, 2023)

would implement them. The alternative is that a cost-of-service scheme would have implied more lines being built. Overcoming these barriers requires investments in technology, training and infrastructure upgrades.

Figure 14. Capacity potential from DLR versus Static Line Ratings (SLR)



Source: US Department of Energy, Citi Research

(b) Advanced Power Electronics

Power electronics (PE) technologies are key to managing electrical power transformation and distribution. They offer flexibility, improved response times, and enhanced grid stability. The adoption of PE technologies allows for higher penetration of Distributed Energy Resources (DER), new grid architectures, and more efficient response to grid events.

Examples of how PE can be integrated into the grid include the development of high-power drivers, HVDC systems, FACTS (Flexible Alternating Current Transmission System), and energy storage systems. Solid-state power substations (SSPS) could help raise the flexibility and controllability of conventional substation, through automation and increased power and information exchanges to automate the power flow.

(c) Dynamic Topology Optimization

Dynamic Topology Optimization allows for the reconfiguration of grid lines and nodes to optimize power flow, which would generally result in a more efficient and reliable power grid. This method, which can involve switching certain lines in and out of service, can enhance system capacity, utilization, reduce congestion costs and improve overall grid operations.

One way to implement is to have a "digital twin" model that models the physical infrastructure of the grid for evaluation. Advances in sensing, computing, communication systems and machine learning help to facilitate this kind of optimization now — something not quite possible in the past due to the computational complexity. The US Department of Energy (DOE) and its associated national laboratories are among entities that have developed such advanced optimization methods.

Besides the need to overcome computation complexity, topology optimization can become more effective by improving variable selection and the ability to get accurate data. Limiting the size of the grid being optimized would certainly help ease the computational complexity. Variable selection is also important because not all variables can be captured and used effectively. Further, it can strain physical infrastructure and lead to grid stability issues due to frequent switching operations.

Nonetheless, successful demonstration and implementation would strengthen the confidence in adopting such a framework.

(d) Artificial Intelligence (AI)

Artificial Intelligence (AI) could be truly transformational. While many look at AI from its power demand perspective, AI would also vastly improve the building and operation of the power grid. The grid could become more efficient and reliable in integrating renewable energy sources. AI could help improve forecasts of power demand, weather and wind/solar generation; enhance grid stability, reliability and demand-side management; and optimize energy storage operation and market design.

AI's capability in the energy sector is primarily driven by its ability to assess massive amounts of data through increased processing power, thereby enabling more sophisticated analyses, and faster and more intelligent decision-making. AI is able to incorporate more data and variables, upon choosing appropriate neural network models. AI-managed smart grids, embedded with an information layer through smart meters and sensors, would enable two-way communication between utilities and consumers, facilitating real-time grid management, fault detection, predictive maintenance, and renewable energy forecasting.

Examples of how AI would improve the operation of the power market:

Weather, renewables and demand forecasting: **Some AI models are already producing better forecasts than traditional, meteorologically-driven estimations**. Weather affects both demand and, increasingly, supply of electricity — through temperature, precipitation, wind, solar irradiance and cloud cover. Weather forecasting, mostly reliant on major agency models, such as the GFS in the US and the ECMWF in Europe, have improved gradually but major gaps remain. At the sub-hourly, hourly and daily levels, rising shares of intermittent solar and wind power generation require much better forecasts over time and space. At the seasonal level, forecasts could benefit from much better estimates of resource-adequacy. **AI, through analyzing meteorological data, can better predict outputs of solar and wind power, and help to improve unit commitment, dispatch efficiency, reliability and reserve margins, such as how much, when and how long backup power should be available to support renewables**.

Demand forecasting is also being transformed by AI's ability to incorporate and predict network load, consumer habits and weather's impacts on net power demand, after factoring in supply from distributed energy resources (DERs). In the past, demand forecasting was simpler and mostly used weather and, for longer-term analyses, macro variables. Now, demand forecasting is much more complicated, due to more behind-the-meter or distributed solar in homes, a greater integration of energy storage, demand response and other measures. These all make forecasting net demand for power from centralized generation much more difficult.

Examples: The "GraphCast" model from Google's DeepMind and the "Pangu-Weather" model from Huawei could generate rolling 24-hour weather forecasts that are either "more accurate than nearly any weather agency's" or be portable so that a desktop computer could give similar weather forecast in under one minute when many weather agencies would take longer and more computing power.[3] NVIDIA's Earth-2 climate digital twin cloud platform would facilitate the simulation and visualization of

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[3] https://www.science.org/content/article/ai-churns-out-lightning-fast-forecasts-good-weather-agencies (Nov 14, 2023)

weather at high resolution. NVIDIA demonstrated at its GPU Technology Conference how its model evaluates typhoon tracks and impacts on Taiwan at a very high resolution.[4] Its FourCastNet (*Four*ier Fore*cast* Neural *Net*work) is able to generate a week-long weather forecast in less than two seconds, much faster than standard models in the industry, such as ECMWF's Integrated Forecasting System.[5]

Market operation optimization: AI-based models are deployed for real-time market operation optimization, allowing operators of power networks — the Independent System Operators (ISOs) in competitive power markets, for instance — to adjust to changes in power supply and demand.

Enhancing grid stability: Besides predicting renewable energy output, sensors and AI could help detect disturbances in the grid, such as those due to power plant or power line outages. The information obtained and quick decisions made would help to quickly rebalance the grid. This reduces the duration or spread of any outage or disruptions, the need for backup power sources, and energy wastage.

Energy storage operation: AI can raise the efficiency of energy storage systems by helping to make decisions regarding storing and discharging energy, after considering factors such as demand and energy price paths.

Predictive maintenance: AI helps in predictive maintenance, raises energy efficiency and reduces costs. GE in Japan uses AI to enhance wind turbine efficiency, thereby reducing maintenance costs by 20% and increasing power output by 5%.[6] In Canada, AI supports power and natural gas utility Manitoba Hydro in identifying system faults and restoring power swiftly at critical points on its grid.[7]

Demand side management: A facility on the consuming side could optimize its energy use and could more dynamically adjust its demand for electricity based on power market conditions, including operational and weather data. Even for households, AI technologies enable smart devices to optimize household energy consumption and storage. Further, for electricity consumers that could adjust demand based on power prices and fundamentals, AI or other optimization algorithms could work to adjust its demand, which could either earn the facility demand response payments or help ease demand on the grid, especially during periods of extreme tightness. For example, Google's DeepMind AI has helped to reduce power demand for cooling at data centers. Further, given how consumers increasingly act as both producers and users of energy (prosumers) with the spread of distributed generation, AI could optimize the operation of distributed generation in its contribute to the grid.

Operational efficiency in power plants: AI can help predict the optimal times for electricity generation, considering factors such as fuel costs, maintenance schedules, and market prices.

AI can excel in the challenge of designing wind farms. The challenge lies particularly in dealing with wake effects. Designing wind farms is not as simple as just adding wind turbines. Wake effects happen when adding a turbine changes the wind flow or reduce the wind speed that affects the

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[4] https://nvidianews.nvidia.com/news/nvidia-announces-earth-climate-digital-twin (Mar 18, 2024)

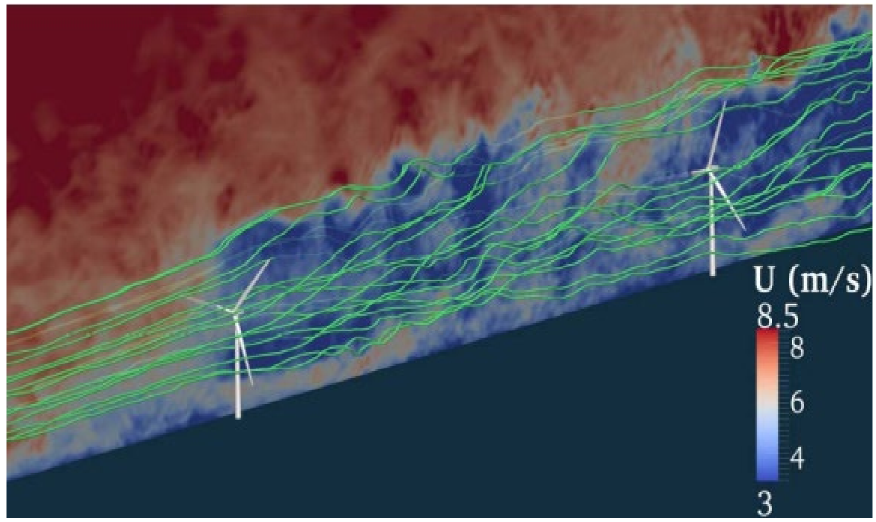
[5] https://docs.nvidia.com/deeplearning/modulus/modulus-sym/user_guide/neural_operators/fourcastnet.html

[6] https://asia.nikkei.com/Business/AI-to-propel-wind-farm-efficiency-in-Japan (Mar 11, 2017)

[7] https://www.ifc.org/en/insights-reports/2020/artificial-intelligence-in-the-power-sector (Apr 27, 2020)

operational efficiency of the next set of turbines behind or nearby (Figure 15). Wake steering is a possible mitigation strategy by misaligning the turbines to inflow wind direction. This deflects wakes away from the next set of turbines that improve the overall performance of the wind farm.[8] Measuring and simulating these effects take complex calculations.

Figure 15. Two NREL 5-MW turbines subject to atmospheric conditions showing the instantaneous streamwise velocity with streamlines



Source: NREL

Example: NVIDIA collaborates with Siemens on wind farm design that allows for simulations that run significantly faster than traditional methods. As mentioned earlier, "digital twin" models of the physical network help to estimate various drivers and conditions that affect power operation. Similarly, NVIDIA's digital twin platform for scientific computing[9] helps to run thousands of simulations of turbine operation, wind flow and various fluid dynamics effects faster than existing methods, such as large eddy simulations. **NVIDIA suggests that "this up to 4,000x speedup allows the rapid and accurate simulation of wake effects."**

Despite its potential, AI in the power sector faces challenges such as technological maturity, data quality and availability, cybersecurity, and the need for skilled professionals.

(3) Flexing Supply: Decentralization, Microgrids, Virtual Power Plants

Anthony Yuen
Maggie Lin

Commodities Strategy

Flexible supply can help to minimize the need for new grid infrastructure. By providing local power generation, flexible generation can reduce the load on transmission lines and alleviate grid congestion. It involves using energy sources and technologies that can quickly adjust output to match varying demand of electricity. This flexibility is key to integrating more renewable energy sources such as wind and solar power.

Decentralization could ease the reliance on long-haul transmission infrastructure by using local distributed energy resources to adjust power supply. A microgrid is an example: power supply and demand are

[8] https://www.nrel.gov/docs/fy23osti/84403.pdf

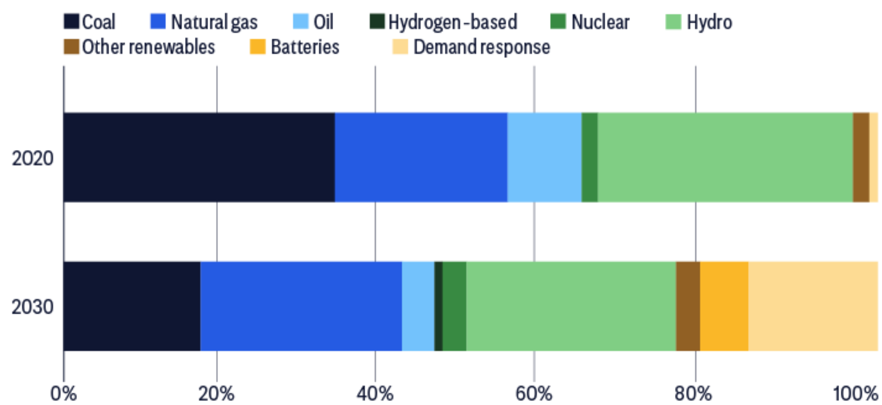
[9] https://resources.nvidia.com/en-us-energy-utilities/siemens-gamesa-wind (Mar 22, 2022)

managed within a localized network. It could be connected to the broader main power grid or be separated and operate in an "island" mode.

(a) Flexible Supply

Flexible supply includes both traditional generation, dispatchable renewables generation, energy storage solutions and decentralized energy systems. Demand response involves adjusting the demand side of power to match supply. It's a flexible approach that can complement generation sources. IEA estimates that by 2030, around 16% of the flexible supply could come from demand response, up from 1% in 2020. Around 6% or so could be from batteries (Figure 16).

Figure 16. Electricity system flexibility by source, 2020 and 2030



Source: Citi Research, IEA

Among traditional generation, natural gas fired or even fuel oil fired power plants, especially those using peaking technologies, are highly flexible. They can ramp up or down quickly, making them suitable for balancing variations in renewable energy output, though their emissions are a problem. Some large data centers include on-site gas power plants.

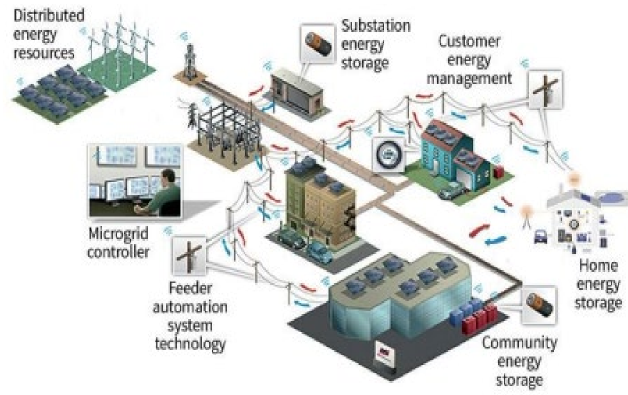
Dispatchable renewables generation include hydropower as well as biomass and biogas plants. Hydropower, particularly with pumped storage, which could be part of the energy storage category, offers considerable flexibility. It can be rapidly adjusted to meet peak demand or to store excess renewable energy. Biomass and biogas plants can provide a steady, controllable source of energy, and improve the grid's flexibility.

Energy storage, including both 1-to-4–hour batteries and long duration energy storage (LDES), releases stored energy to the grid, providing a fast response to demand changes and supporting grid stability.

(b) Decentralization, distributed energy resources and microgrids

Flexible supply can also make use of Decentralized Energy Systems. Decentralized Energy Systems refer to energy generation, storage and management systems located close to the point of use, rather than centralized production facilities such as large power plants. Their use is in some ways an attempt to reduce the reliance on the centralized power grid. Two key related aspects of decentralized energy systems are distributed energy resources (DERs) and microgrids (Figure 17).

Figure 17. Conceptual picture of distributed energy resources with other energy storage facilities and microgrid controller



Source: OSTI of the US Department of Energy

DERs are generally small-scale generation or storage sources like rooftop solar, small wind turbines, even biogas plants, and home battery systems. They can be aggregated to provide a flexible response to grid needs. These systems can be integrated into the existing grid infrastructure, providing electricity in tandem with traditional power plants. Their supply response quickly locally means less demand for long-haul transmission or distribution lines with the main power grid.

DERs can operate independently or in conjunction with the grid, and could enhance energy resilience and flexibility. DERs allow for more efficient management of energy resources, as they can be scaled up or down based on local demand without affecting the entire grid. In case of a central grid failure, DERs can continue to supply power locally. By generating electricity close to where it is consumed, DERs help to reduce transmission and distribution losses associated with transporting electricity over long distances. They also contribute to demand response strategies by allowing consumers to generate their own electricity during peak periods, reducing the load on the central grid. Nonetheless, managing a grid with numerous decentralized energy sources requires sophisticated grid management systems and regulations that can accommodate and optimize these diverse sources.

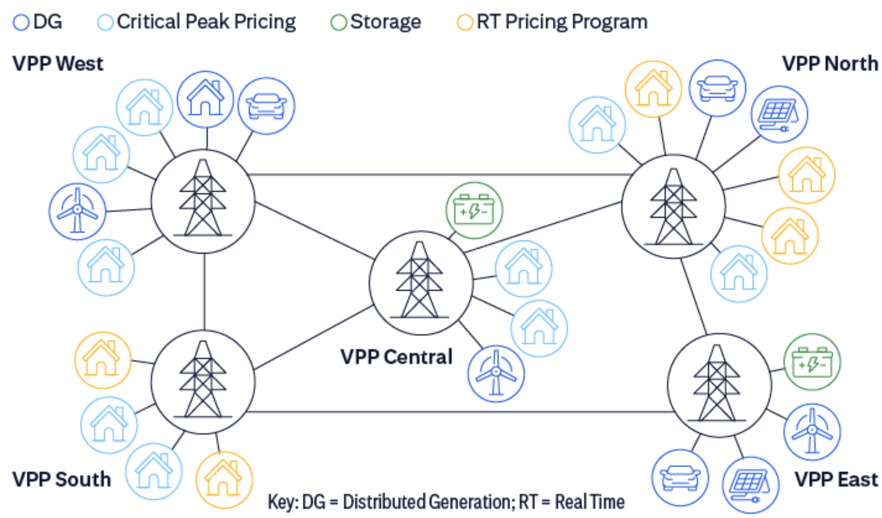
In a more coordinated manner, a group of DERs can be centrally managed to make up a microgrid. A microgrid "is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to operate in grid-connected or island mode."[10] Due to this generally self-sufficient nature that improves resilience, microgrids help to reduce the need for transmission or distribution power lines, especially by integrating local renewable resources. However, their upfront costs could be high and would require specialized control systems to coordinate power generation and demand, particularly when the microgrid is disconnected from the main power grid outside. There are numerous examples of microgrids, with the merits of each depending on the technical complexity, value proposition and revenue streams, as noted in a prior study commissioned by the State of California.[11]

[10] https://www.energy.gov/sites/default/files/2024-02/46060_DOE_GDO_Microgrid_Overview_Fact_Sheet_RELEASE_508.pdf (Jan 2024)

[11] https://www.energy.ca.gov/sites/default/files/2021-06/CEC-500-2018-022.pdf (Aug 2018)

A related but distinct concept is the virtual power plant (VPP), where a group of geographically disperse DERs can be coordinated together through some Distributed Energy Resource Management System (DERMS) to effectively act as a single power generation source (Figure 18). Demand response could be part of it. But successful implementation does require a thorough understanding of the physical topology and connectivity of the power network and system, as well as their responses. Nonetheless, resources coordinated properly could also reduce the need for extensive expansions of the grid to draw power from far-flung locations.

Figure 18. Virtual power plant



Source: US Department of Energy, Citi Research

Even a building itself could adjust its energy consumption and power supply procurement to sharply reduce the amount and variations of electricity supply needed from the main power grid. The large and time varying electricity demand for a building could be cut and flattened through greater energy efficiency, use of solar power during the day, and load flexibility. Energy storage could help as well.

(4) Flexing Consumption: Demand Response

Anthony Yuen
Maggie Lin

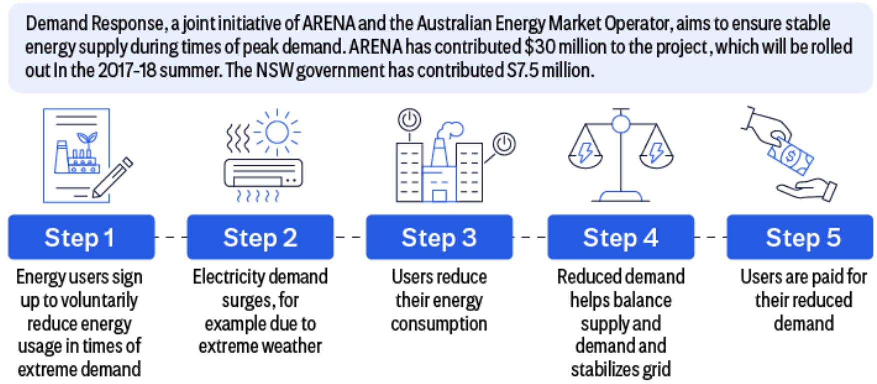
Commodities Strategy

Demand response is a key element in maintaining grid flexibility and partially help to alleviate the need to build more power lines.

Demand response is a voluntary program where electricity customers enrolled, when called upon by grid operators, to reduce or shift their electricity usage in times of high demand, while receiving payback in return. This gives consumers the ability to "see" the fluctuating wholesale prices[12], particularly for retail consumers who normally get charged based on average electricity prices, and therefore provide them opportunities to react when prices are high (Figure 19).

[12] "What is Demand Response" (PJM)

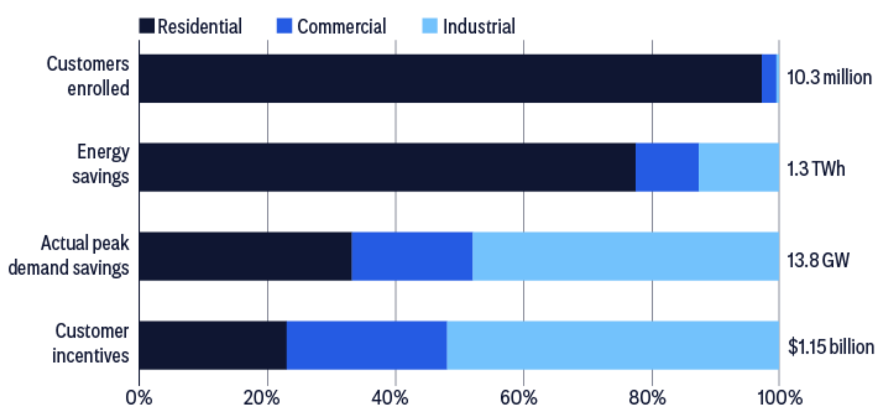
Figure 19. How demand response program works



Source: Citi Research, Australian Renewable Energy Agency

In the US, most of the 10 million customers that enrolled in demand response programs in 2022 are in the residential sector, but it is industrial customers that contributed the most to actual peak demand savings and getting paid the most incentives (Figure 20). On average, each residential customer saved 100 kilowatt-hours (kWh) in 2022 while receiving $26 in return. Meanwhile, average individual commercial and industrial customers saved 538 kWh and 4,117 kWh in 2022, respectively, and received incentives of over $1,200 and $15,000. Interestingly, while California used to be the most active state in US demand-response markets with 20% of total demand-response customers in 2016[13], it only ranked 8th with 6% of total demand response customers in 2022. The top 3 states with most demand-response customers in 2022 are Maryland, Florida and Arizona, indicating a wider adoption of demand response programs across the US.

Figure 20. Sectoral composition of demand response programs in the US, 2022



Source: Citi Research, IEA

Not only could demand response stabilize power grids, but it could also lead to cost savings and lower CO_2 emissions, as it cuts reliance on fossil fuel plants that do not need to be called up during peak demand periods. As illustrated by Australia Renewable Energy Agency (ARENA, Oct 11, 2017), some natural gas fired plants may only be running for as little as 20 hours per year — i.e., only at times of extreme demand — but they cost hundreds of millions of dollars to build, which leads to inflated electricity bills.

[13] "Demand response saves electricity during times of high demand" (EIA, Feb 8, 2016)

Therefore, demand response offers a cost-efficient demand-side solution to grid imbalances than the traditional supply-side solutions.

Demand responses can be either priced-based or incentive-based. Price-based programs, such as real-time pricing, critical-peak pricing and time-of-using tariffs, give customers time-varying rates to encourage customers cut electricity usage when electricity prices are high. Meanwhile, incentive-based programs pay participating customers directly when they react to requests by the program sponsor[14] (Figure 21).

Figure 21. Demand response options

Price-based	Incentive-based
Time-of-use tariff (TOU): A rate with different unit prices for usage during different blocks of time, usually defined for a 24-hour day.	**Direct load control:** Primarily offered to residential or small commercial customers, where program operators remotely shut down customers' electrical equipment on short notice.
Real-time pricing (RTP): A rate that typically fluctuates hourly reflecting changes in wholesale power prices. Customers are notified of RTP prices on a day-ahead or hour-ahead basis.	**Interruptible/curtailable service:** Traditionally offered only to the largest industrial or commercial customers, who will receive a rate discount or bill credit for reducing load during contingencies or get penalties for failure to curtail.
Critical peak pricing (CPP): A rate that is a hybrid of TOU and RTP design. While based on TOU, provision is made for replacing the normal peak prices with a much higher CPP under specified trigger conditions.	**Emergency Demand Response Programs:** Provide incentive payments to customers for load reductions during periods when reserve shortfalls arise.

Source: Citi Research, DOE

(5) Storing for a Rainy Day — Energy Storage: Increasingly from Short-Duration to Long Duration

Anthony Yuen
Maggie Lin

Commodities Strategy

Energy storage is vital in integrating renewables by helping to deal with their intermittency itself and other issues, from generation curtailment and frequency regulation, to peak shaving and improving grid resilience.

- **Energy storage can store excess renewable power during periods of low demand to reduce the need for curtailment.** NREL found that deploying 12 GW of energy storage in California could cut renewable curtailment by up to 30%. Energy storage can quickly respond to grid frequency fluctuations and help to maintain grid stability.

- **Energy storage can also discharge during peak demand periods, reducing the need for more power lines and peaker power plants, and lowering overall system costs**. (Peaker plants are generally small power plants start generating when demand is very strong.) NREL found that deploying 35 GW of energy storage in the US by 2025 could reduce peak demand by 8%. Energy storage can provide backup power during outages and improve grid resilience. Storage capacity should be enough to cover critical loads during outages. The exact amount depends on local needs and outage duration.

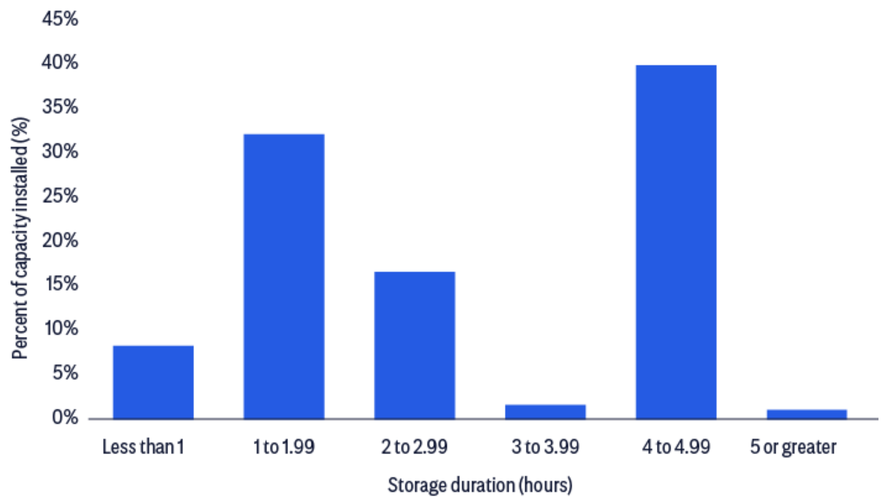
[14] "Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them" (DOE)

Currently energy storage is dominated by capacity of 4 hours or less, but longer-duration storage would increasingly be critical and sizable.

(a) Short duration energy storage

Installation statistics show the dominance of the 4-hour storage in recent years. Since 2010, more than 38 GW of energy storage has been added to the US grid, predominantly in the form of lithium-ion batteries with duration of 4 hours or less. This trend stems from the "4-hour capacity rule" in several market regions, where storage with at least 4 hours of rotation receives full compensation in capacity markets or contracts for firm capacity (Figure 22).

Figure 22. Distribution of energy storage durations for capacity completed during 2010–2022



Source: Citi Research, NREL

Why 4-hour storage? Historically 4-hour storage has been sufficient for providing capacity during summer peaks, such as in many parts of the US. Its role is enhanced with greater deployments of solar energy. However, changing weather patterns and electrification are leading to longer winter demand peaks, which are often beyond the effective service range of 4-hour storage. Storage plants providing peaking capacity derive value from physical capacity and energy time-shifting/arbitrage. The ability to store low-cost off-peak energy and sell it during high-price periods aligns with periods of highest demand, maximizing revenue.

Substantial ESS market potential for lithium-ion batteries

Jack Shang
Jimmy Feng

Basic Materials and Battery Materials
Equity Research

To estimate lithium-ion batteries (LiBs) energy storage systems (ESS) installation based on renewables' installation, key assumptions include the LiB ESS penetration rate, matching rate of ESS to renewables, and average duration of energy storage.

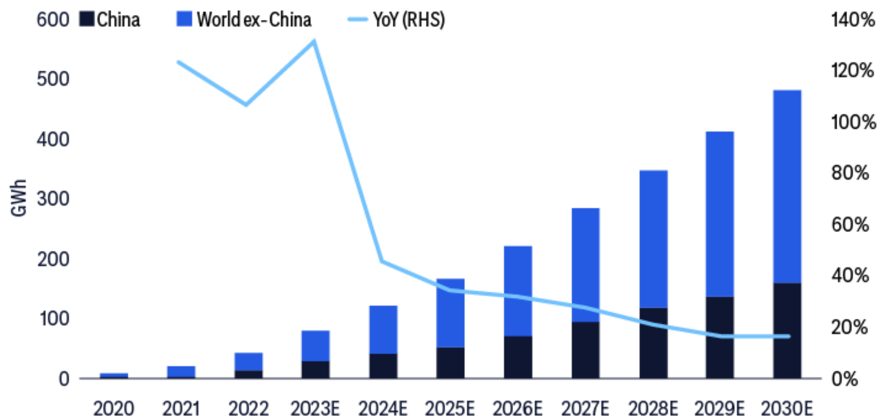
Lithium Battery ESS penetration rate: China's LiB ESS penetration rate reached 52% in 2022, and should remain at 52% till 2025 and reach 60% in 2030 due to the limitations of pumped storage hydropower. The global ex-China LiB ESS penetration rate was 92% in 2022, and should remain flat into 2030, as the penetration rate has already reached a high level.

Matching rate of ESS to renewables: China's matching rate of ESS to renewables was 11% in 2022, and should gradually rise to 16% in 2025 and reach 30% in 2030. The matching rate reached 8% globally excluding China in 2022, and should rise to 15% in 2025 and to 30% in 2030.

Average duration of energy storage: The average duration of energy storage in China was 2.1 hours in 2022 and should rise to 2.3 hours in 2025 and 2.8 hours in 2030. Per BNEF, the global average duration for energy storage reached two hours in 2020. Global energy storage duration should climb to 2.4 hours in 2025 and 2.9 hours in 2030. A higher ratio of renewable power generation requires longer energy storage.

Global cumulative LiB ESS installations should reach 489 gigawatt-hours (GWh) and 2,461 GWh in 2025 and 2030, respectively, with compound annual growth of 74% and 51%, respectively. In China, we expect that the cumulative LiB ESS installation will reach 162 GWh and 824 GWh in 2025 and 2030 respectively, with compound annual growth of 85% and 54%, respectively (Figure 23).

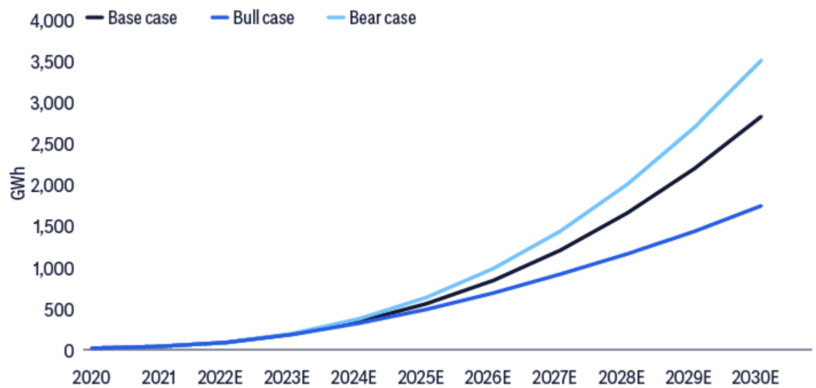
Figure 23. Annual lithium-ion batteries energy storage systems installation (GWh)



Source: Citi Research

Scenario analysis: We expect global cumulative LiB ESS installations to be 3,195 GWh in a bull-case scenario and 1,536 GWh in bear-case scenario (Figure 24). As lithium-ion battery ESS is still at an early stage of development and currently remains largely policy driven, long-term adoption might depend on a range of factors including cost savings, business models of ESS operators, and competition with other ESS technologies. In the bull case, we expect a faster increase in the matching rate. The matching rate in China/ex-China is expected to reach 20%/18% (vs. 16%/15% in base case) in 2025 and 40%/38% (vs. 30%/30% in base case) in 2030. In the bear case, we expect energy storage hours will remain flat at 2.5 hours after the increase to this level. In addition, we also assume a slower increase in matching rate.

Figure 24. Sensitivity analysis: Cumulative lithium-ion batteries energy storage systems installation (GWh)



Source: Citi Research

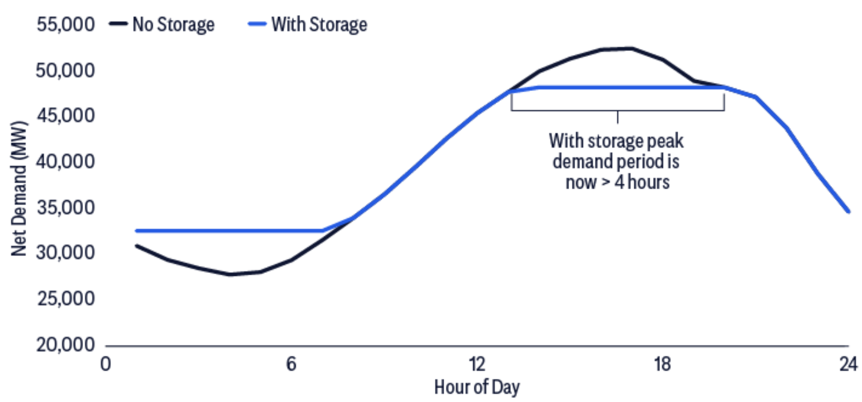
(b) Evolving from short to long duration energy storage

Anthony Yuen
Maggie Lin

Commodities Strategy

At first glance, the use of energy storage helps to flatten peak demand, thereby reducing the amount of power supply needed to meet power demand during high usage period (Figure 25).

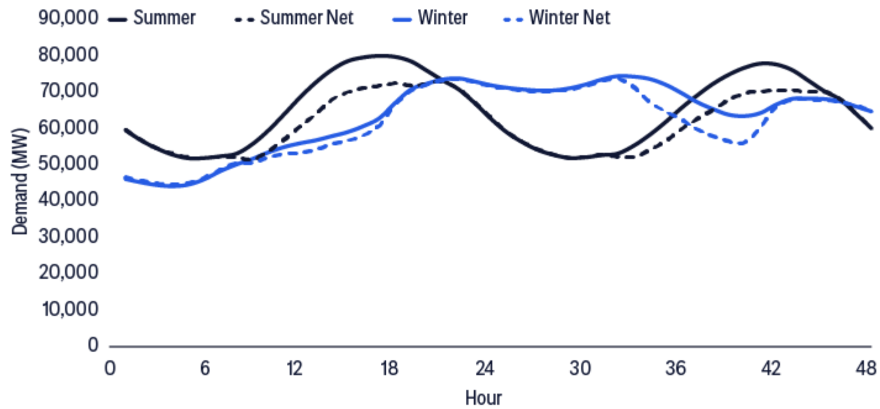
Figure 25. Simulated impact of 4-hour storage on net load in California demonstrates how storage can reduce the net load peak, but prolongs it, reducing the capacity credit for the 4-hour storage asset.



Source: NREL, Citi Research

However, as more energy storage capacity enters service, power demand in some regions should shift to a longer winter peak than the historical summer peak (Figure 26). That's because solar output during the day better fits the profile of greater cooling demand around mid-day, thereby offsetting the need for more electricity supply from traditional sources. **Even as there would be an evening ramp in demand as people gather before sleep, the duration of the evening ramp is typically limited.**

Figure 26. The solid lines show ERCOT's normal demand profile: the summer peak (July 20-22, 2022) was ~8% higher than the winter peak (December 22-24, 2022). But the dashed lines show the net peak with solar, where strong solar generation led to a net winter peak overall.



Source: NREL, Citi Research

With winter demand peaks, colder weather and the use of electric heating would lead to a higher and longer peak in power demand, including at night, which would not benefit from having solar power generation to meet demand. The longer duration of winter peak demand at night means that the typical 4-hour storage might not be sufficient. The shift to winter demand peaks will create opportunities for longer duration storage. As net peak demand periods shift to winter due to large solar supply, longer-duration storage becomes more valuable.

With climate change intensifying and the generation share of renewables rising, the resulting longer periods of oversupply or undersupply of power would raise the need for dispatchable power supply beyond typical 4-hour storage solutions. More extreme weather and longer periods of such weather would affect power demand. Periods of stronger demand often coincide with periods of shortages in renewables. Very hot weather might come with low wind speed and low precipitation, which lower wind and hydro generation. Very cold weather with large snow cover could affect wind turbine and solar panel efficiency.

Therefore, the market will require energy storage solutions beyond the 4-hour storage norm, aside from the use of more flexible generation. The economic opportunities are vast, but regulations will have to evolve as technology continues to advance. While new technologies must compete with Li-ion's cost reductions and potential for longer discharge durations, supporting a variety of technologies to meet the evolving needs of the grid becomes a necessity, due to known limitations of Li-ion based storage. Cost parity will depend on large-scale deployments and policies supporting a diverse portfolio of longer-duration storage technologies.

For details on Long Duration Energy Storage (LDES), please see the spotlight section on page 7.

Anthony Yuen
Maggie Lin

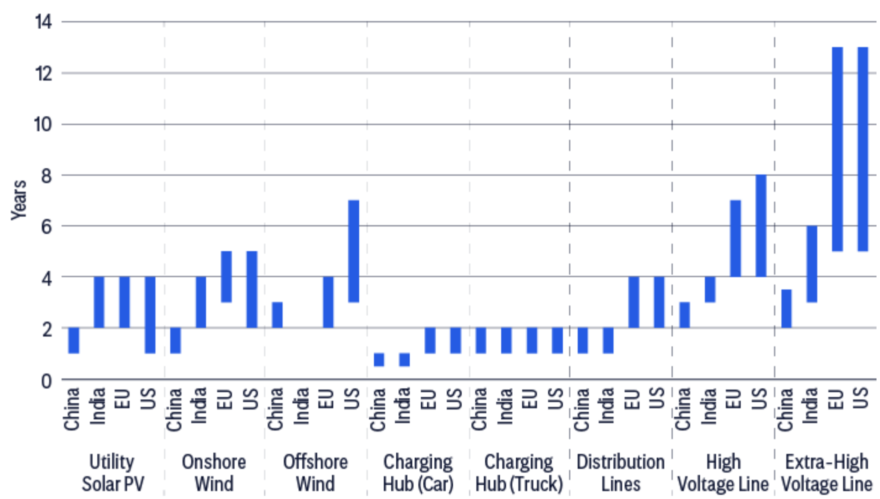
Commodities Strategy

(6) "Permit Me" — Regulatory, Market Reforms and Financing

To accelerate the grid modernization process, drive private investments and unlock the full potential of renewable energy, we must prioritize regulatory reform, streamline permitting processes, promote stakeholder engagement to deal with NIMBY (Not In MY Backyard) issues, and provide incentives for private sector investments. Regulatory issues and NIMBY problems affect private sector investments through increased project risks and higher costs. Increased project risks stem from lengthy permitting processes, regulatory uncertainties, and NIMBY opposition. These could lead to higher costs, such as delays due to regulatory hurdles and NIMBY challenges.

Permitting often takes a longer time than construction in Europe and the US due to factors such as complex administrative processes, insufficient government staffing and legal challenges. This has led to long queues of renewables power projects waiting to get interconnection approved and significantly delayed renewables buildout (Figure 27).

Figure 27. Deployment time ranges for solar, wind, EV charging and power grid developments



Source: Citi Research, IEA

(b) Potential reforms

Reforms are under way but more needs to be done. There are possible solutions, but they do require additional measures to mitigate those obstacles. Solutions that streamline permitting procedures include the centralization of permit issuance, setting maximum timelines, using existing right-of-way, designating infrastructure corridors, or raising the threshold for application.

(i) A "one-stop-shop" approach, centralization, standardization and coordination could help.

(ii) Using the existing right-of-way or designating some infrastructure corridors should help to reduce the number of permits needed.

(iii) In addition to utilities' existing efforts in public interactions, being more targeted and active in engaging local communities and stakeholders early in the project planning process could be useful in

addressing concerns and reducing NIMBY issues. It is important to educate the public on the benefits of grid improvements, such as increased grid reliability, reduced carbon emissions, and economic growth.

(iv) At times utilities also have to take initiative to improve the grid in a cost-effective manner. In some jurisdictions where the cost-of-service scheme is the rule, utilities are incentivized by the rules to build costly infrastructure. Thus, alternatives include providing incentives for utilities to invest in grid modernization, such as performance-based regulation that rewards utilities for achieving efficiency improvements, reducing carbon emissions, and enhancing grid reliability.

(v) Technology can help, such as in accelerating the evaluation process as noted in the last section. Utilizing digital tools and innovative practices could simplify and speed up permitting and construction processes, particularly in evaluating impacts of integrating renewables on the grid.

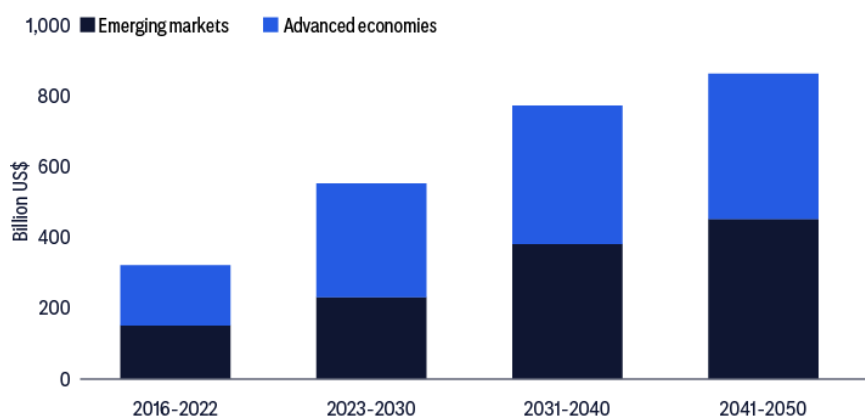
More frequent grid planning exercises, done in coordination with other sectors, are necessary. Technology could help accelerate the planning process, as mentioned in the section on optimization. Electrification of the transport and heating sectors would mean more power demand and flow, particularly with more distributed energy resources in the grid.

(c) Financing

The world clearly needs more grid infrastructure investments. During the past decade, annual global investments have been around $300 billion, which will need to rise to $450 billion on average in the current decade according to IEA[15]. In 2041–2050, annual investments of $870 billion will be required (Figure 28). BNEF also has similar forecasts under its Net Zero Scenario[16], which calls for grid investments of about $600 billion in 2030, $760 billion in 2040 and $870 billion in 2050.

There are a number of solutions to these financing challenges, but clearly what's right is very much location-specific. These solutions include public-private partnerships, incentivizing private investments, regulatory framework overhaul, targeted investment programs, international funding and support, and identifying new sources of value.

Figure 28. Investments required in distribution grids in IEA's Announced Pledges Scenarios (annual average)



Source: Citi Research, IEA

[15] IEA (2023) Electricity Grids and Secure Energy Transitions

[16] BNEF (2023) "New Energy Outlook: Grids"

(7) Regional Grid Outlooks

(a) United States Grid Outlook

Ryan Levine

US Utilities
Equity Research

The outlook for the US grid is that growing demand for electric transmission is spurred by renewable buildout and drives regional plans for transmission buildout targeting in service by the end of the decade, but it is difficult to execute due to the following challenges: (1) public sentiment as shown in our proprietary survey; (2) federal/state permitting (modestly addressed through National Environmental Policy Act [NEPA] revisions) and long regional interconnect queue; and (3) supply chain bottlenecks.

Drivers for Transmission Demand

Interconnect new renewable generation to grid. New transmission infrastructure is needed to connect new built utility-scale renewable into the grid, as renewable generation is built to meet both load growth and state decarbonization goals.

Upgrade or extend existing transmission to meet reliability & resiliency requirements. The US transmission and distribution (T&D) system is aging, with 70% transmission lines and transformers 33+ years or older, according to a 2015 Department of Energy study. To "keep the lights on", maintain reliability and prevent system failure due to aging infrastructure, US utilities invest a significant portion of capex in advanced hardening and resiliency (AHR). In 2022, 34% of transmission capex is related to AHR spending, including relocating transformers in flood prone regions, reinforcing transmission structures in high wind speed zones, installing higher temperature-rated transformers for extreme heat, installing sensors and AI to monitor system and detect threats, remote monitor & control, and energy storage.

Implement regional long range transmission plans. Under FERC Order 1000, regional ISO/RTOs are developing longer-term transmission plans to accommodate the future generation fleet in the region (after planned coal/gas retirement and future renewables coming online), improve transmission congestion and system flexibility, and address electrification demand brought by building electrification and EV adoption. Incumbent utilities have ROFR rights to develop transmission projects in their jurisdiction, and other utilities can bid for developing rights of other lines in a competitive process. Current plans include MISO Long-range Transmission Plan, CAISO 20-year Transmission Outlook, and ISO-NE 2050 Transmission Study (Figure 29).

Figure 29. Longer-range transmission plans

MISO Tranche 1 $10.3B, Tranche 2 between $20B and $30B (to be announced); ISO-NE $16-$17B in basic scenario and $23-$26B in advanced scenario.

Source: Citi Research, MISO, CAISO, ISO-NE

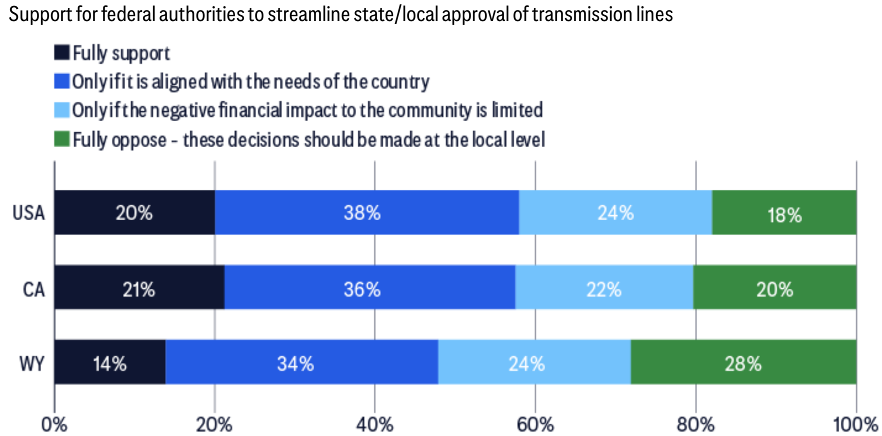
Challenges to Execute Transmission Lines

We engaged the Research Innovation Lab to conduct a comprehensive survey of 3,000 adults nationwide and ~2,500 adults from various states on their views of electric transmission. Beyond a national study, we oversampled ~2,500 adults in state level surveys for California, Indiana, Louisiana, Massachusetts, Michigan, Minnesota, New Jersey, New York, Ohio, Texas, West Virginia, Wisconsin, & Wyoming. Public sentiment towards building large transmission lines is more positive vs. two years ago, driven by economics and reliability. However, many respondents still showed a general sense of concern related to health effects and safety, especially impact on children and falling lines due to weather events which could cause wildfires in the West. California is the only state where residents are less supportive for building new lines than two years ago, with safety concerns being the main driver.

While most respondents support of some federal oversight in the approval process of transmission lines, more are unsure when it comes to federal funding. Wyoming respondents are more skeptical about federal involvement than other states (Figure 30).

Figure 30. Attitudes toward permitting reforms

Support for federal authorities to streamline state/local approval of transmission lines



Source: Citi Research

The US debt ceiling deal in June placed a limit on NEPA review timeline (two years or one year depending on environmental impact), which enabled the DOE to propose a rule to streamline permitting for high-voltage transmission in August. The proposed rule makes DOE the lead agency for NEPA reviews, targets a 2-year federal decision timeframe. It establishes the CITAP program which can serve three ~1GW high-voltage transmission projects per year according to DOE estimates.

The NEPA improvements and DOE's proposed rule could help reduce permitting time, especially for interstate transmission lines, but execution challenges remain:

1) Paying: Cost allocation between two (or more) RTOs is difficult as it cannot be done under current cost recovery mechanisms (state commissions, etc.). FERC in theory has the power to coordinate between RTOs but no precedents.

2) Permitting: Lines can be held up for years due to a snag in the long permitting process involving multiple field offices of multiple agencies, especially in the West. Democrats has been advocating for FERC's federal authority to approve if the line is in the national interest, whereas Republicans pushed back citing state rights.

3) Planning: There are no precedents for multiple RTO/ISOs to plan transmission lines together; previous intrastate transmission lines were planned by a single RTO/ISO with their own calculating mechanisms.

(b) European Grid Outlook

Piotr Dzieciolowski
Jenny Ping

European Utilities Research

Why there is such big need for investment in power networks?

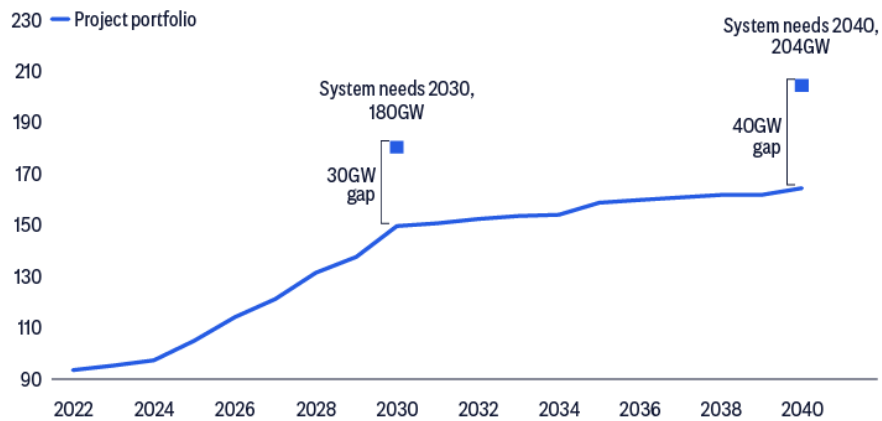
Historically, most of the European electricity systems consisted of a small number of large power plants — e.g., nuclear or coal plants in each country — and the electric grid was meant to distribute power from these power plants to points of consumptions. There was also limited cross border capacity. The rise of renewable power is changing the generation pattern as the location and concentration of wind and solar assets is very different but also consumption patterns are anticipated to change materially.

As a result, we see a number of new features that electricity transmission and distribution grid needs to facilitate energy transition:

- **Connecting renewable assets to grid and facilitating power flows** – the location of newer renewable assets is very often in different areas — i.e., certain areas have better wind or solar conditions, and this requires grid connections. The grid also has to be strengthened to facilitate power flows from generation sources to consumption centers — the best example is connecting the offshore grid in the north of Europe, which requires not only connection but also transmission corridors from the south to the middle of the continent. Overall, ENTSO-E, the association for the cooperation of the European transmission system operators (TSOs), identifies a system need for 43,000 km of additional transmission lines by 2040. The second leg of development may take place on distribution system operators (DSOs) but there is limited aggregated data on the size of investments.

- **Increasing grid reliability** – The more renewables we have in the system the bigger and more volatile the pressure on grid stability. The grid needs to be strengthened internally to facilitate changing power flows, which can also be volatile on an intraday basis. The other way to improve grid safety is to improve cross-border interconnections between countries. At present, Europe's electricity system is the biggest interconnected electrical grid in the world. ENTSO-E identifies the need for 180GW of cross-border transmission capacity in 2030 to meet the EU energy transition targets. Based on the current project portfolio, however, planned capacity is lagging the system needs by around 30GW (Figure 31).

Figure 31. Interconnector portfolio lagging system needs



Source: Citi Research, ENTSO-E

Accommodating change in demand patterns – The electric grid also needs to be strengthened to the changing consumption patterns on the low voltage grid. As an example, a retail client may not only have its own volatile production source such as rooftop solar, but it may also have a much higher or different demand than in the past in case they install power heat pump and EV.

What are the key drivers for grid operators' financial performance?

Electricity network operators exist as natural monopolies and therefore work under regulated business model. They develop networks based on technological needs in close cooperation with regulators based on a pre-approved plan. We think the key factors important for their financial performance are:

1. The **level of investment** that goes into the network development, which will determine the pace of asset growth. This is determined by the technical needs of the network.

2. The framework for regulated **returns** set by the national regulatory authorities, which is key element for financial performance of any TSO/DSO.

3. The quality of the company that will determine the **level of operational and financial performance**. This is determined typically based on a benchmarking exercise.

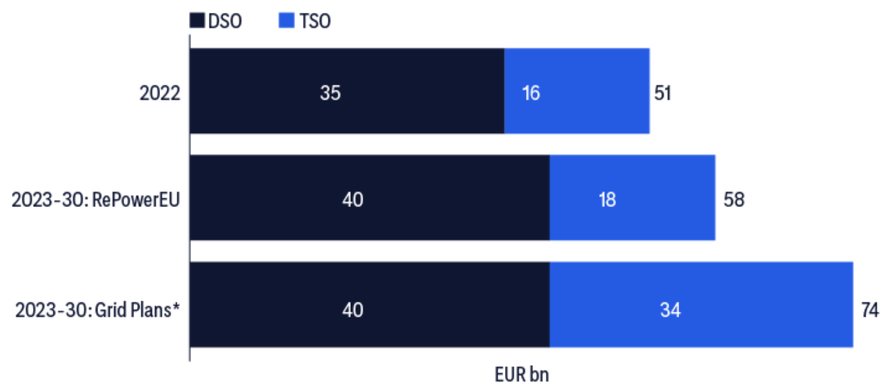
Power grid investment in Europe is very big

In order to achieve the EU's target of 45% renewables share in 2030, around €180 billion in investments into the high voltage electricity grids is required, according to the European Commission's (EC) RePowerEU. This is almost double the current RAB of the main European TSOs, which we estimate at around €105 billion, and suggests an average annual spend of

€18 billion which is slightly ahead of investment spend in 2022 of €16 billion.

However, if the main European TSOs perform against their announced grid investment plans which imply an average annual spend of more than €33 billion, the sector is well on track to surpass the RePowerEU requirement (Figure 32).

Figure 32. EU-27 average annual power grid investment (€bn)



*We use the ECs investment requirement for DSOs given lack of availability of DSO plans
Source: Citi Research, Deloitte Monitor, IEA

From the DSO perspective, tracking actual investment spend from a bottom-up perspective is very difficult considering there are tens or hundreds of DSOs companies in Europe. Overall, we estimate that the pace of annual RAB growth for both TSOs and DSOs will be a mid to high single digit percentage increase.

How do grid operators make money?

Grid operators (both TSOs and DSOs) are natural monopolies and therefore are regulated. Their P&L typically works on a regulated basis and is based on a Regulatory Asset Base model with an allowed regulated return – WACC. The WACC, as well as the entire regulatory framework, is determined by the relevant national regulatory authority and it can differ between countries based on the adopted methodology. For most of the jurisdictions, the nominal and pre-tax WACC is used to calculate the allowed return. However, some countries such as the UK, Italy and Sweden use a real pre-tax WACC. For example, based on the differing regulatory frameworks used, we expect the return generated by the key European TSOs to increase from around €6 billion in 2022 to €15 billion in 2030.

Figure 33. European Electricity TSO Regulatory Environment

Country	2015	2016	2017	2018	2019	2020	2021	2022	2023	Current regulatory period	WACC methodology
Austria	6.42%	6.42%	6.42%	4.88%	4.88%	4.88%	4.88%	4.88%	4.88%	2023	Nominal pre tax
Switzerland	4.70%	4.70%	3.83%	3.83%	3.83%	3.83%	3.83%	3.83%	3.83%	2023	Nominal pre tax
Estonia	6.74%	6.74%	4.46%	4.46%	4.46%	4.51%	4.51%	4.51%		2023	Nominal pre tax
Spain	6.50%	6.50%	6.50%	6.50%	6.50%	6.00%	5.58%	5.58%	5.58%	2020-2025	Nominal pre tax
Finland		6.55%	6.19%	5.78%	5.36%	4.89%	4.52%	4.13%	5.24%	2020-2023	Nominal pre tax
France	7.25%	7.25%	6.13%	6.13%	6.13%	6.13%	6.13%	4.60%	4.60%	2021-2024	Nominal pre tax
Lithuania	5.23%	5.23%	5.23%	5.23%	4.94%	5.01%	5.34%	4.03%	4.09%	2022-2026	Nominal pre tax
Norway	6.39%	6.39%	6.32%	6.10%	5.69%	5.15%	5.37%	7.47%	7.68%	2023	Nominal pre tax
Portugal	5.99%	6.13%	6.33%	5.17%	4.88%	4.60%	4.50%	4.70%	5.30%	2020-2024	Nominal pre tax
Slovenia	7.14%	7.14%	7.14%	7.14%	5.26%	5.26%	5.68%	5.95%		2023	Nominal pre tax
Germany	9.05%	9.05%	9.05%	9.05%	6.91%	6.91%	6.91%	6.91%	6.91%	2019-2023	Equity (nominal pre corporate tax, post trade tax assets - assets>=2006)
UK			4.23%	4.13%	3.95%	3.75%	3.45%	3.04%	2.96%	2021-2026	Real pre tax (vanilla)
Greece	8.50%	7.50%	7.30%	7.00%	6.90%	6.50%	6.30%	6.10%	6.10%	2022-2025	Real pre tax
Italy	6.30%	5.30%	5.30%	5.30%	5.60%	5.60%	5.60%	5.00%	5.00%	2016-2023	Real pre tax
Netherlands	3.60%	3.60%	3.60%	3.00%	3.00%	3.00%	3.00%			2022-2026	Real pre tax
								2.04%			Real plus 50% inflation (pre-tax)
Sweden	5.20%	5.85%	5.85%	5.85%	5.85%	2.35%	2.35%	2.35%	2.35%	2020-2023	Real pre tax
Romania	7.70%	7.70%	7.70%	7.70%	7.70%	7.39%				2020-2024	Real pre tax

Source: Citi Research, Council of European Energy Regulators

Return on Capital (WACC*RAB) is only one element of the regulated revenues. The other key building blocks are depreciation, operating costs and other incentives/adjustments typically set by the regulator for TSOs/DSOs to achieve certain targets. Depending on the exact regulatory framework, companies can outperform regulation mainly by operating at a more efficient cost structure while at the same time adhering to all quality parameters of the network or by adopting different financial structure or obtaining lower cost of funding. The exact magnitude of cost outperformance or underperformance will vary significantly between companies and countries.

The **allowed revenue components** comprise the following:

Depreciation
\+ Operating Costs
\+ Tax
\+ Return on Capital (WACC x RAB)
\+ Incentives, Penalties & Other Adjustments

What is the impact on the broader utility sector?

Although there is a short-term focus on increasing gas supply as Europe replaces Russian gas, we expect the rise in clean energy technology and solutions to result in falling natural gas demand over the long-term, impacting especially gas DSOs operators by increasing the risk of stranded assets. Gas transmission lines and other logistic infrastructure like LNG terminals or storages will still be required as gas is likely to be a transition fuel to fully decarbonised the economy. Moreover we also see within REPowerEU targeting a combined 20 million tonnes of demand for green gases, which will require selected transport infrastructure.

(c) China Grid Outlook

Pierre Lau

Asia Utilities and Clean Energy Equity Research

14th Five-Year Plan on grid equipment

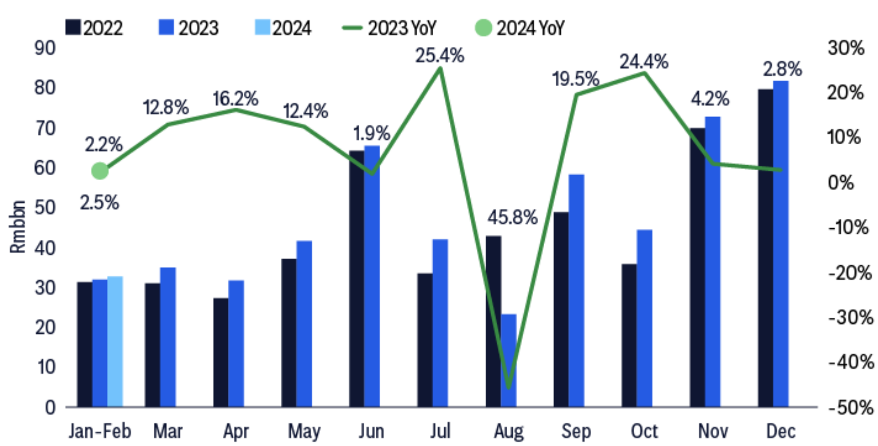
State Grid Corporation of China (State Grid) and Southern Grid have budgeted to spend more than Rmb2,230 billion and Rmb670 billion respectively for grid development in energy internet and renewable energy in the 14th Five-Year Plan; these comprised Rmb501 billion (+2.0% year over year) in 2022 and Rmb526 billion (+5.4% year over year) in 2023 (Figure 34). Among these capex outlays, around 60% were related to electricity distribution, to cater to increasing uses of renewables as well as clean energies conducive to emission cuts. Figure 35 shows China's monthly power grid investment.

Figure 34. China capex for power grid system and segments

	Planned	Actual	Planned	Actual		Planned		
Rmbbn	2022E	2022	2023E	2023	yoy	2024E	yoy	Mix
Capex of Smart Power Grid	112	n/a	115	n/a	n/a	n/a	n/a	n/a
Capex of Power Distribution Grid	115	n/a	115	n/a	n/a	n/a	n/a	n/a
Capex of UHV lines	201	n/a	200	n/a	n/a	230	n/a	41%
Capex of Smart Electric Meters	12	n/a	13	n/a	n/a	n/a	n/a	n/a
Others	81	n/a	80	n/a	n/a	n/a	n/a	n/a
Subtotal capex from State Grid	522	498	523	n/a	n/a	559	7%	100%
Subtotal capex from China Southern Power Grid	138	101	107	n/a	n/a	114	7%	n/a
Less: non-grid adjustments	-106	-98	-103	n/a	n/a	-108	5%	n/a
Total PRC power grid capex	555	501	526	528	5%	565	7%	n/a

Source: State Grid, Beijixing, Citi Research

Figure 35. China's monthly power grid investment



Source: China Electricity Council, Citi Research

In the 14th Five-Year Plan, China aims to accelerate the intelligent transformation of grid infrastructure and the construction of smart micro-grids, improve power system complementary and intelligent adjustment capabilities, strengthen the connection between source-grid-load-storage, increase clean energy consumption and storage capacity, improve transmission and distribution capacity for remote areas, promote the flexible refitting of coal-fired power plants, and accelerate the construction of pumped storage power stations and the large-scale application of new energy storage technologies. China also plans to improve the utilization rate of UHV transmission lines.

Ambitious UHV Expansion

China has 36 UHV lines in operation with total investment of Rmb651 billion so far.

China has 10 UHV lines under construction with a total investment of Rmb194 billion, including 5 DC UHV lines and 5 AC UHV lines.

Stable, safe and reliable UHV transmission lines are needed for renewable energy consumption system since China aims to build 450GW of big wind and solar farms in desert and Gobi areas, including 97GW under construction so far. China aims to build a total of 38 UHV lines in the 14th 5-year period, including 24 AC and 14 DC ones, totaling more than 30,000 km at capex of Rmb380 billion according to China Energy News. Based on these plans, PRC investment in UHV lines will reach historical highs.

China's wind and solar resources are uneven as wind power is mainly concentrated in the northern region and solar power is mainly located in the western desert. Local consumption there is very limited, and UHV transmission lines are needed to transfer the electricity out to eastern and central China (70% of electricity consumption) and increase the utilization ratio.

More Power Distribution & Transmission

PRC grid companies will prioritize power distribution, transmission and consumption segments in the smart grid construction, according to the Intelligent Planning General Report (Figure 36). The grid automation in power distribution and transmission becomes the key investment area since power generated by renewable energy is intermittent and fluctuating. China Southern Grid has included power distribution as the work focus in the 14th Five-Year Plan, and plans to invest 48% of total grid investment or Rmb320 billion in this area. We expect power distribution, transmission and consumption segments will have higher growth due to large investment compared to other segments.

Figure 36. PRC capex of smart grid and its segments

Rmbbn	2009-10	Mix	2011-15	Mix	2016-20	Mix	2021-25E	Mix
Power generation	0.6	1.8%	3	1.6%	3	1.4%	4	2.0%
Power transmission	2.2	6.5%	9	5.2%	13	7.1%	16	8.0%
Power transformation	1.7	5.0%	37	20.9%	37	20.9%	30	15.0%
Power distribution	5.6	16.4%	38	21.7%	46	26.1%	60	30.0%
Power consumption	10.1	29.6%	58	33.1%	51	28.9%	50	25.0%
Grid dispatching	3.3	9.7%	6	3.5%	5	3.0%	10	5.0%
Communication information platform	10.6	31.1%	24	14.0%	22	12.6%	30	15.0%
Total capex	34.1	100%	174.9	100%	175.0	100%	200.0	100%

Source: Qianzhan Industry Institute, Citi Research Estimates

According to Guiding Opinions on Energy Work in 2022, the NEA proposed to construct a new energy supply and consumption system based on large-scale wind and solar bases, supported by clean, efficient, advanced and energy-saving coal-fired power, and with stable, safe and reliable UHV transmission lines as the carrier. Therefore, **the automation and information communication in power grids need to be improved to maintain grid stability.**

PRC grid companies also target to add inter-regional and inter-provincial power transmission capacity from the current 240GW to more than 370GW in 2030 to fully support the construction of large-scale wind and solar power bases, and provide strong grid support for the development of various other clean energy sources.

(d) Australian Grid Outlook

James Byrne

Australian Energy Equity Research

Australia's national emissions targets

Australia has undertaken a commendable commitment, articulating an ambitious objective of achieving a 43% reduction in national emissions by 2030 (based on 2005 levels) and sourcing 82% of its electricity from renewable sources under the "Powering Australia" plan. The strategic policy played a pivotal role in securing victory for the Australian labor Party in the 2022 Australian federal election. Looking beyond 2030, Australia is actively developing a comprehensive Net Zero Plan setting the trajectory towards achieving net zero emission by 2050. This underscores Australia's dedication to environmental sustainability, through emissions reductions.

Net zero: a system transformation

Australia's Electricity Market Operator (AEMO) published an outlook for the forecast NEM (National Electricity Market) capacity under its base-case Step Change scenario. In order to reach a net zero emissions target by 2050, three key outcomes have been identified:

- The NEM must approximately double the delivery of electricity to households and industry by 2050.
- The NEM must withdraw coal-fired generation earlier than currently scheduled which corresponds to a ~60% withdrawal by the end of the decade.
- ~10,000km of additional transmission lines must be built to support new generation and battery infrastructure at a cost of

~$12.7 billion (real to calendar year 2022). While this only represents ~4% of the total spend needed to develop, operate and maintain generation, storage and future network investments for the NEM out to 2050, it is critical to improve system-wide connectivity to support the shifting mix of electricity sources.

There is also likely to be additional transmission infrastructure requirements in Australia outside of the NEM.

Headwinds facing the grid transformation

There are several key execution challenges in Australia which put the nation at risk of falling short of its committed emission targets. These risks include contracting ROIs for proposed projects, notably with higher costs and project delays (ignoring the overlay of incentive benefits).

- **Global decarbonisation mineral scarcity and bottlenecks**: At a time where energy transition is a global priority, there is heightened demand for critical minerals and securing manufacturing capacity. These risks are driving up construction costs and creating project delays with increased difficulty in procuring key materials and equipment.

- **Talent shortages**: A lack of abundant skilled labour in Australia is driving up demand for specialist positions, increasing construction costs and extending project lead times. Australia is becoming increasingly reliant on immigration to supply skilled labourers to meet increasing demand.

- **Social license** - New transmission lines are critical to connect the grid; however, private land access and a strong sense of “NIMBYism” (not in my backyard) is proving a predominant headwind to a timely build-out. High community engagement levels aim to mitigate this risk.

- **Slow regulatory approval processes** – Slow approvals for major projects are common due to the extensive consultation and environmental approval work required. This is particularly onerous for transmission developments due to wide areal coverage impacting a relatively high number of direct stakeholders. This often results in delayed final investment decisions.

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Appendix A-1

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