Liquefied Natural Gas (LNG) Alternatives for Clean Electricity Production

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Acronym Definitions

Acronym	Definition
A-CAES	Adiabatic Compressed Air Energy Storage
CCGT	Combined Cycle Power Plant
CCS	Carbon Capture and Sequestration
CO_2	Carbon Dioxide
CT	Combustion Turbine Power Plant
ELCC	Effective Load-Carrying Capacity
E3	Energy and Environmental Economics, Inc.
EGS	Enhanced Geothermal Systems
EU	European Union
GT	Giga-ton
LCOE	Levelized Cost of Energy
LDES	Long-Duration Energy Storage
Li-Ion	Lithium-Ion Battery
LNG	Liquefied Natural Gas
NO_x	Oxides of Nitrogen
NRDC	Natural Resources Defense Council
OSW	Offshore Wind
PSH	Pumped Storage Hydroelectricity
PV	Solar Photovoltaic
RTE	Round-Trip Efficiency
SMR	Small Modular Reactor
SRMC	Short Run Marginal Cost
WACC	Weighted Average Cost of Capital

Introduction

Executive Summary

This paper evaluates the feasibility of alternatives to liquified natural gas for power generation, including renewable generation combined with storage, as well as emerging low-carbon technologies. While the demand for liquefied natural gas (LNG) has been growing globally, these alternatives to LNG are also increasingly attractive from a cost, risk and environmental perspective.

New LNG-to-power infrastructure requires significant capital investment which must be recovered over a long operating life. LNG-to-power projects require long-term contracts committing the buyer to high levels of natural gas consumption in order to recover this investment and deliver the intended project economics. The long-term, high-fixed cost nature of LNG-to-power projects place buyers (and consumers) at high risk of stranded costs and "locked-in" GHG emissions over many years—at a time when the risks and adverse impacts of climate change are escalating[1] and decreasing GHG emissions is critical for limiting these impacts on human societies and natural systems.[2]

It is important for decision-makers to exercise care and diligence prior to making significant commitments to new LNG-to-power infrastructure—especially to evaluate costs, risks, and reliability needs compared to lower-emissions alternatives for power generation.

Energy and Environmental Economics, Inc. (E3) was commissioned by the Natural Resources Defense Council (NRDC) to evaluate the economic viability of alternatives to new LNG-to-power projects in both emerging and developed countries. Specifically, this report details alternatives to LNG use in three countries: Germany, Pakistan, and Vietnam. These three countries were selected because they encompass a range of factors influencing LNG-to-power planning decisions, including:

- Current electricity resource mix
- Available domestic natural resources (hydro, coal, gas, and renewables)
- Economic development, including income and electricity consumption per capita
- Load growth and load shape (influenced by climate and electricity end-uses)
- Grid reliability needs.

This paper presents an overview of LNG demand in each country, followed by an overview of the reliability needs of electricity grids and how reliability can be secured while transitioning the electric system to a low-carbon future. Following the discussion of what the electric system requires and how various

[1] "AR6 Synthesis Report Headline Statements," Intergovernmental Panel on Climate Change (IPCC), 2023, AR6 Synthesis Report: Summary for Policymakers Headline Statements (ipcc.ch), B2.
[2] IPCC, B3.

technologies can contribute, we present the current state of commercial and emerging low-carbon technologies for electricity generation and storage and an evaluation of the potential for these technologies in each of the three countries selected. Finally, we conclude with an evaluation of the cost of these lower-carbon alternatives to LNG-derived electricity and key considerations for decision-makers and stakeholders regarding new LNG-to-power infrastructure.

Currently, LNG imports in Pakistan, Vietnam, and Germany are being driven by shortages in conventional supplies of natural gas (e.g. natural gas delivered via pipeline, rather than liquified and delivered via tanker). However, LNG use in the electricity sector could be significantly reduced or replaced by renewable energy generation alone or augmented by battery storage and demand-side management tools (for example: energy efficiency and demand response).

Commercial renewable energy resources offer lower cost, lower criteria pollutants and GHG emissions, and increased energy security which makes these resources into compelling alternatives to new LNG-to-power projects for meeting near term energy needs in each of the three countries evaluated in this study. Using a range of historical LNG prices, we find that wind energy is currently lower-cost than LNG-derived electricity on an unsubsidized basis in each country, while solar photovoltaic (PV) energy is potentially cost-competitive. Furthermore, commercialized li-ion batteries can be cost-effective resources for grid reliability (capacity) and renewable integration (frequency regulation and operating reserves) compared to LNG-fired generation. Emerging technologies such as various forms of long-duration storage and power generation from green hydrogen also hold potential, but require additional development and cost declines to become more attractive alternatives to wind, solar, and li-ion batteries in the near term.

We find that the cost of investment capital is very impactful for the economic viability of renewable and storage technologies vs. LNG-fired power generation—for example, if the cost of capital in Pakistan could be reduced to the cost of capital in Germany, both onshore wind and utility-scale solar in Pakistan would be materially cheaper than LNG-fired generation has been in the last several decades. There are many ways to reduce the cost of capital for infrastructure projects—this has been the focus of numerous national and international programs and initiatives. While analysis of such programs is beyond the scope of this paper, our conclusions affirm the importance of lowering financing costs for renewable energy infrastructure. This is particularly important because concessional or preferential financing has a larger impact on renewable energy and battery projects than it does on LNG-to-power projects—renewable energy and battery projects have higher upfront costs but much lower operating costs relative to LNG-to-power projects. On an equal playing field for the deployment of lower-cost capital from governmental, multilateral, and private sector sources, renewables and battery storage are lower risk, lower cost, and lower emissions compared to LNG-to-power projects, and should be prioritized accordingly.

Our conclusions regarding cost competitiveness are based on an analysis of the levelized cost of electricity (LCOE) of these technologies versus LNG-derived electricity. LCOE is an industry-standard measure of the cost of one unit of electricity (MWh or kWh) from a given resource, taking into account all costs of upfront investment, return on investment to lenders and owners, operations and maintenance, and fuel consumption over the useful operating life of the resource. All assumptions for our LCOE calculations are documented from public sources and presented in the Assumptions and Methods section of this report.

In addition to the value proposition for renewables to replace energy generated from LNG at lower cost and with lower emissions, proper accounting of the capacity value of renewables and short-duration storage in power system portfolios may help Pakistan and Vietnam avoid costly new offtake commitments for LNG on the basis that LNG-fired power generation may not be needed for grid reliability as is often assumed in LNG-to-power project feasibility analyses. Germany is already proceeding with plans to use renewables to displace fossil fuels in its grid mix—particularly as renewables offer energy security benefits which are especially compelling at a time when Germany's gas imports have been disrupted by the Russia-Ukraine conflict.

In the long term, zero-carbon firm generation technologies may play an important role in bringing the electricity sector from low-emissions to zero-emissions (in absolute or "net" terms), but many of these technologies remain in the demonstration stage today and require commercial-scale deployments to prove out projected cost and performance targets. However, even if Pakistan, Vietnam and Germany retained fossil fueled generators for providing power during peak demand periods, renewable energy resources could displace most of the fuel demand from these generators, resulting in the generators running at much lower capacity factors than they do today. Under these circumstances, the overall fuel demand for these generators to supply power only "when needed" for reliability would be much lower, which could allow countries to rely on domestic fuel supplies (rather than high contracted volumes of imported LNG). Additional analysis would be required to study reliability needs in a decarbonized electricity grid in greater detail in each country.

Introduction

Liquefied Natural Gas Market Growth and Future Trends

Liquefied Natural Gas (LNG) is a liquid form of methane, which exists as a gas at standard temperature and pressure but which can be converted to its liquid form by "super-cooling" the gas to -260° F in a process known as liquefaction.[3] In liquid form, methane is 600 times denser by volume compared to gaseous methane in a conventional pipeline.[4] The energy density of LNG is the primary reason for its commercial attractiveness as a means of supplying natural gas to places where a conventional natural gas supply (well-head plus onshore pipeline) does not exist or is limited—in most use cases, natural gas (delivered as LNG) primarily competes with oil or coal for end uses ranging from industrial processes and chemical production to heating and power generation.

Due to the energy-intensive nature of LNG production, transport, and delivery, the lifecycle greenhouse gas emissions from LNG are significantly higher than conventional natural gas. In the electric sector, LNG lifecycle emissions can be as high as 60-75% of the lifecycle emissions of coal.[5]

Energy use and GHG emissions occur across the LNG value chain. Modern liquefaction facilities consume 8-10% of the natural gas delivered to the facility for the liquefaction process alone, with additional consumption required for on-site power generation and other facility needs.[6] Additional energy is consumed during shipping because some LNG is lost as a portion of the liquid fuel reverts to its gaseous state—this loss is known as "boil-off gas" and it is an unavoidable reality of LNG transportation which commonly accounts for around one-third of the charter costs of LNG shipping.[7] Boil-off gas can be reliquefied (requiring additional on-ship equipment and energy consumption), consumed by the ship itself for locomotion or electricity (or both), or simply combusted safely on the ship and wasted. Boil-off gas is often flared during the loading, unloading, and gasification stages of LNG deliveries, and it accounts for a significant portion of the lifecycle greenhouse gas emissions from LNG cargoes.[8]

Despite the energy-intensive nature and high cost of LNG, LNG has been traded as a commodity since the 1960s, and the market for LNG has grown significantly in the last decade and is expected to continue to grow into the future. Historical and projected future LNG demand is driven by three principal factors:

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[3] "Natural Gas Explained." U.S. Energy Information Agency (EIA). https://www.eia.gov/energyexplained/natural-gas/#:~:text=Natural%20gas%20is%20a%20fossil,hydrogen%20atoms%20(CH4).

[4] EIA.

[5] *Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States*. U.S. Department of Energy National Energy Technology Laboratory (NETL). DOE/NETL-2014/1649. May 29, 2014. life-cycle-greenhouse-gas-perspective-exporting-liquefied-natural-gas-united-states (energy.gov). 9.

[6] EIA.

[7] "LNG: What is Boil off Gas and What Does it Do?" Fluenta. LNG: what is boil-off gas and what does it do? | Fluenta.

[8] "Gas Flaring within the Global LNG Supply Chain—Insights from Real-time Analytics." FlareIntel. Gas flaring within the global LNG supply chain – insights from real-time analytics | FlareIntel

+ **LNG can serve as an additional source of natural gas supply:** LNG can serve as a “drop-in” fuel alternative (or complement) to existing natural gas supplies, which in many countries are limited due to geopolitical or physical conditions.

  In areas without access to conventional natural gas, LNG provides an alternative to other fossil fuels such as coal and oil for diverse applications, from industrial and transport applications to heating and power generation. While demand for LNG (and alternative fuel sources) comes from across economic sectors, this paper is focused on LNG demand (and alternative resources) for the electric power sector. Additional analysis is warranted to compare LNG to alternative resources for other applications, including industry and transport.

+ **LNG has been considered to be a less volatile and lower-cost alternative to oil:** The widespread deployment of hydraulic fracturing (“fracking”) in the U.S. enabled high production of natural gas at low cost from “unconventional” shale reserves, which in turn allowed U.S. natural prices to become decoupled from global oil prices. This price decoupling has created the potential for U.S. LNG to be a lower cost and less volatile alternative to oil for power generation and other uses (see Figure 1 below).

  Globally, natural gas prices continue to be benchmarked to either Henry Hub in the U.S. or to global oil prices, and the future “decoupling” or “recoupling” of oil and natural gas prices remains uncertain. Delivered “ex-ship” LNG prices will likely continue to be less volatile than oil prices, because delivered LNG prices contain a commodity cost (i.e. Henry Hub natural gas) plus multiple layers of fixed costs for liquefaction and shipping. While LNG prices may remain relatively more stable than oil prices, the high content of fixed costs in delivered LNG prices also establishes a robust and costly minimum price for LNG offtake. Additionally, the fixed costs are attributable to long-lived assets which are part of the LNG value chain, and as such suppliers (from owners of liquefaction facilities to chartered LNG carrier ships) typically require long term contracts with only limited flexibility in terms of gas purchase commitments in order to recover these investments from LNG customers.

+ **LNG has been considered to be a “transition fuel” for lowering greenhouse gas emissions in the electricity sector:** LNG (and natural gas in general) is often considered to provide two potential benefits for decarbonizing the electricity sector in many countries: i) replacing or avoiding coal-fired power generation, and ii) supporting grid reliability by enabling gas-fired generation technologies to be a flexible, “dispatchable” complement to variable and intermittent renewable energy resources such as wind and solar.

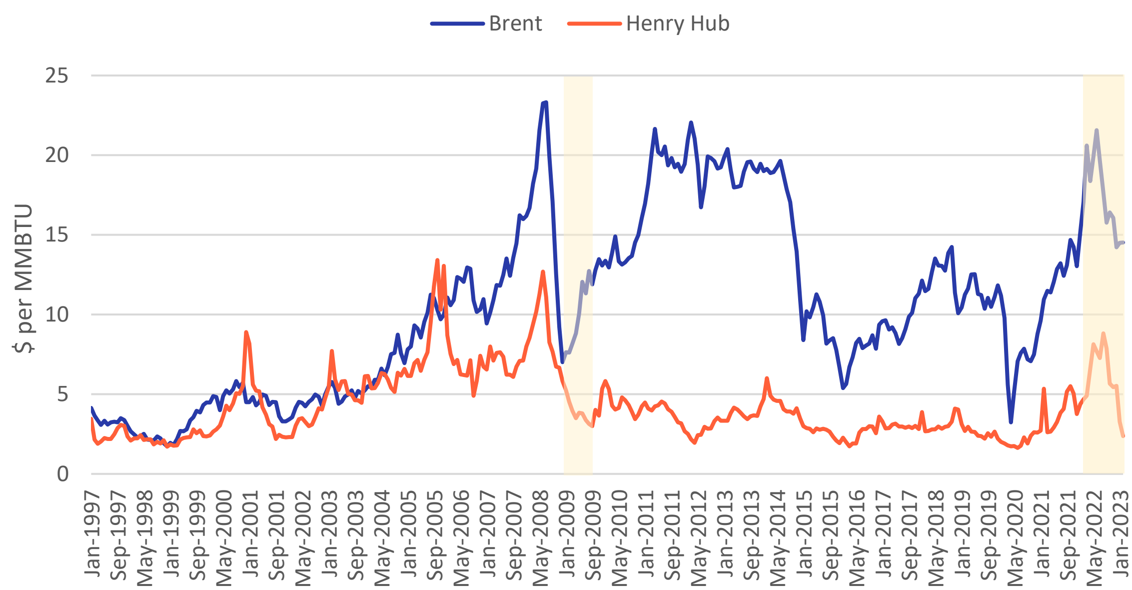
  These potential benefits are far from certain, however, and often miss the full picture. The lifecycle GHG emissions of LNG-to-power projects are actually as much as 60-75% of the GHG emissions from coal-fired power generation.[9] Furthermore, commercialized, large-scale renewable energy resources offer lower cost alternatives to coal and LNG-fired generation with lower risks and lower emissions (both criteria pollutants and greenhouse gases). Additionally,

[9] NETL 2014.

renewable energy and battery storage can provide significant reliability benefits which can also be more cost-effective than coal or LNG power generation, as discussed in this report.

The figure below presents the history of natural gas and oil prices from January 1997 to March 2023 to illustrate the price coupling and subsequent "decoupling" of oil and gas prices since the emergence of significant levels of shale gas production in the U.S. in the late 2000s.

Figure 1 Historical Spot Prices of Natural Gas (Henry Hub) and Oil (Brent) in $ per MMBTU



Sources: U.S. EIA. *Price of Liquefied U.S. Natural Gas Exports (Dollars per Thousand Cubic Feet)*. http://www.eia.gov/dnav/ng/hist/n9133us3a.htm.
U.S. EIA. *Europe Brent Spot Price FOB (Dollars per Barrel)*. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=M.
Note: Henry Hub and Brent spot prices are monthly. Brent prices are converted from $ per barrel to $ per MMBTU using a conversion rate that one barrel of crude oil contains 5.691 MMBTU of energy.

The first highlighted bar in the figure shows the beginning of the significant price divergence or "decoupling" between natural gas and oil prices in 2009. From 2009 to 2020, gas prices remained much flatter and less volatile than oil prices, but gas and oil prices started to move in tandem again during the global COVID-19 pandemic, and this movement has been more pronounced in recent price spikes which occurred after Russia's invasion of Ukraine in February 2022 (second highlighted bar). By Feb-March 2023, natural gas prices have fallen again in the U.S. while global oil prices have remained quite high.

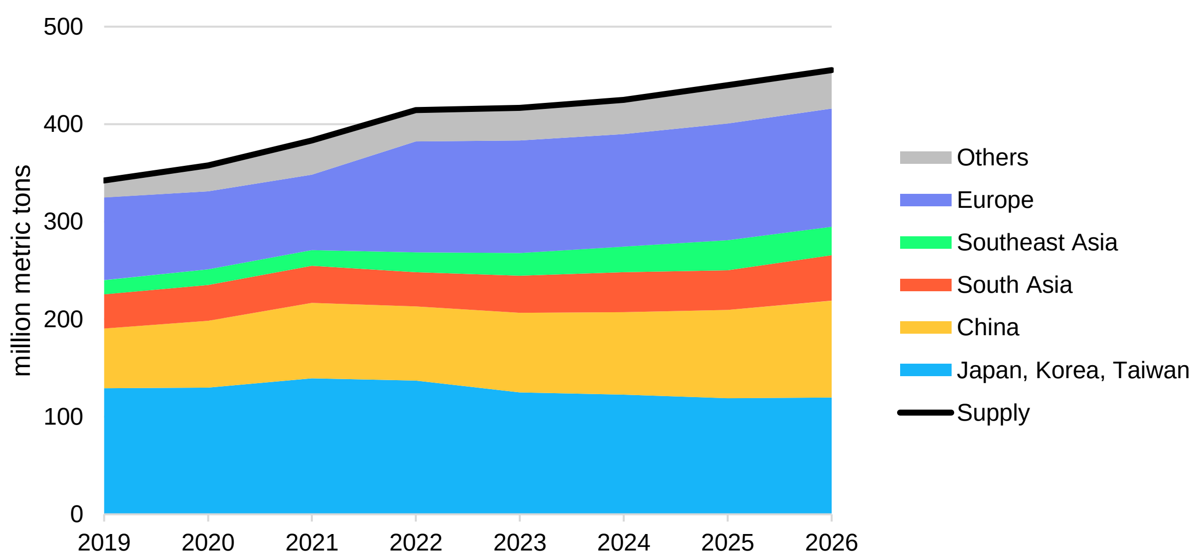
Historically, LNG demand has been driven by an absence of domestic natural gas and the use of LNG to replace coal and oil for a variety of end-uses, including power generation. Growth in LNG demand in the 2010s through 2021 was led by continuous growth in China's natural gas consumption, due to China's limited domestic supplies of natural gas.[10] LNG export capacity growth has been led by Australia, the U.S.

[10] *2022 World LNG Report*. International Gas Union. July 6, 2022.

and Qatar in the last decade to meet this growing demand. [10,11] Since 2022, the war in Ukraine has dramatically reduced the European Union (EU)'s access to pipeline-based Russian natural gas. This has fueled growth in EU LNG demand as the EU has sought to replace Russian gas imports. The vast majority of LNG sold to the EU has been supplied by the U.S. via long-term fuel contracts.[12] The EU has also invested heavily in LNG import capability, much of which is expected to come online in 2023.[13] LNG demand is projected to continue growing through 2026, led by European consumption and followed by China, Japan, Korea, and Taiwan as shown in Figure 2 below.[14]

Many countries in Asia had previously planned to rely heavily on LNG imports to satisfy domestic demand for natural gas. However, the growth in long-term LNG supply contracts to the EU may sustain higher LNG prices and force Asian buyers into direct competition with Europe.[15] In the long run, LNG supply may increase to stabilize prices, but elevated LNG prices create opportunities for countries to identify and secure lower cost and lower risk alternatives for the power sector.

Figure 2: Global LNG supply and demand



Source: Bloomberg NEF. *Global LNG outlook overview. Tight supply expected until 2026*. June 29, 2022. https://www.bloomberg.com/professional/blog/global-lng-outlook-overview-tight-supply-expected-until-2026.

Liquefied Natural Gas Use Drivers in the Electricity Sector

While LNG demand growth is being driven by multisectoral forces, this report will specifically focus on the LNG demand in the electricity sector. In this section, we outline high level drivers for LNG use in the power

[11] *LNG Market Trends and Their Implications*. Joint Study of the International Energy Agency and Korea Energy Economics Institute. June 2019.
[12] Farrer, Giles. *LNG: seismic shifts as Russia/Ukraine conflict makes waves*. Wood Mackenzie. August 22, 2022.
[13] Paul, Corey and Chase, Dylan. *Global LNG tightness means 'extreme market volatility' in 2023*. S&P Global. Dec. 8, 2022. S&P
[14] Bloomberg NEF. *Global LNG outlook overview. Tight supply expected until 2026*. June 29, 2022.
[15] Bloomberg NEF.

sector in Germany, Pakistan, and Vietnam. These three countries were selected because they encompass a range of factors influencing LNG-to-power planning decisions, including:

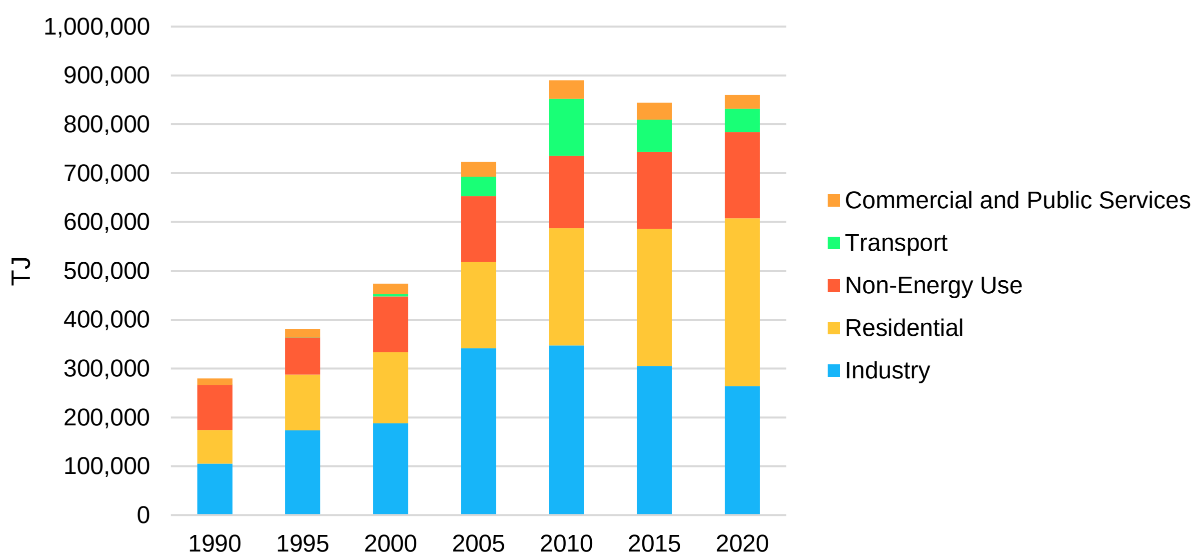
- Current electricity resource mix
- Available domestic natural resources (hydro, coal, gas, and renewables)
- Economic development, including income and electricity consumption per capita
- Load growth and load shape (influenced by climate and electricity end-uses)
- Grid reliability needs.

At a high level, shortages in domestic or pipeline-based natural gas supplies are causing LNG demand to grow in each country.

LNG Use Drivers in Pakistan's Electricity Sector

As shown in Figure 3, Pakistan's gas demand is largely driven by the power and residential building (domestic) sector. The country's gas consumption grew substantially in the first five years of the 2000s as Pakistan developed domestic natural gas reserves. Production from these domestic sources has since fallen, and new reserves have not been developed, in part because domestic market prices for natural gas have been insufficient to support additional investments in domestic production.[16] LNG has increasingly been used to augment the country's domestic natural gas supplies, as natural gas demand has doubled over the past twenty years.[17]

Figure 3: Pakistan's Historical Gas Consumption



Source: IEA. Gas Information 2022. https://www.iea.org/data-and-statistics/data-product/natural-gas-information.

[16] Spencer, Richard. *Increasing domestic gas availability in Pakistan*. End Poverty in South Asia. World Bank Blogs. 2015.
[17] Isaad, Haneea and Samuel Reynolds. *Rising LNG Dependence in Pakistan Is a Recipe for High Costs, Financial Instability, and Energy Insecurity*. Institute for Energy Economics and Financial Analysis (IEEFA). June 2022.

Residential natural gas consumption has increased four-fold, even while industrial use has declined. Transportation consumption has increased from almost nothing in 2000 to 5.6% of total gas consumption in 2020.[18] Although consumption has stabilized over the past decade, growth in high-demand sectors is still expected to increase aggregate gas demand.

LNG Use Drivers in Vietnam's Electricity Sector

LNG is also being proposed as a means to satisfy growing demand for electricity in Vietnam. Currently, Vietnam relies primarily on hydroelectricity, coal, domestic natural gas, solar photovoltaic power (PV), and imports from China and Laos to power its electricity grid.[19] Vietnam's existing natural gas reserves are declining, and while offshore natural gas reserves near Vietnam may prove an option to supply more domestic gas to the country,[20] these reserves had not been developed into active fields at the time of writing. Though its long-term capacity expansion planning process has not been finalized, Vietnam has therefore proposed relying heavily on LNG to power its future electric generation fleet, along with increasing offshore wind and solar power, storage, and increasing coal use.[21] The degree to which Vietnam's future generation fleet will rely on LNG is, however, contentious and uncertain.[22,23]

LNG Use Drivers in Germany's Electricity Sector

Germany's reliance on LNG in the electricity power sector is a recent phenomenon caused by the war in Ukraine, rather than specific a planned to increase in LNG use in the power sector. However, at the same time, due to the high price of LNG, as well as Germany's long-standing climate goals, Germany is actively accelerating efforts to reduce its LNG use in the electricity sector. Germany added more wind and solar power in 2022 than in any previous year.[24] This, along with using more coal to generate electricity than in previous years, drove down natural gas use in the power sector from 2021 to 2022.[25] Germany's coal use increased over this time period as natural gas supplies from Russia declined as a result of the Russia-Ukraine war, while France experienced a number of major outages at nuclear power plants (which

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[18] IEA. Gas Information 2022. https://www.iea.org/data-and-statistics/data-product/natural-gas-information.
[19] EVN. Annual Report 2021. https://en.evn.com.vn/c3/gioi-thieu-l/Annual-Report-6-13.aspx.
[20] Energy Voice. "Eni Discovery dents Value of ExxonMobil's Blue Whale in Vietnam." 2020. https://www.energyvoice.com/oilandgas/asia/264328/eni-exxonmobil-vietnam.
[21] "Decision Approving the National Power Development Plan in the 2021-2030 Period, with Vision to 2045. https://vepg.vn/wp-content/uploads/2021/09/5.9.2021-Draft-PDP8_En.pdf.
[22] Baker McKenzie. "Vietnam: October 2021 Updates to the Draft PDP8." 2021. https://insightplus.bakermckenzie.com/bm/attachment_dw.action?attkey=FRbANEucS95NMLRN47z%2BeeOgEFCt8EGQJsWJiCH2WAUTleh6%2BAJHruNkrWNztLuO&nav=FRbANEucS95NMLRN47z%2BeeOgEFCt8EGQbuwypnpZjc4%3D&attdocparam=pB7HEsg%2FZ312Bk8OIuOIH1c%2BY4beLEAeK13zYkvUKc8%3D&fromContentView=1.
[23] Vietnam Investment Review. "Vietnam to cut gas power capacity in electricity development plan." 2022. https://vir.com.vn/vietnam-to-cut-gas-power-capacity-in-electricity-development-plan-96455.html.
[24] Apunn, Kerstine, Yannick Haas, and Julian Wettengel. *Germany's Energy Consumption and Power Mix in* Charts. Clean Energy Wire. April 18, 2023. https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts.
[25] BDEW. "Jahresbeicht: Die Energieversorgung 2022." 2022. https://www.bdew.de/service/publikationen/jahresbericht-energieversorgung-2022.

historically export power to Germany and to the UK). Germany ultimately plans to provide 100% of its electricity from renewables by 2035—a more aggressive target set after the onset of war in Ukraine.[26]

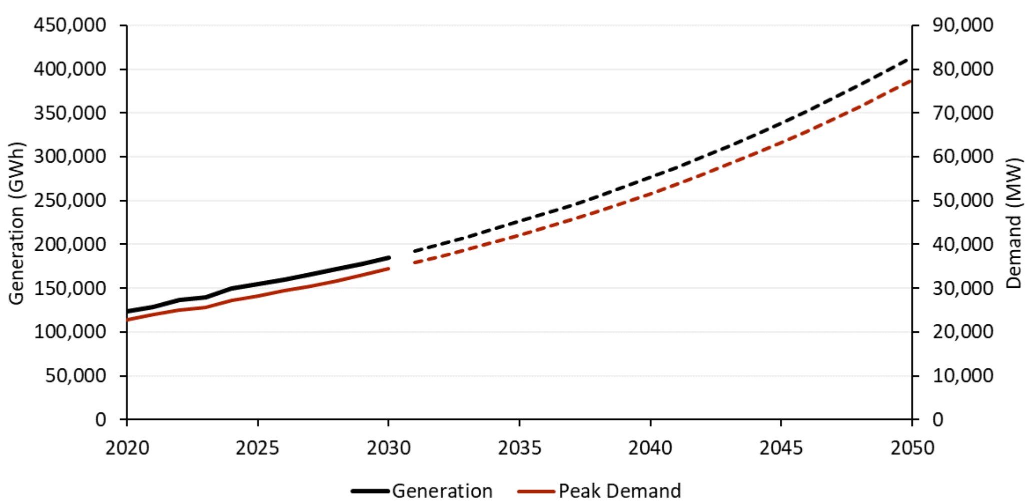
Demand and Load Growth in Each Country

Current and Future Electricity Grid Needs

Pakistan

Growth in economic output and population have driven demand for electricity (and peak electric loads) in Pakistan, yet the energy sector has struggled to meet this growing energy demand. Pakistan has continued to experience rolling blackouts due to under-investment in the electricity sector and fuel supply challenges. The electric sector is struggling financially with circular debt—a situation in which subsidies and unpaid bills result in inadequate revenues to cover the costs of power generation and grid maintenance, resulting in short term borrowing to fund the gap which then adds to the financial shortfall in the next funding period.[27] In addition, high global fuel prices and the weak value of Pakistan's currency to the U.S. dollar have made the issue harder to solve.[28] Amidst these challenges, electricity demand is projected to grow significantly through 2050 as presented in Figure 4 below.

Figure 4: Pakistan's Generation and Peak Demand Forecast



Source: *Indicative Generation Capacity Expansion Plan (IGCEP) 2021-30*. National Transmission and Despatch Company. 2021.
Note: Forecast from 2031 to 2050 is based on the annual average growth rate projected by the NTDC from 2021-2030.

[26] Bloomberg. "Germany Brings Forward Goal of 100% Renewable Power to 2035." 2022. https://www.bloomberg.com/news/articles/2022-02-28/germany-brings-forward-goal-of-100-renewable-energy-to-2035.

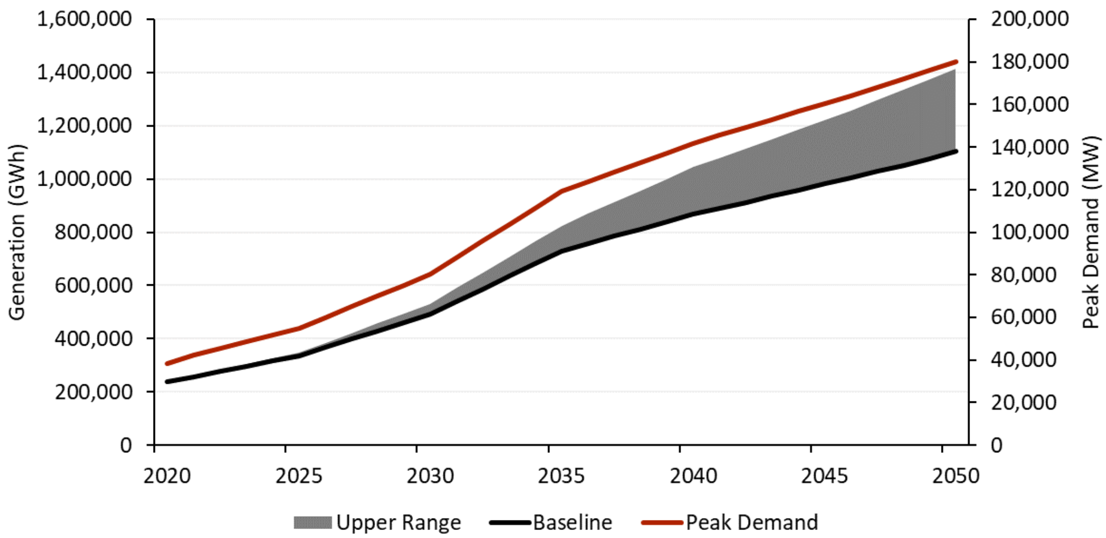
[27] *Study Recommends In-Depth Audit of IPPs to Solve Pakistan's Circular Debt Issue*. ProPakistani. May 2, 2023. https://propakistani.pk/2023/05/02/study-recommends-in-depth-audit-of-ipps-to-solve-pakistans-circular-debt-issue/.

[28] Shahzad, Asif. *Facing 'severe' energy crisis, Pakistan reverts to five-day work week*. Reuters. 2022.

Vietnam

Vietnam is also experiencing rapidly increasing electricity demand from a growing population and continued economic growth. Vietnam's long range plan for the power sector (the National Power Development Plan) uses a range of scenarios which all include significant growth in electricity demand, as shown in Figure 5.[29]

Figure 5: Vietnam's Generation and Peak Demand Forecast



Source: *Annual Report 2021*. Vietnam Electricity (EVN). https://en.evn.com.vn/userfile/User/huongBTT/files/2021/10/EVNAnnualReport2021%20final%2022_10_2021.pdf. *Approving the National Power Development Plan in the 2021-2030 period, with vision to 2045*. No: 1208/QD-TTg. Office of the Prime Minister, Vietnam. https://vepg.vn/wp-content/uploads/2021/09/5.9.2021-Draft-PDP8_En.pdf.

Notes: Electricity demand in 2020 is from the EVN Annual Report 2021. Demand forecasts for 2025, 2035, 2040, and 2045 are from the National Power Development Plan. All intervening years are linear interpolations of 5-year forecasts. Projections from 2046 to 2050 are based on the average growth rate projected from 2040-2045. Peak demand is projected based on 2020 and 2021 values from the EVN Annual Report 2021 and peak demand growth is assumed to match annual demand growth from the National Power Development Plan.

Germany

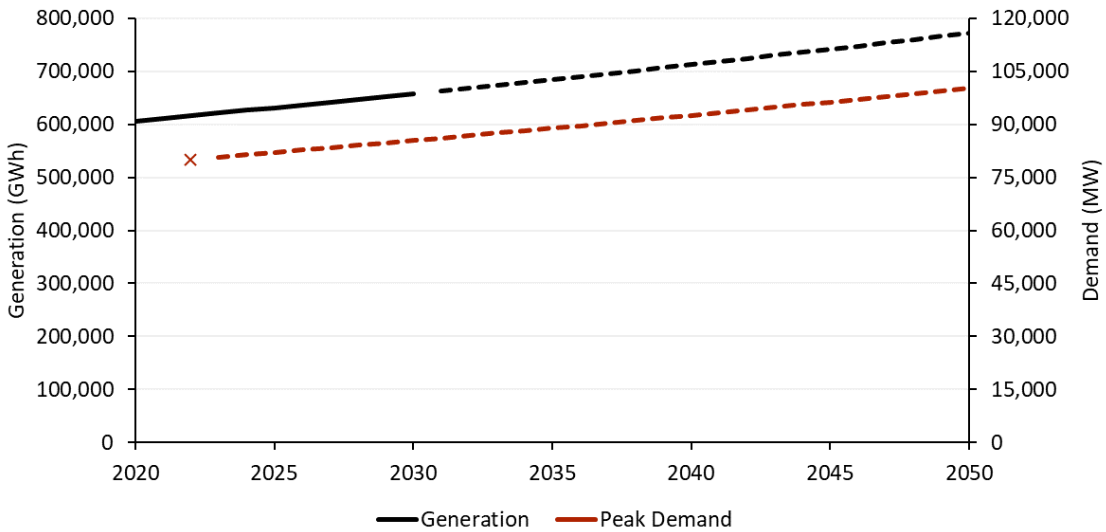
Germany's annual load and peak demand growth is expected to be more moderate than that of Pakistan or Vietnam. According to the German Federal Ministry of Economic Affairs and Climate Action (BMWK), electricity consumption is expected to increase from 595 TWh in 2018 to 658 TWh in 2030, a roughly a 1% annual increase in load (see Figure 6).[30] Load growth is expected to be driven by electrification of the

[29] *Approving the National Power Development Plan in the 2021-2030 period, with vision to 2045*. No: 1208/QD-TTg. Office of the Prime Minister, Vietnam. https://vepg.vn/wp-content/uploads/2021/09/5.9.2021-Draft-PDP8_En.pdf.

[30] Entwicklung des Bruttostromverbrauchs bis 2030. BMWK. October 22, 2021. https://www.bmwk.de/Redaktion/DE/Downloads/E/prognos-bruttostromverbrauch-2018-2030.pdf?__blob=publicationFile&v=2.

transportation and building sectors as well as industrial demand for green hydrogen production and battery manufacturing.[31]

Figure 6: Germany's Generation and Peak Demand Forecast



Sources: *Entwicklung des Bruttostromverbrauchs bis 2030*. BMWK. October 22, 2021. https://www.bmwk.de/Redaktion/DE/Downloads/E/prognos-bruttostromverbrauch-2018-2030.pdf?__blob=publicationFile&v=2.
Heymann, Eric. *German energy supply at a historical turning point*. March 25, 2022. Deutsche Bank.
Notes: Projected electricity demand (GWh) is based on linear interpolation of 2018 to 2030 projected demand from the BMWK demand forecast cited above. Demand is assumed to grow at the same annual rate through 2050. Peak demand is assumed to grow at the same rate as energy demand from 2022 peak load (Deutsche Bank source) through 2050.

Decarbonized Electricity Grids

Overview of Grid Needs

This section provides an overview of the needs of reliable electricity grids, and frames those needs in terms of the transition from a fossil fuel-dominated grid generation mix to a decarbonized grid, in the context of evaluating low carbon alternatives to the use of LNG for power generation. Reliability is an important concept in power system planning and operations—no one wants to experience a blackout—but it is important to establish some fundamental definitions around what reliability means before embarking on a discussion of how resources contribute to grid reliability.

To maintain grid reliability, electricity grids must match electricity demand with supply at any given moment. Electricity demand varies within the hour, hourly, diurnally, and seasonally, with grids often

[31] Federal Ministry for Economic Affairs and Climate Action. Minister Altmaier presents preliminary electricity consumption estimate for 2030. Press Release. July 21, 2021.

exhibiting peak demand when temperatures are extremely high or low (i.e., in summer or winter). Therefore, grid planners typically plan system resources such that expected electricity production is sufficient to meet expected energy demand in all hours on "typical" days, while additional resources are available "as needed" to produce additional power to meet expected periods of high "peak" demand.

A reliable electricity system has adequate resources to meet demand (and maintain system frequency) according to an "acceptable standard" of certainty over the range of future conditions. In other words, all electric grids are reliable to some standard and not to other standards—no grid is 100% reliable under all possible conditions. Furthermore, 100% reliability under all conditions is not a desirable planning standard, because achieving this standard would require a very costly overbuild of resources which would not be required 99.9% of the time. Additionally, no resource is 100% reliable—fossil-fueled power plants, fuel supply networks, renewables, and storage all have limitations—and all have a reliability less than 100%.

Reliability planning requires planners to carefully evaluate and consider the capabilities, risks, and costs of each kind of generator compared to the range of system conditions and loads that may be experienced. Establishing an acceptable "reliability standard" is also critically important—a common industry standard in the U.S. is the "1 in 10" standard, which is commonly defined as "one day of outage in ten years of expected conditions," and even this standard is interpreted and applied differently in different regions. Assigning capacity values to each resource and evaluating each resource's contribution to reliability according to the intended standard is a critical exercise to avoid over (or under) paying for reliability.

In many countries, the levelized cost of energy (LCOE) from wind and solar energy has declined below the cost of new fossil fuel generators.[32] This cost advantage for wind and solar is likely to grow as their costs continue to decline relative to fossil fuel power plants.[33,34] Given this cost spread, the decarbonized electricity grid of the future will most likely rely on large increasing amounts of wind and solar, as well as short-duration (less than 8-hour) lithium-ion battery storage to serve electric load under many conditions.

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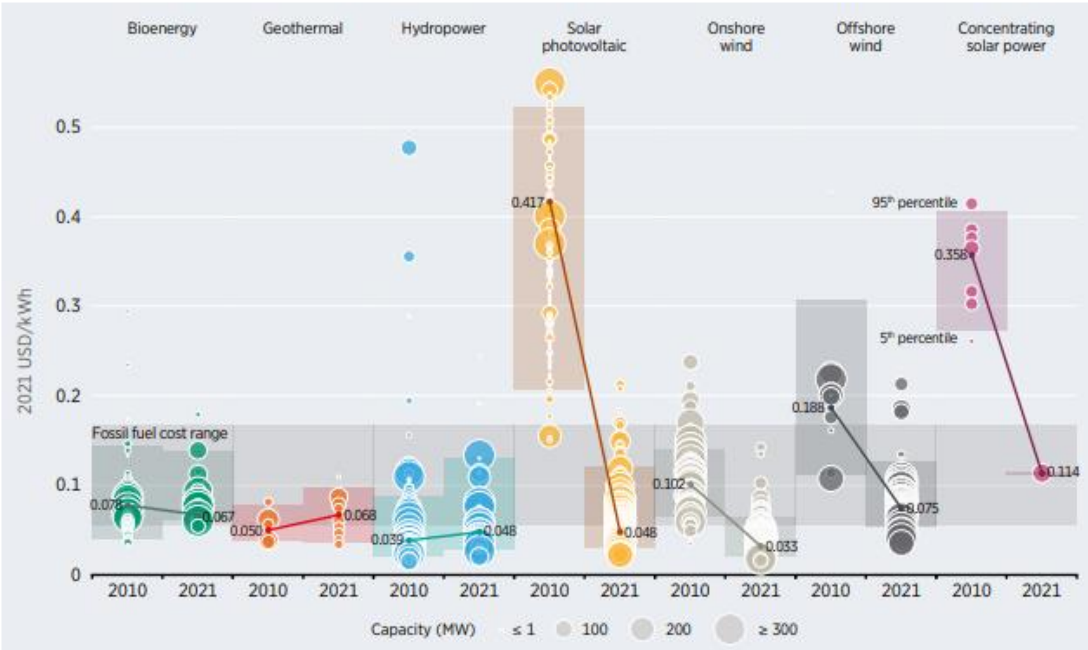
[32] International Renewable Energy Agency (IRENA). Renewable Power Generation Costs 2021. page 32. Renewable power generation costs in 2021 (irena.org).

[33] U.S. Energy Information Administration. Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021. 2021. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[34] International Energy Agency. Projected Costs of Generating Electricity 2020. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020.

Figure 7: Levelized Cost of New Renewable Energy Projects in 2010 vs. 2021



Source: IRENA. Renewable Power Generation Costs 2021. page 32. https://www.irena.org.

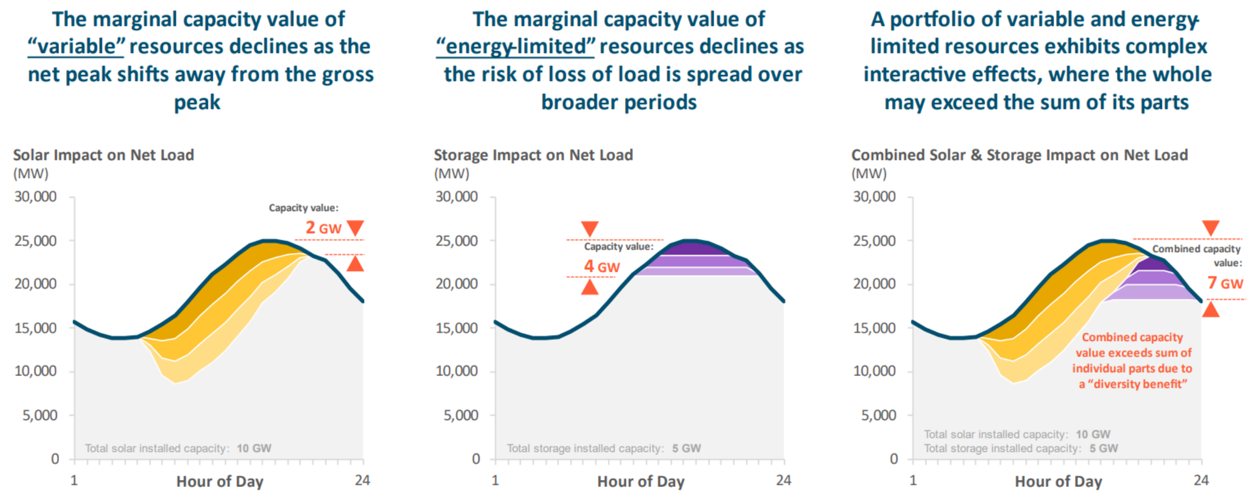
These low-cost portfolios of wind, solar, and storage also support the grid's capacity needs because they provide an expected quantity of generation that can be relied upon during periods of peak electricity demand. Just as fossil-fueled generators provide an expected capability to generate during peak periods, renewables and storage resources also have an expected generation during peak periods which can be calculated based on the correlations between the resource generation profile and electric load. The attribution of capacity value to renewable resources has become well-established using a framework known as "Effective Load Carrying Capability" (ELCC) which is currently in use in major U.S. electricity markets including PJM,[35] New York,[36] and California.[37] Many resources have complementary interactions with one another in which the capacity value (or ELCC) of both resources together is greater than the sum of the resources individually. This interaction is illustrated with an example of solar PV and battery storage in Figure 8 below.

[35] *Effective Load Carrying Capability (ELCC)*. PJM. https://www.pjm.com/planning/resource-adequacy-planning/effective-load-carrying-capability.

[36] *Capacity Accreditation: Implementation Details*. New York Independent System Operator (NYISO). Dec. 14, 2022. https://www.nyiso.com/documents/20142/34963268/4%20CA%20Capacity%20Accreditation%20pres.pdf. page 12.

[37] *Reliability Filing Requirements for Load Serving Entities' 2022 Integrated Resource Plans – Results of PRM and ELCC Studies*. California Public Utilities Commission. July 29, 2022. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/2022-irp-cycle-events-and-materials/20220729-updated-fr-and-reliability-mag-slides.pdf.

Figure 8: Complementary Resources Such as Solar and Storage Provide Greater Capacity Value Together than Either Resource Alone



Source: *Resource Adequacy in the Desert Southwest*. Energy and Environmental Economics, Inc. (E3). February 2022. page 3. https://www.ethree.com/wp-content/uploads/2022/02/E3_SW_Resource_Adequacy_Final_Report_FINAL.pdf.

Deeply decarbonized generation portfolios that combine renewables, storage and firm generation technologies, which are not weather-dependent or duration-limited, have been shown to result in the least cost, reliable grid mix in many other studies.[38] Traditionally, grid planners have relied on fossil fueled generators, hydroelectric power, and nuclear power to provide this firm generation capacity. However, lower-cost renewables and short-duration battery storage can provide significant capacity value as well if evaluated properly.

For example, LNG-to-power infrastructure can be disrupted by many different factors, including i) failure of an LNG shipment to be delivered (due to weather, economic, or geopolitical conditions), equipment failure in any part of the supply chain, and forced outage on the domestic pipeline or power plant. Wind generation, on the other hand, is dependent on weather conditions (cut-in and cut-out windspeeds) and its capacity value is based on the expected value of generation during peak load events, which must be measured based on the variability of generation at the wind site and its correlation with system loads.

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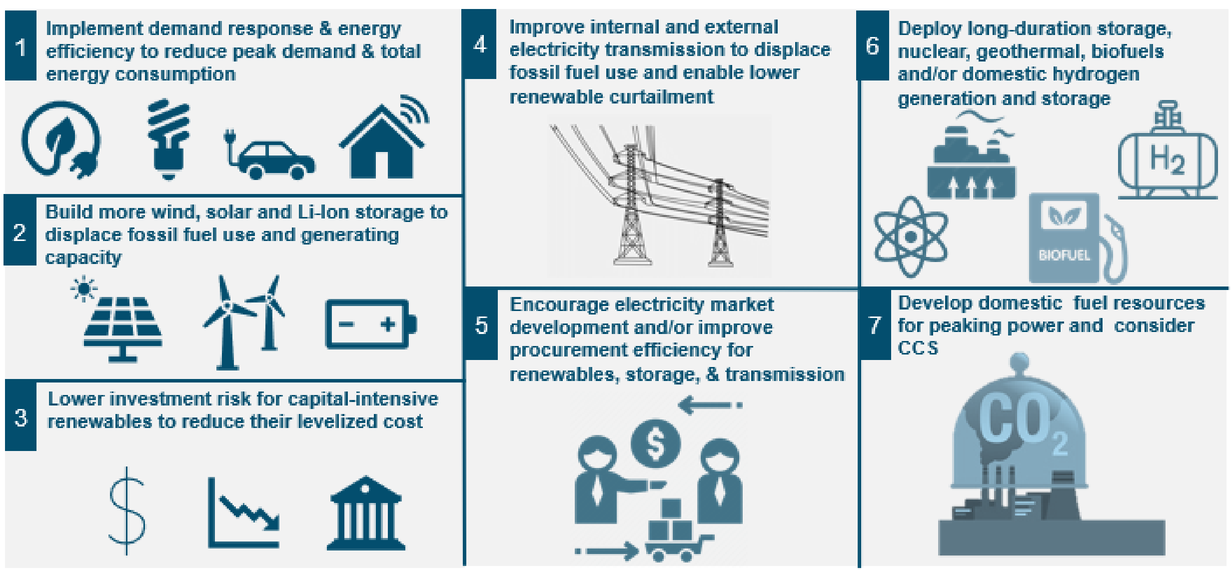
[38] Ming, Z. et al. Resource Adequacy in the Pacific Northwest. 2019. https://www.ethree.com/wp-content/uploads/2019/03/E3_Resource_Adequacy_in_the_Pacific-Northwest_March_2019.pdf .
Shaner, M. et al. Geophysical constraints on the reliability of solar and wind power in the United States. 2018. https://doi.org/10.1039/C7EE03029K.
National Renewable Energy Laboratory. LA100: The Los Angeles 100% Renewable Energy Study Executive Summary. 2021. https://www.nrel.gov/docs/fy21osti/79444-ES.pdf.
Mettetal, L. et al. Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future. 2020. https://www.ethree.com/wp-content/uploads/2020/11/E3-EFI_Report-New-England-Reliability-Under-Deep-Decarbonization_Full-Report_November_2020.pdf.
Princeton University Net Zero America Interim Report. 2021. https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.
Armond Cohen et al. Clean Firm Power is the Key to California's Carbon-Free Energy Future. 2021. https://issues.org/california-decarbonizing-power-wind-solar-nuclear-gas/.

In addition to the importance of assessing the reliability contributions (and risks) of all generation resources on the grid, new classes of emerging technologies may enable power system operators to shift away from using fossil fueled generators altogether in the future. These emerging technologies are discussed in more detail in subsequent sections of this report.

Overview of Strategies to Decarbonize Electricity Grids

In this section, we outline steps that countries can take to decarbonize electricity grids and reduce LNG use at the lowest cost. These are listed in ascending order of cost and difficulty, though all of these efforts will need to take place in parallel due to the long implementation time frame and interdependent nature of individual measures. These steps are depicted in Figure 9 below.

Figure 9: Strategies for Decarbonizing Electricity Grids While Reducing Liquefied Natural Gas (LNG) Demand



1. Implement demand management measures to reduce peak demand and total energy consumption

- Decarbonizing economies will require large-scale electrification of end uses that currently use fossil fuels. This will necessarily increase electricity consumption overall and likely increase peak electricity demand as well. Rapid growth in developing countries' populations and economic output will also drive significant growth in peak and average energy use.
- Demand management is an important tool for system planners and policymakers to effectively meet increasing electricity demand while ensuring that the resource mix is reliable and cost-effective. Demand management is a broad category of tools which all relate to lowering or shaping the use of electricity from consumers. Demand management tools fall into three broad categories, as follows:

- **Energy efficiency** focuses on reducing the overall electricity consumption from the device/point-of-use—energy efficiency measures can range from standards (and/or incentives) for new devices/appliances/equipment to retrofits of existing buildings or equipment.
- **Demand response** refers to the curation of dynamic, intentional, and time-dependent shifts in electricity use—typically to lower electricity use during peak demand periods and shift electricity use to periods of lower demand and/or higher renewable energy generation. Demand response measures can be implemented using a variety of tools, from price incentives to automatic controls and remote management systems and even behavioral nudges for customer responses.
- **Rate design** is also an important tool for demand management because retail electricity rates can be structured to provide price signals and incentives to customers to use electricity in a way that best supports the function of the power grid. Time-of-Use (TOU) rates are a well-established and effective form of rate design in which customers pay a higher price for electricity during peak system hours (where costs to serve load are higher) and pay a lower price for electricity during "off-peak" hours where electricity costs are lower and the grid has more resources available.

- Many future electric loads such as electric vehicles and smart appliances will be capable of great flexibility as to when and how much power they use. Demand response programs with strong price incentives and good retail rate design will be critical tools for integrating these loads into a future power grid that is reliable, renewable, and low-cost.
  - For example, public policy makers and utilities can develop demand response programs which provide paid incentives to large users or household customers to reduce consumption during system peak hours—such programs can also benefit from load control technologies which allow the utility to turn down major equipment or appliances (such as air conditioners) during peak hours.
  - Implementing time-of-use (TOU) electricity rates also helps customers save money on electricity bills by shifting consumption away from peak hours and towards hours with cheaper and more available generation resources. Utilities or policymakers can launch outreach campaigns to increase public awareness of the value of shifting electricity out of peak load hours.
  - Countries can promote the deployment of energy efficiency through various means such as mandating the adoption of building and appliance efficiency standards, and through providing energy efficiency incentives that offset some of the cost of implementing efficiency measures.

2. **Build more wind, solar and Li-Ion storage to displace fossil fuel consumption for power generation, recognize and evaluate the capacity contributions of these resources for grid reliability, and ensure cost-based generator dispatch of the bulk power system.**

- Wind and solar power can displace significant amounts of fossil fuel generation. Adding Li-Ion storage can further reduce fossil fuel generation by shifting renewable power to hours in which there is less wind and solar power available.
- Countries can take steps to incentivize the development of wind, solar and storage resources, depending upon the regulatory and market structures employed.
    - **Establishing clean energy policies** with clear definitions, measurement mechanisms, and binding, enforceable targets creates an important foundation of common expectations for stakeholders and market participants. **Renewable or Clean Energy Standards (RPS or CES)** are well-established forms of clean energy policies which work by setting an amount of electricity generation (or retail demand) which must be met by eligible renewable or low-carbon resources in each year. Eligible resources produce credits (Renewable Energy Credits or RECs) for each unit of power produced (MWh) and responsible parties (usually utilities) must purchase and retire these credits to demonstrate achievement of the RPS or CES target. These policies can be strengthened and enforced by the use of a penalty ($ per MWh) payable by the utility for falling short of the target—this penalty then acts as a price cap for RECs in the market.
    - **Centralized, competitive procurement processes** are a proven, efficient mechanism for procuring new renewable resources. Using clear, standardized long-term power purchase agreements and establishing multi-year forward procurement targets helps to increase private sector participation and build the market over time, resulting in more competition, lower risk, and lower PPA prices. Competitive centralized procurements are essential tools for developing renewable energy resources efficiently in vertically-integrated markets, and these procurements also work very well alongside an established wholesale electricity market because PPAs provide stable, lower-risk revenues to mitigate merchant price volatility and anchor project financing for new resources.
    - **Providing clear market price signals** is also important for ensuring successful and cost-effective renewable energy development (and long-term electric sector investment in general). Market price signals should allow for renewable energy resources to be priced fairly and on equal footing with fossil-fuel resources. Market price signals and compensation schemes for renewable energy resources should be adjusted to correct for any distortions created by fossil fuel subsidies to ensure sound economic decision making for the development, investment, and operations of renewable energy projects.
- **Assessing the capacity value of renewable energy and battery storage resources** (alongside other types of generators) is important for good electric system planning and resource development decisions. Planning for and operating a reliable and cost-effective electricity system starts with the establishment of a reliability standard for the system which represents the target performance of the system and the acceptable incidence of loss of load events. Once a reliability standard is set, it is important for system planners to evaluate all resources (fossil-fueled generators, renewable generators, and customer-side resources such as distributed energy resources and demand response) using a well-

established empirical standard for how each resource contributes to the capacity needs of the system. Effective Load Carrying Capability (ELCC) is one well-documented and tested approach which is used in the U.S. to determine the capacity contributions of various resources, including renewables and fossil fuel generators.

3. **Take steps to lower investment risk for capital-intensive technologies to reduce their levelized cost versus fossil fuel generation**
    - Low-carbon energy technologies such as wind and solar generally exhibit high capital costs and comparatively low variable costs, whereas fossil fuel generators typically exhibit low capital costs and high variable costs (primarily fuel consumption). In developing economies, higher investment risk increases the cost of capital relative to developed economies, and a higher cost of capital has a larger impact on the levelized cost of resources with higher investment costs (like renewables) compared to resources with lower investment costs (like gas turbines).
    - To lower the cost of capital in emerging economies, government agencies and financial institutions (including multilateral development financial institutions and export credit agencies) can support policies to provide lower cost loans for low carbon energy technologies, such as loan guarantees, export credit support, and concessional loan terms (lower interest rates and longer tenors or otherwise flexible repayment terms).
    - Developing economies can also work to reduce investment risk by taking steps to improve revenue and payment certainty for renewable energy resources. For example, countries can enable utilities to procure electricity via long-term power purchase agreements, which provide stable revenue streams that can reduce investment risk. Cost-recovery tariffs and sound utility financial health (including good credit ratings) are important factors for lowering the risk of a PPA, allowing independent project developers to achieve higher levels of debt and lower costs of equity, which reduces the total financing costs for new renewable projects.
4. **Improve electricity transmission system to increase access to renewable energy resources, optimize dispatch of all generators on the system, and reduce renewable curtailment**
    - Renewables are generally sited further from load centers than traditional fossil fuel generators since renewables require more land per unit of installed capacity and must be sited where resources are high (high wind speeds and strong solar irradiation).
    - Implementing electricity transmission planning processes allows one to ensure that adequate capacity exists to transport renewable energy to load centers. This can help reduce curtailment of renewable resources and unlock the best renewable sites. Enabling renewables to be built in various locations connected by transmission also allows one to take advantage of geographical diversity to ensure that areas with high renewable production can power those with low renewable production in any given moment. This increases the capacity value of renewables and storage and reduces the need for back up fossil fuel generators to operate during low renewable output periods.
5. **Encourage electricity market development and long-term planning processes for new generation and transmission investments**

- Developing markets that allow for efficient resource procurement sends market signals that can drive investments in clean energy, transmission, demand management, and storage assets.
- Wholesale electricity markets can be developed that provide energy, capacity, ancillary services, and clean energy credit products. These are useful for fully compensating generation resources in a transparent fashion.
    - Competitive wholesale energy markets send transparent and dynamic price signals to generators and consumers to support sound investment and consumption decisions which can adapt as system conditions change over time.
    - Capacity markets (or other forms of resource adequacy compensation) provide stable compensation (and revenue certainty) for generators to remain online and available to meet system reliability needs. A well-functioning capacity market has a clear methodology for crediting various generators according to their capacity contributions to system peak needs, and capacity markets can also help to signal (and compensate) new capacity resources when needed.
    - Clean or renewable energy credits (RECs) allow for the monetization of environmental benefits that renewable and low-carbon generators provide—RECs are most effective when integrated under a clear policy framework such as a Clean Energy Standard or Renewable Energy Standard.
- Developing long-term resource planning processes enables one to determine the least-cost blend of generators, storage and transmission assets needed to hit certain grid decarbonization goals through time. These results can then be used to inform generation, storage, and transmission procurement processes by utilities, government agencies, or other relevant/responsible entities in the sector.
- Renewable and storage resources can have significant combined benefits for grid reliability, as shown in Figure 8. In many cases, system planners can avoid new fossil fuel generation by properly determining the capacity contribution of their renewable and storage portfolios—and by compensating these resources for their services.

6. **Deploy alternative low-carbon technologies which can support the power system in longer-duration reliability events**
    - Meeting reliability needs in a deeply decarbonized grid will require i) sufficient energy production (such as from wind and solar resources), ii) adequate transmission, and iii) a mix of "dispatchable" resources which can shift or generate energy on-demand. Low-carbon dispatchable resources include short-duration battery storage as well as longer-duration energy storage technologies and low-carbon generation technologies such as advanced geothermal or the combustion of renewable fuels such as green hydrogen.
    - Establishing formal mechanisms for compensating resources for their capacity values—through centralized or bilateral capacity markets or other resource adequacy constructs—provides stable revenues to ensure the availability and performance of resources according to their contributions to grid reliability. Such mechanisms are particularly important for supporting long duration storage and alternative low-carbon fuel technologies which may be needed for long-term system reliability but which may not provide large volumes of energy to the grid on a regular basis.

7. **Reserve domestic fossil fuels for limited operations of existing generators to support system reliability needs as a "bridge" while the power grid transitions, and consider carbon capture and sequestration (CCS) for these resources**
    - Through the steps described above, low-cost renewable energy resources can be deployed on a large scale to meet the energy needs of the power grid while replacing energy generated from fossil-fuel generators, leading to a significant decrease in fossil-fuel use (and emissions) in the power sector in a cost-effective manner.
    - To maintain grid reliability by ensuring adequate generating capacity is available for peak system hours, existing generators are likely to be needed alongside capacity contributions from renewable energy and battery storage, at least until low-carbon firm generation technologies such as long duration energy storage and alternative low-carbon fuels (green hydrogen or others) are available for large-scale deployment.
        - Existing fossil-fuel generators will be needed during fewer hours as renewable energy resources replace more and more of their energy output—the capacity factor of these resources will decline as renewable deployment increases.
        - As generation declines, existing fossil fuel generators will require less fuel—only enough to generate during more limited periods of time when they are needed for grid reliability.
        - The lower fuel requirements of these generators may allow countries to rely more on domestic fuel sources and reduce or avoid imports of more expensive and carbon-intensive fuels such as LNG.

Low- and Zero-Carbon Electricity Generation Technologies

Introduction

In this section, we describe various classes of generators that grid planners can use to reliably serve electrical demand. We specifically focus on commercialized technologies, as well as emerging technologies that can provide firm generation capacity. We also discuss the pros and cons of individual technologies.

Commercialized Technologies

Table 1 below shows a selection of commercialized technologies that can generate or store electricity. We describe these technologies as providing either energy or both capacity and energy in a deeply decarbonized grid.

Table 1: Commercialized Low- or Zero-Carbon Electricity Generation Resources

Technology	Generation or Storage Technology
Nuclear Power Plant	Generation
Conventional Hydroelectric Power Plant (Hydro)	Generation
Solar Photovoltaic (PV) Power Plant	Generation
Onshore Wind Power Plant (Wind)	Generation
Offshore Wind Power Plant (OSW)	Generation
Lithium-Ion Battery (Li-Ion)	Storage

Emerging Technologies

Emerging technologies that can provide low- or zero-emissions electrical power exist at various levels of commercialization. We detail a selection of these that can provide firm generation capacity to help maintain the reliability of electricity grids in the long term:

- Long-duration energy storage (LDES)
- Carbon-free Electrofuels and Energy Reconversion Technologies
    - Hydrogen generated using electrolyzers
    - Stored with geologic salt cavern storage
    - Discharged using hydrogen combustion turbines
- Combined cycle (CCGT) and combustion turbine (CT) plants with post-combustion carbon capture and sequestration (CCS) and oxyfuel-based (Allam cycle) CCS
- Enhanced Geothermal Systems (EGS)
- Small modular nuclear reactors (SMRs)
- Adiabatic Compressed-Air Energy Storage (A-CAES).

Further details on each of these technologies, their pros and cons, and deployment considerations are provided below.

Long-duration energy storage

LDES can take various forms. We detail generic LDES as a resource option, but various forms, such as electrochemical, thermal-, pressure-, and gravity-based storage exist. Electrochemical LDES operates similarly to a Li-Ion battery but employs different materials with lower costs and typically lower round-trip efficiency (RTE) than a Li-Ion battery. Thermal energy storage stores electricity in the form of heat, and then converts the heat back into electricity upon discharging. Gravity-based storage typically moves water or heavy objects upwards relative to the earth's gravity to store energy, then discharges by letting those objects return downwards while powering generators.

Emerging long-duration storage technologies offer various advantages relative to today's Li-Ion batteries. These potential advantages include:

- LDES technologies are designed for longer durations of sustained power output and offer lower capital costs per MWh of storage compared to Li-Ion batteries. Many LDES technologies are designed such that the capital costs per MWh declines with longer design durations, meaning these technologies are more and more economically attractive as duration increases.
- Use of more abundant and lower-cost commodity components, which could enable a more rapid and sustained scale-up of manufacturing and deployment at lower cost than Li-Ion.
- Safety and performance improvements under high-load and in hot temperatures, without the same cooling requirements required to prevent thermal overloading.
- Complementarity with existing infrastructure—some emerging storage technologies could potentially re-use or re-purpose turbines or other equipment at existing power plants, and/or provide inertia to the power grid with the use of turbine-based generators.

LDES technologies tend to have lower round-trip efficiencies (40%-70%) compared with Li-Ion batteries (80%-90%), but even the comparatively lower efficiencies of LDES technologies are higher compared to the round-trip efficiency of electrofuel synthesis-based energy storage. Furthermore, electrochemical or thermal-based systems could be located at convenient grid interconnection points rather than requiring geological formations suitable for underground storage, as is necessary for A-CAES and electrofuels. The primary disadvantages of emerging LDES technologies are lower round-trip efficiency, potential geographic or siting limitations, and uncertainties in costs and operating performance due to the limited commercial scale and operating histories of these technologies today.

The LDES technology used for cost analysis in this report is based on iron-air batteries with a very long duration (150 hours).

Electrofuels and Energy Reconversion Technologies

Electrofuels are a class of fuels generated using electricity, water, and in some cases CO_2 to generate fuel. In this analysis we provide data for hydrogen, which is a subclass of electrofuels. We detail costs for low-temperature electrolysis technologies (e.g. alkaline or polymer electrolyte membrane electrolyzers), which use electricity and water as inputs to produce gaseous hydrogen and oxygen. Hydrogen can be pressurized and stored underground in geologic formations and reconverted to electricity using combustion in a purpose-built combustion turbine.

We consider geologic hydrogen storage because it is thought to offer a comparatively inexpensive cost for long-duration fuel storage[39] sufficient to provide hydrogen combustion turbines with enough stored fuel to meet infrequent high-need grid reliability events. However, the geologic formations that are suitable for hydrogen storage are not ubiquitous and are not thought to exist in Vietnam.[40,41]

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[39] Ahluwalia et al. 2019. System Level Analysis of Hydrogen Storage Options. https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf

[40] Duong, M., Nguyen-Trinh, H. "Two scenarios for carbo capture and storage in Vietnam." Energy Policy. 2017. 110, 559-569. https://www.sciencedirect.com/science/article/abs/pii/S030142151730544X

[41] Lord, A. , Kobos, P., Borns, D. "Geologic Storage of hydrogen: Scaling up to meet city transportation demands." International Journal of Hydrogen Energy. 39 (2014): 15570-15582. https://doi.org/10.1016/j.ijhydene.2014.07.121.

The primary advantage of electrofuels is that they can be stored at very low energy cost, enabling very long-duration storage akin to that of the natural gas pipeline system. The disadvantages of electrofuels are their low round-trip efficiency, the need for specific geologic formations to enable low-cost storage, and the need to build new gas storage and gas pipeline infrastructure for hydrogen. Additionally, there are criteria pollutant emissions if hydrogen is combusted in conventional power plants—emissions reduction technologies will be needed to address this issue.

Combined Cycle Power Plants with Carbon Capture and Allam Cycle Power Plants

These two technologies involve natural gas combustion with carbon capture and sequestration (CCS). CCGT with post-combustion capture uses a CCS system as an addition to a conventional CCGT. Allam cycle power plants are a class of CT that separates oxygen from air, and burns natural gas in a mixture of oxygen, water vapor and recycled CO_2. CO_2 can then be captured from the CT exhaust in an already pressurized, concentrated state.

The advantages of CCGTs with post-combustion capture is the technology is more mature than Allam cycle plants, and the technology may be retrofitted to certain types of existing natural gas plants. The disadvantage is such plants are less efficient than Allam cycle plants, do not enable 100% CCS, and do emit oxides of nitrogen (NO_x) and other criteria pollutants. Allam cycle plants offer higher efficiency, little or no emissions of criteria pollutants, and the potential for 100% carbon capture from their fuel use. The disadvantages are that this is a lower maturity, higher cost technology which requires oxygen separation units. Both CCS technologies rely on constructing an extensive network of CCS pipelines and wells, and neither technology would mitigate upstream emissions and other impacts from extracting and transporting natural gas. CCS technologies may generally face political opposition due to their continued reliance on the use of fossil fuels, and these facilities would require long-term monitoring to ensure that captured CO2 does not leak from long-term storage facilities.

Enhanced Geothermal Systems (EGS)

EGS are analogous to conventional geothermal, but rely on accessing heat from wells that conventional systems cannot access using advanced well drilling and subsurface permeability enhancement technology. These two features increase the technical geothermal power generation potential relative to conventional geothermal technologies.

The advantages of such systems are that the technical power generation potential and locations in which one could install geothermal power plants increase through the use of novel well drilling techniques. The primary disadvantages are that these systems are technologically immature, have highly uncertain future costs, may induce seismicity, and have potentially higher costs than other zero-carbon generation resources.

EGS resources have not been included in the cost analysis in this report due to the uncertain geologic resource potential in the three focus countries.

Small Modular Nuclear Reactors

SMRs are a class of nuclear power plants that use smaller-scale reactors that could potentially be produced at scale in factories using a standardized design and be deployed modularly to fit various power system needs. Standardized, modular, factory-built components could deliver significant cost savings relative to conventional nuclear reactors. While there are many potential nuclear reactor designs that could be deployed in this fashion, we focus on light-water reactors.

The primary advantage of SMRs is there may be significant cost and construction lead time reductions compared to conventional nuclear reactors enabled by standardization and higher production rates. The disadvantages are that the technology has an uncertain pathway to cost reductions, would still produce nuclear waste and have the same attendant nuclear security risks, and certain countries (including Germany) have already decided against new nuclear plants for policy reasons. Nuclear fuel security and waste management remain significant challenges to widespread nuclear generation deployment.

SMRs have not been included in the cost analysis in this report due to the complex policy and international security challenges related to the supply, use, and disposal of nuclear materials.

Adiabatic Compressed Air Energy Storage (A-CAES)

In CAES systems, electric energy is converted into mechanical energy by rapidly compressing air and storing it at high pressure in underground reservoirs. Energy is recovered by driving the pressurized air through a turbine, thereby generating electricity. The most mature forms of CAES are diabatic (D-CAES),[42] which do not recover the heat released from the rapid compression of air, requiring reheating of air during discharge with fuel combustion, which typically emits CO_2 and reduces the roundtrip efficiency of the plant (around 50%).[43]

A-CAES is an emerging technology that captures and stores the heat released by air compression in a thermal storage medium. A-CAES has the advantages of eliminating fuel use (and subsequent potential CO_2 emissions) on discharge and having higher roundtrip efficiencies (up to 70%)[44] in comparison to D-CAES. However, the prime disadvantage is the incremental cost of a thermal energy storage medium.

The advantage of A-CAES relative to other emerging technologies described here is that it could provide emissions-free, long-duration operation with reasonably high round-trip efficiency. The primary disadvantage of A-CAES is that it requires specific underground geologic formations which may not be located at ideal points for grid interconnection. These geologic formations may compete with those used for hydrogen storage.

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[42] Pacific Northwest National Laboratory. “Compressed Air Energy Storage,” 2018. https://caes.pnnl.gov/.

[43] Pacific Northwest National Laboratory. “Compressed Air Energy Storage (CAES)”. https://www.pnnl.gov/compressed-air-energy-storage-caes/.

[44] Wolf, D. Dynamic simulation of possible heat management solutions for Adiabatic Compressed Air Energy Storage. http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-1039740.pdf.

Liquefied Natural Gas Alternatives Analysis

Introduction

Having listed various technologies that could help displace LNG use, as well as provided a guide for the implementation of these technologies, we performed a high-level screen to evaluate the extent to which commercialized renewable energy, Li-Ion battery storage, and emerging technologies could displace the cost and need for additional LNG-to-power infrastructure in the representative countries of this study: Germany, Pakistan, and Vietnam. This analysis is focused on the renewable energy resource potential and cost competitiveness of commercialized and emerging low-carbon technologies compared with LNG for power generation. This analysis does not consider all of the measures presented in the section *Overview of Strategies to Decarbonize Electricity Grids*, as the implementation of many of these measures such as market design, demand management, and country-specific reliability analysis is beyond the scope of this study and would be best addressed in detail through future analysis. As such, the findings in this study should be considered as a conservative estimation of the potential for renewable energy, storage, and emerging technologies to displace fossil-fuel use and LNG imports in the power sector globally.

Resource Option Screen 1: Can Renewables and Storage Displace LNG Use for Energy?

Deploying renewable energy resources to displace fossil fuel use—and LNG demand in particular—for power generation is only reasonable if there is sufficient renewable energy potential to meet each country's electricity needs. E3 presents a high-level screen assessing renewable energy potential compared with electricity demand for each country, recognizing the inherent uncertainties around the economics of accessing total renewable energy potential as well as the uncertainties in load growth projections.

Table 2 provides approximate projected annual energy demand by country based on approximate scaling methods. Table 3 summarizes the technical potential of onshore wind, offshore wind, and solar PV in each country. The sums of these renewable resource potentials are divided by the estimated 2050 electricity demand in each country to estimate the extent to which renewable energy resources could meet demand.

This projection indicates that all countries should have enough renewable potential to satisfy total projected energy demand to 2050—in fact, renewable energy potential is significantly greater than projected future demand by factors of 2x to 12.5x. This is likely to be the case even assuming typical 85% round-trip efficiencies of Li-Ion batteries. Thus, at a high level, there are no binding resource availability limitations that would prevent renewables from replacing LNG use (and even all fossil fuel use for power generation) to meet total future energy demand absent considerations of capacity needs or cost.

Table 2: Forecasted Electricity Demand by Country

Year	Germany		Pakistan		Vietnam	
	TWh/yr	Δ to 2022	TWh/yr	Δ to 2022	TWh/yr	Δ to 2022
2025	632	16	155	18	335	58
2030	658	42	185	48	491	214
2035	685	69	226	89	729	452
2040	713	97	277	140	867	590
2045	742	126	339	202	981	704
2050	772	156	414	277	1,103	826

Sources: See Figure 4, Figure 5, and Figure 6 in Demand and Load Growth in Each Country.

Table 3: Renewable Potential by Country vs. Forecasted Electricity Demand in 2050

	Germany			Pakistan			Vietnam		
	Potential GW	Capacity Factor %	Output TWh/yr	Potential GW	Capacity Factor %	Output TWh/yr	Potential GW	Capacity Factor %	Output TWh/yr
Solar	481	12%	506	2,420	20%	4,240	2,465	15%	3,239
Wind	184	45%	727	264	37%	857	113	36%	357
Offshore Wind	61	60%	322	18	46%	72	404	54%	1,910
Total Renewable Energy Potential (TWh/yr)			1,560			5,168			5,505
Forecast 2050 Energy Use (TWh/yr)			772			414			1,103
Ratio of Total Renewable Energy Potential to 2050 Energy Use			2.0			12.5			5.0

Sources: *A Pathway for the German Energy Sector Compatible with a 1.5 °C Carbon Budget*, Fraunhofer ISE, Solargis, Global Wind Atlas.
Technical Potential for Offshore Wind in Pakistan Map. World Bank. March 2020.
Lee, Nathan, Cardoso de Oliveira, Ricardo, Roberts, Billy, Katz, Jessica, Brown, Thomas, and Flores-Espino, Francisco. 2019. *Exploring Renewable Energy Opportunities in Select Southeast Asian Countries: A Geospatial Analysis of the Levelized Cost of Energy of Utility-Scale Wind and Solar Photovoltaics*.
Offshore Wind Roadmap for Vietnam. World Bank Group. June 2021.
Minh Ha-Duong, Sven Teske, Dimitri Pescia, Mentari Pujantoro. *Options for wind power in Vietnam by 2030*.

Resource Option Screen 2: Geology of Countries with Respect to Future Energy Infrastructure

In this section, we perform a high-level assessment of the availability of carbon sequestration and hydrogen storage as firm capacity resource options for displacing LNG in Germany, Pakistan, and Vietnam. We limit our screen of geologic hydrogen storage formations to salt beds and salt domes, which are the only geologic formations that have been commercially demonstrated to store hydrogen at scale.[45] It is worth noting that both CO_2 and hydrogen could potentially be imported or exported via pipeline or other

[45] Lord, A., Kobos, P, Borns, D. "Geologic Storage of hydrogen: Scaling up to meet city transportation demands." International Journal of Hydrogen Energy. 2014. https://doi.org/10.1016/j.ijhydene.2014.07.121

means by the countries studied in this analysis. However, we do not consider this resource option due to the uncertainty of the costs for building these transportation networks.

This screening exercise is intended for a high level assessment of potential hydrogen storage—the development of green hydrogen infrastructure for production, transportation, storage, and combustion will require additional detailed feasibility analysis to optimize infrastructure to account for a range of important variables including geography, hydrogen consumption patterns and end-use locations, and pipeline and electric transmission costs.

Pakistan

Pakistan has an estimated 32 gigatons (GT) of CO_2 storage potential, though this is classified as inaccessible (as compared to the U.S. which has an estimated 8,000+ GT).[46] The Potwar Plateau and salt range south of the Himalayas offer significant potential for underground hydrogen storage in salt caverns.[47] Salt caverns sit close to the country's North–South gas pipeline and within the major city of Islamabad, creating a good location for transmission access near major loads.

Vietnam

Prior studies of Vietnam's carbon storage potential indicate that there are at least 0.9 GT of CO_2 storage potential in offshore fossil fuel wells.[48] Though the authors do not believe the subject has been studied in depth, Vietnam is not thought to contain salt formations, and thus we do not consider hydrogen combustion turbines as a resource option in Vietnam in our analysis.[48]

Germany

Germany possesses extensive geological structures capable of storing carbon dioxide and hydrogen. These are concentrated in the northern state of Lower Saxony and offshore in the North Sea. Conservatively, one study estimates that the onshore technical potential for geologic hydrogen storage is 14 quadrillion BTU,[49] which exceeds total 2022 German natural gas use.[50]

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[46] Global CC Institute, Global Status of CCS 2021.

[47] Cortes-Aranda, J., et al., *Holocene shortening rates and seismic hazard assessment for the frontal Potwar Plateau, NW Himalaya of Pakistan: Insights from 10Be concentrations on fluvial terraces of the Mahesian Anticline*, Quaternary International (2017), http://dx.doi.org/10.1016/j.quaint.2017.02.032

[48] Duong, M., Nguyen-Trinh, H. "Two scenarios for carbo capture and storage in Vietnam." Energy Policy. 2017. 110, 559-569. https://www.sciencedirect.com/science/article/abs/pii/S030142151730544X

[49] Caglayan, D., Weber, N., Henrichs, H., Linben, J., Roninius, M, Kukla, P, Stolten, D. "Technical Potential of Salt Caverns for Hydrogen Storage in Europe." International Journal of Hydrogen Energy. 2019. https://doi.org/10.1016/j.ijhydene.2019.12.161

[50] https://www.cleanenergywire.org/news/energy-crisis-pushes-german-energy-use-2022-lowest-level-reunification.

Resource Option Screen 3: LNG Alternatives in Pakistan, Vietnam and Germany

Introduction

In this analysis, we compare the country-specific economic competitiveness of some of the technologies presented above. This screen is meant to capture the effects of varying the following:

- The capacity factor of wind and solar using typical average values in each country
- Investment risk as determined by the weighted average cost of capital (WACC) in each country
- Approximate energy revenues for dispatchable resources in each country
- Approximate capacity factors for dispatchable resources based on typical operating behavior
- A range of potential future LNG prices based on historical prices globally.

We analyze the Levelized Cost of Energy (LCOE) for LNG-fired power generation and a range of alternative low-carbon resources in two stages.

- **"Energy Only":** First, we consider the cost of new renewable energy resources compared with LNG to provide energy to the grid, with each resource providing the most energy it can at the lowest cost, and without consideration of the timing or ability to schedule this energy. We evaluate three types of commercialized renewable energy resources: solar PV, onshore wind, and offshore wind against the LCOE of LNG-fired Combined Cycle Gas Turbine (CCGT) power plant running at a high capacity factor (85%).
- **"Firm Generation":** Next, we consider the value of "firm generation"—resources which can be dispatched (and relied upon) to generate a specific amount of power in a specific time window. Firm generation resources contribute more to the capacity needs (reliability) of the grid than non-firm generation resources such as standalone wind and solar PV generation. We compare the LCOE of LNG-fired generation to various low-carbon firm generation resources: wind and solar projects paired with LI-Ion batteries, long-duration energy storage, A-CAES, and generation from green hydrogen.

Assumptions and Methods

We assume that the installed capital costs, fixed costs, variable costs and efficiency of technologies are the same in each country. The capital, variable and fixed costs of generation and storage technologies are derived from various sources outlined in (see Table 6 below).

Table 4. The Weighted Average Cost of Capital (WACC) for each country is presented in Table 5, as are the classifications of which technologies are commercialized and which are emerging. The WACCs are ultimately derived from an E3 analysis that factors in expected debt-to-equity ratios for emerging and commercialized technologies, the corporate tax rate in each country, and the costs of debt and costs of equity in each country. As a sensitivity, we provide a case where the borrowing cost in Pakistan, which has the highest WACC, is lowered to equal the WACC in Germany. This case is meant to provide a bookend to show the effect of reducing financing costs in improving the economics of renewable energy and storage technologies in emerging economies.

We use the levelized cost of energy (LCOE) as a metric for directly comparing resources on an energy generation cost basis. All technologies except LNG-powered generators use a mid-trajectory estimate of their LCOE as derived from data sources listed in Table 4 below.

For Li-Ion batteries paired with renewables, we assume plants are configured with 4-hour batteries sized in a ratio of 2 units (MWac) of renewable capacity to 1 unit (MWac) of battery capacity, with the batteries assumed to charge and discharge fully each day. This sizing ratio is typical of commercial-scale projects being developed in the U.S. today.

We estimate the LCOE of future LNG-fired generation for a range of potential LNG prices based on the historical average annual U.S. LNG export prices observed from 2000 to 2022,[51] adjusted for inflation to $2022. This yields a range of LNG prices (in real $2022) of $5.09 to $17.60 per MMBTU, with a mid-range price of $8.87/MMBTU based on the 2000-2022 historical average. These historical LNG export prices are presented by the U.S. EIA as "Free on Board (FOB)," meaning that the prices include all costs up to the point of export (including commodity costs and liquefaction fees), but these prices do not include the costs to receive the ships, re-gasify the LNG at a floating or onshore terminal, and transport the gas to a power plant via pipeline or other delivery mechanism. These costs vary widely depending on the specific locations and infrastructure used—for this analysis, E3 uses a conservative assumption of $1 per MMBTU to cover all costs of LNG receipt, regasification, and delivery to a power plant. **This assumption results in a range of LNG prices delivered to a power plant of $6.09 to $18.60 per MMBTU and an expected price of $9.87 per MMBTU (in real $2022).**

The capacity factor of each generation and storage resource assumed in this comparison is provided in Table 7. Capacity factors assumed for solar, onshore wind, and offshore wind are based on average values for each country, whereas other capacity factors are based on typical illustrative values expected of such generators operating on a typical large power system.

To determine the competitiveness of emerging and commercialized technologies that can provide firm generation capacity, we calculate the LCOE net of expected energy revenues. This is like the framework of comparing resources by their net cost of new entry (net CONE), and we apply it to standardize the treatment of these resources given the varying status of electricity market deregulation in Pakistan, Vietnam and Germany. We use this approach to calculate the residual LCOE of technologies because firm generation and long-duration storage resources may operate during more hours of the year than just peak demand conditions, thus earning energy revenues that would offset some of the total resource costs. We note that the LCOEs are *not* net of any incentives that might be available for these generation resources. The bounds of LCOEs provided in the analysis encompass technology capital cost uncertainty bounds, as well as variations in fuel price for LNG-powered generators.

Additionally, given the novel nature of hydrogen-fueled power generation, E3 has defined a new generic green hydrogen project for use in this analysis—this project is assumed to produce green hydrogen through electrolysis powered by dedicated renewable energy resources. All hydrogen operations from production to combustion for power generation are assumed to occur onsite, and our estimate of

[51] U.S. Energy Information Agency. "Price of Liquefied U.S. Natural Gas Exports." 2022. https://www.eia.gov/dnav/ng/hist/n9133us3m.htm.

hydrogen-fueled power generation includes the costs of paired renewable energy, electrolytic hydrogen production, hydrogen storage, and power generation infrastructure (see Table 6 below).

Table 4: Data Sources for Capital, Variable, and Fixed Costs of Generation and Storage

Generation or Storage Technology	Cost Trajectory Assumptions
Long Duration Energy Storage	McKinsey / Long Duration Energy Storage Council[52]
Hydrogen CTs	CEC 2021[53]; NREL H2A[54]; utility IRP filings,[55] Lord et al[56], Ahluwalia et al[57], ANL[58], Hunter et al[59]
A-CAES	PNNL Cost and Performance Database[60]; HydroStor[61]
Allam Cycle CCS	NREL ATB 2022[62], Allam et al.[63], 8 Rivers Capital[64]
Nuclear SMR, CCGT + CCS, CT, Onshore Wind, EGS, Offshore Wind, Solar PV	NREL ATB 2022
Li-Ion Battery	Lazard's Levelized Cost of Storage 7.0 (2021) [65]; NREL's Cost Projections for Utility-Scale Battery Storage: 2020 Update.[66]

[52] Alberto Bettoli, Martin Linder, Tomas Nauclér, Jesse Noffsinger, Suvojoy Sengupta, Humayun Tai, and Godart van Gendt. McKinsey Electric Power & Natural Gas Sustainability Practices. "Net-zero power: Long-duration energy storage for a renewable grid." 2021. https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-power-long-duration-energy-storage-for-a-renewable-grid.

[53] California Energy Commission. The Challenge of Retail Gas in California's Low-Carbon Future. 2021. https://www.energy.ca.gov/sites/default/files/2021-06/CEC-500-2019-055-F.pdf.

[54] National Renewable Energy Laboratory. H2A: Hydrogen Analysis Production Model Archives: Future Central Hydrogen Production from Natural Gas with CO2 Sequestration version 3.101. https://www.nrel.gov/hydrogen/assets/docs/future-central-natural-gas-with-co2-sequestration-v3-101.xlsm.

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[56] Lord, A. , Kobos, P., Borns, D. "Geologic Storage of hydrogen: Scaling up to meet city transportation demands." International Journal of Hydrogen Energy. 39 (2014): 15570-15582. https://doi.org/10.1016/j.ijhydene.2014.07.121.

[57] Ahluwalia et al. 2019. System Level Analysis of Hydrogen Storage Options. https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf

[58] Argonne National Laboratory. Hydrogen Delivery Scenario Analysis Model. https://hdsam.es.anl.gov/index.php.

[59] Hunter, C., Penev, M., Reznicek, E., Eichman, J., Rustagi, N., Baldwin, S. Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids. Joule. 2021. https://doi.org/10.1016/j.joule.2021.06.018

[60] Pacific Northwest National Laboratory. 2020. Compressed Air Energy Storage (CAES). https://www.pnnl.gov/compressed-air-energy-storage-caes

[61] Hydrostor. 2022. "FAQ – Hydrostor." https://www.hydrostor.ca/faq/ Accessed 07/26/2022.

[62] National Renewable Energy Laboratory. 2022 Electricity ATB Technologies. https://atb.nrel.gov/electricity/2022/technologies

[63] Allam et al. Energy Procedia. 2017. Demonstration of the Allam Cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture. https://doi.org/10.1016/j.egypro.2017.03.1731.

[64] "8 Rivers Capital, ADM Announce Intention to Make Illinois Home to Game-Changing Zero Emissions Project.". 2021. https://www.prnewswire.com/news-releases/8-rivers-capital-adm-announce-intention-to-make-illinois-home-to-game-changing-zero-emissions-project-301269296.html.

[65] Lazard's Levelized Cost of Storage Analysis—Version 7.0. 2021. https://www.lazard.com/media/451882/lazards-levelized-cost-of-storage-version-70-vf.pdf.

[66] Cole, Wesley, and A. Will Frazier. 2020. Cost Projections for Utility-Scale Battery Storage: 2020 Update. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-75385. https://www.nrel.gov/docs/fy20osti/75385.pdf.

Table 5: Weighted Average Costs of Capital Used in Analysis

Country	Technology Type	Reference Case WACC (%)	Low Borrowing Cost Case WACC (%)
Germany	Commercialized	6.0%	6.0%
	Emerging	9.9%	9.9%
Vietnam	Commercialized	10.7%	6.0%
	Emerging	17.2%	9.9%
Pakistan	Commercialized	12.8%	6.0%
	Emerging	21.3%	9.9%

Table 6: 2030 Solar-Coupled Hydrogen Resource Levelized Cost Breakdown

		Hydrogen Electrolyzer	Hydrogen Storage	Hydrogen CT	Utility Scale Solar
Levelized Fixed Cost (2022$/kW-yr)	Vietnam	167.02	0.30	251.48	150.83
	Germany	108.67	0.19	166.12	104.11
	Pakistan	201.95	0.36	301.88	174.48
Variable Operations and Maintenance Cost (2022$/MWh)	Vietnam	11.96	-	5.17	-
	Germany	11.96	-	5.17	-
	Pakistan	11.96	-	5.17	-
Assumed H2 Capacity Factor (%)	Vietnam	20%			
	Germany	20%			
	Pakistan	20%			
Sizing Relative to Paired Renewable Resource	Vietnam	1.00	1.00	0.69	1.00
	Germany	1.00	1.00	0.59	1.00
	Pakistan	1.00	1.00	0.94	1.00

Table 7: Assumed Capacity Factors in Analysis

Technology Type	Grid Power Delivery Capacity Factor (%)		
	Germany	Vietnam	Pakistan
Utility-Scale Solar	12%	14%	19%
Onshore Wind	45%	36%	37%
Offshore Wind	60%	54%	46%
Utility-Scale Solar-4-hr Li-Ion Battery Hybrid	29%	31%	36%
Onshore Wind-4-hr Li-Ion Battery Hybrid	62%	53%	54%
Offshore Wind-4-hr Li-Ion Battery Hybrid	77%	71%	63%
LNG-Powered Gas CCGT	85% (base)	85% (base)	85% (base)
LNG-Powered Gas CCGT + CCS	85% (base)	85% (base)	85% (base)
A-CAES	20.5%	20.5%	20.5%
150-hr Long-Duration Battery	28.5%	28.5%	28.5%
Hydrogen CT	20%	n/a	20%

LCOE of Renewable Energy vs. LNG Power Generation

We evaluate the cost competitiveness of commercialized renewable energy resources (solar photovoltaic power, onshore wind, and fixed-bottom offshore wind) with LNG-fired generation based on the Levelized Cost of Electricity (LCOE) of each technology in each of the three countries considered. LCOE comparisons for new resources in 2030 are presented in real $2022, as follows:

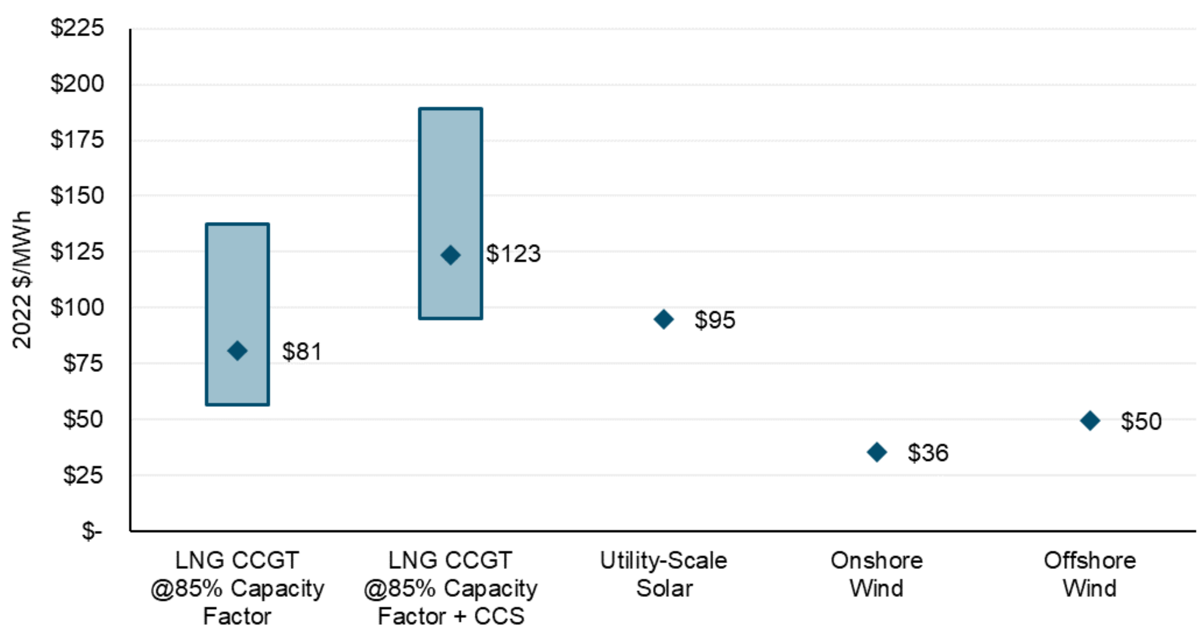
- Figure 10: 2030 LCOE of LNG vs. Renewables in Germany
- Figure 11: 2030 LCOE of LNG vs. Renewables in Pakistan
- Figure 12: 2030 LCOE of LNG vs. Renewables in Vietnam

We find that onshore and offshore wind are very likely to be lower-cost alternatives to CCGTs burning LNG in each country with "mid-range" LNG prices. In Germany, onshore and offshore wind are lower cost than CCGTs burning LNG at the lowest end of LNG prices. This is due primarily to the lower borrowing costs in Germany versus Pakistan and Vietnam.

Solar power is more expensive than wind in each country on an LCOE basis, but solar PV remains within a competitive range of LNG generation. The relatively higher cost of solar vs. wind is driven primarily by the comparatively low capacity factors for solar in each country, which range from 14% to 19%. For reference, the best solar PV resources in the United States are in the Southwest (including California and Arizona) which can achieve capacity factors above 30%.[67]

We note that CCGT plants with CCS are more expensive than CCGT plants with no carbon capture.

Figure 10: 2030 LCOE of LNG vs. Renewables in Germany



[67] National Renewable Energy Laboratory. "NREL System Advisor Model (SAM)." 2022. https://sam.nrel.gov/.

Figure 11: 2030 LCOE of LNG vs. Renewables in Pakistan

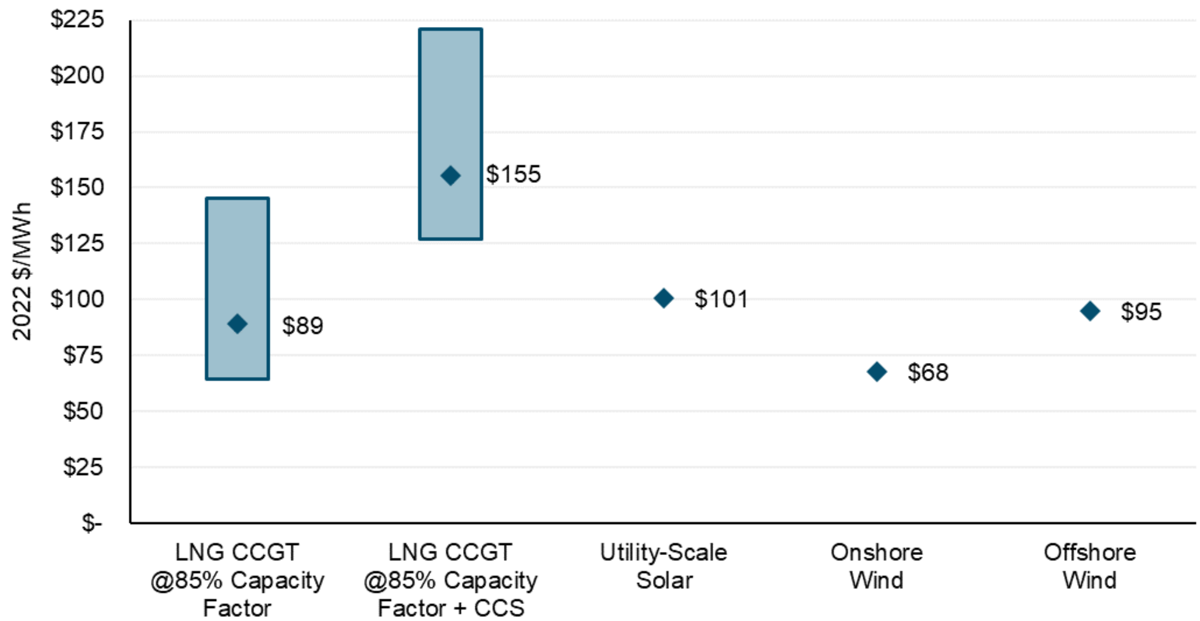
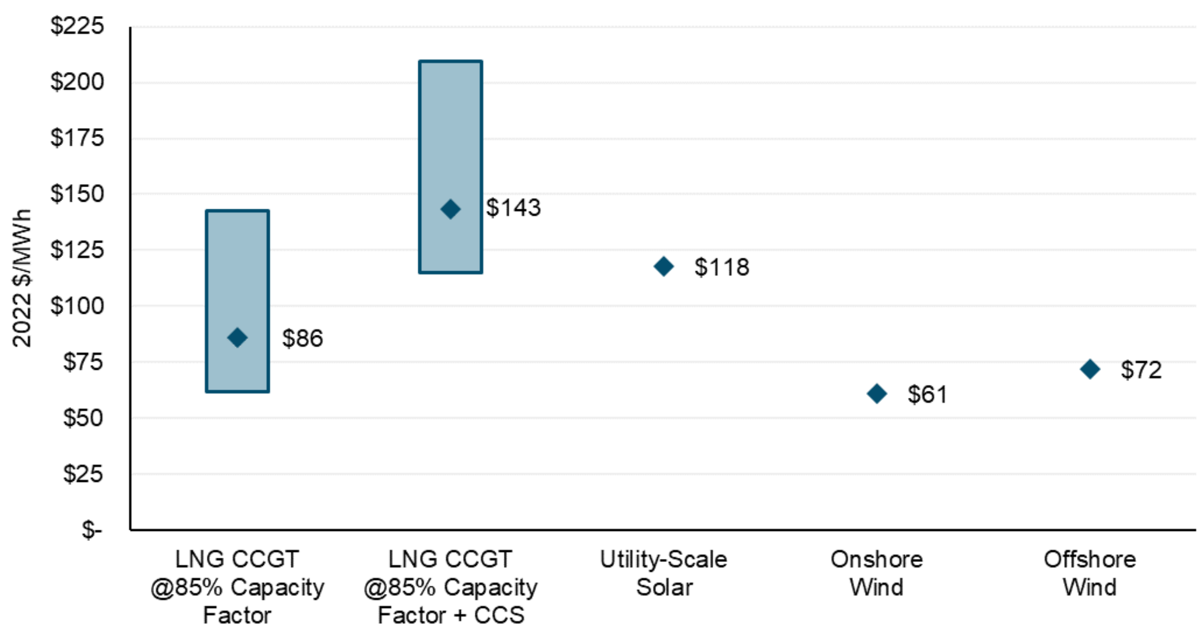


Figure 12: 2030 LCOE of LNG vs. Renewables in Vietnam



We also consider the effect of the cost of capital on renewable energy costs in Pakistan and Vietnam by evaluating the LCOE of renewables vs. LNG-fired generation under a scenario in which the WACC of projects in these countries is reduced to equal the WACC in Germany.

In this case, renewable energy resources—solar PV, onshore wind, and offshore wind—are found to be even more cost-competitive with LNG, as shown in Figure 13 and Figure 14 below.

Figure 13: 2030 LCOE of LNG vs. Renewables in Pakistan with Low Cost of Capital

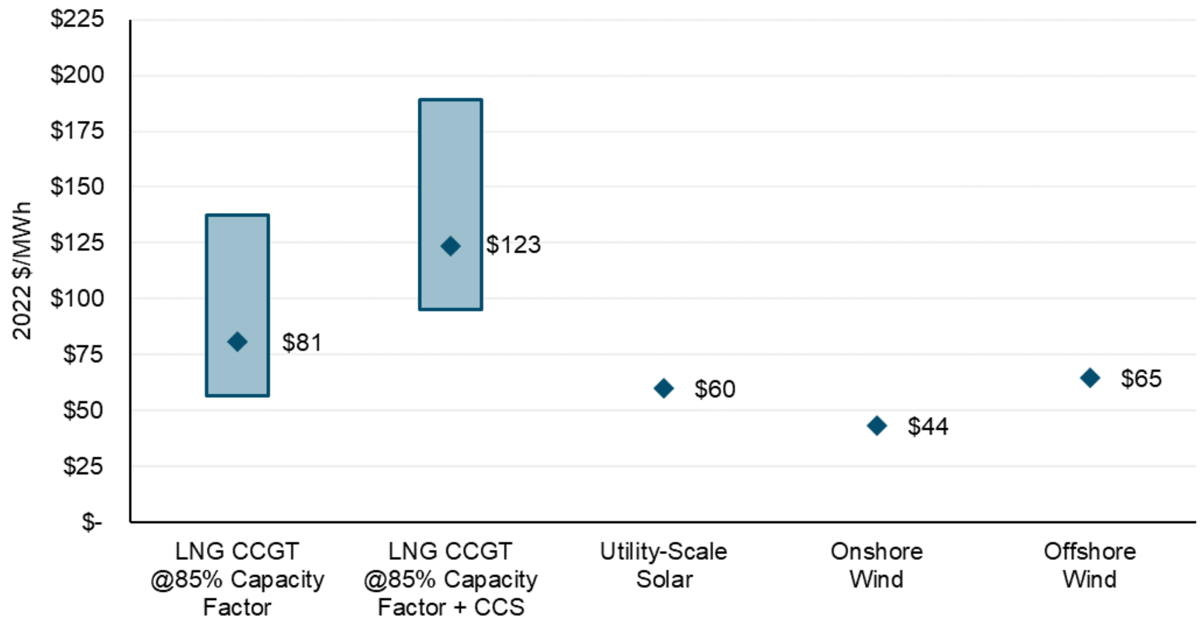
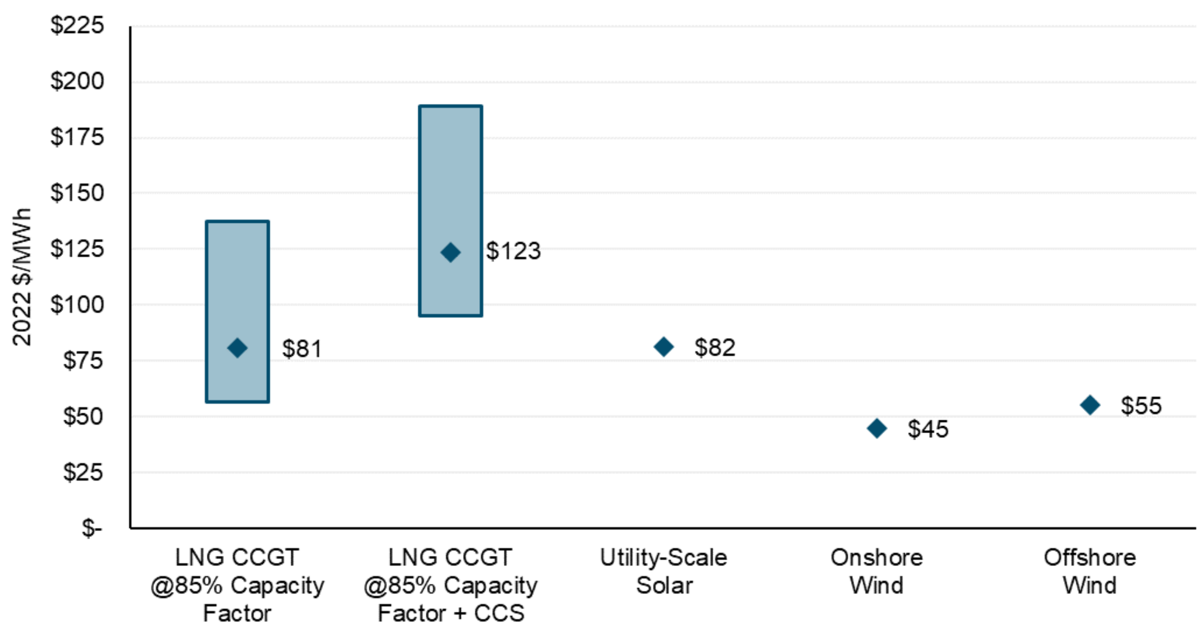


Figure 14: 2030 LCOE of LNG vs. Renewables in Vietnam with Low Cost of Capital



LCOE of Low-Carbon Firm Generation Resources vs. LNG Power Generation

It is quite clear that new renewable energy resources can provide energy to the power grid for lower costs compared to LNG-fired power generation in each country studied—even more so if the cost of capital can be reduced in developing economies through financial engineering and lower-cost lending. Furthermore, renewable energy resources offer more stable energy costs compared with LNG generation because the lifetime energy costs of renewables do not vary with global gas or oil prices as LNG prices do. Finally, renewable energy offers significant environmental benefits compared with LNG and domestic fossil-fuel resources (especially coal), including much lower emissions of particulate matter, air pollutant oxides (NOx and SOx), and greenhouse gases.

While LNG-fired generation appears to be more expensive with higher price volatility and higher environmental impacts, LNG-fired power plants also contribute more significantly to grid reliability than variable and intermittent renewable energy resources such as wind and solar PV on their own.

To evaluate LNG-fired generation on more equal footing for its capacity contributions to the grid, we also compare the LCOE of LNG-fired generation against alternative low-carbon sources of firm generation—that is, generators which can similarly be controlled (dispatched by the system operator) to produce energy during specific peak hours as needed by the power grid. We identify five low-carbon alternatives which represent commercialized and emerging technologies, as follows:

- Solar PV with a 4-hour Li-Ion battery
- Onshore wind with a 4-hour Li-ion battery
- Adiabatic Compressed Air Energy Storage (A-CAES) with a 48-hour duration
- Long Duration Energy Storage with a 150-hour duration
- Hydrogen CT producing green hydrogen from electrolysis and onshore wind.

LCOE comparisons for LNG vs. low-carbon alternatives in 2030 are presented in real $2022, as follows:

- Figure 15: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Germany
- Figure 16: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Pakistan
- Figure 17: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Vietnam

In addition to the same range of LNG prices applied in the energy-only LCOE comparison in the previous section, we also include a range of capacity factors (85%, 50%, and 35%) for an LNG-fired CCGT in our analysis of firm generation alternatives. This range of capacity factors is intended to illustrate the effective cost of LNG-fired generation if an LNG-to-power project were developed but found to be less economic over time than originally intended—the higher cost of LNG-fired generation (per MWh) leads to lower use of the power plant, but the plant is still called upon to meet system peak hours (as a firm generation resource). Lower utilization of the LNG-fired power plant (lower capacity factors) results in a higher unit cost of power (LCOE) because the same fixed costs of the plant are spread over a smaller number of megawatt-hours generated. Note that E3's analysis does not include the likely additional costs of the onshore regasification terminal and any gas storage or new pipelines—all of which are project-specific but would add additional fixed costs to an LNG-to-power project, meaning that the LCOE of a new LNG-to-power project is likely to be even higher than estimated in this report.

In all cases, we observe that pairing lithium-ion battery storage with renewable resources—particularly wind-battery hybrid projects—is a lower-cost alternative compared to LNG-fired power generation with carbon capture and sequestration (CCS), and wind-battery hybrids are cost-competitive with the upper range of LNG-fired power generation without CCS.

Emerging technologies (A-CAES, 150-hr storage, and Hydrogen) are more expensive than renewable-battery hybrid resources when applying a higher cost of capital to account for the increased investor risk associated with emerging technologies. However, these emerging technologies become more competitive if their cost of capital declines to the same level as commercial technologies (i.e. wind, solar, and storage), which can occur as these technologies reach commercial maturity (possible for some technologies by 2030) or if other measures are taken to reduce investment risk or lower costs of financing, such as the use of loan guarantees, preferential lending, technology grants, tax incentives, or other financial supports.

Each chart presents LCOE results with the range of LNG capacity factors and fuel prices as well as the LCOE of emerging technologies with a higher cost of capital (base assumption) and with a lower commercial-scale cost of capital. Hydrogen is excluded for Vietnam due to the lack of known geologic storage sites.

Figure 15: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Germany

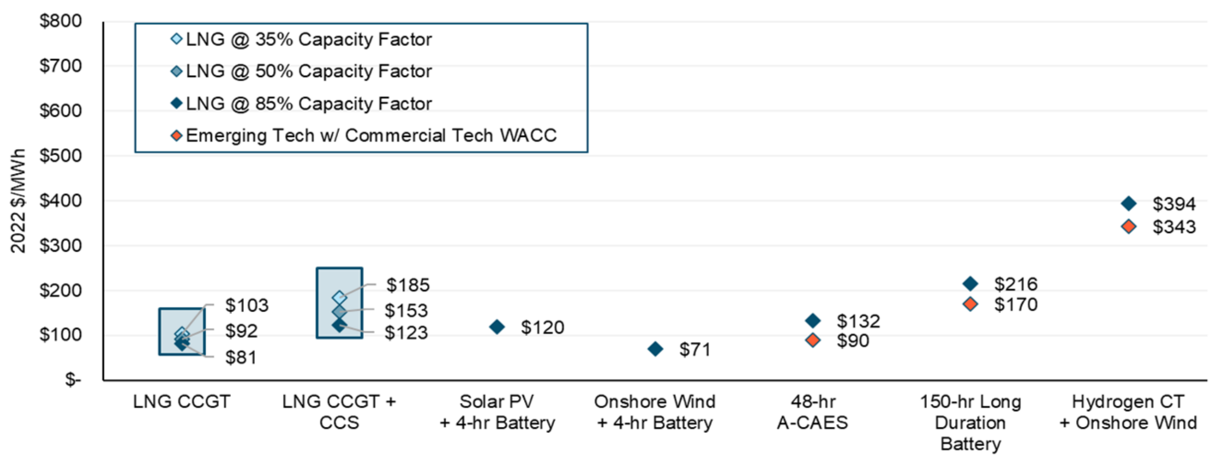


Figure 16: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Pakistan

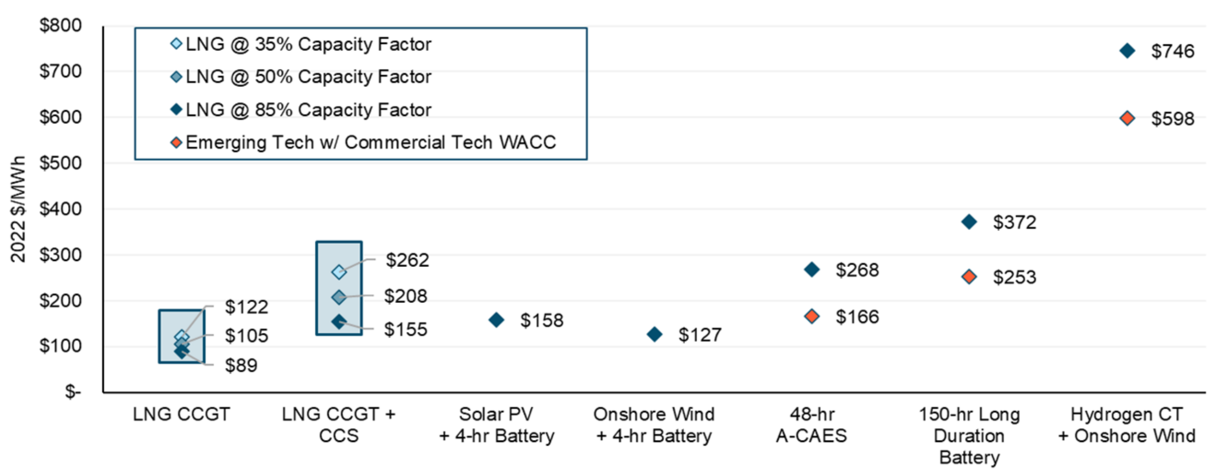
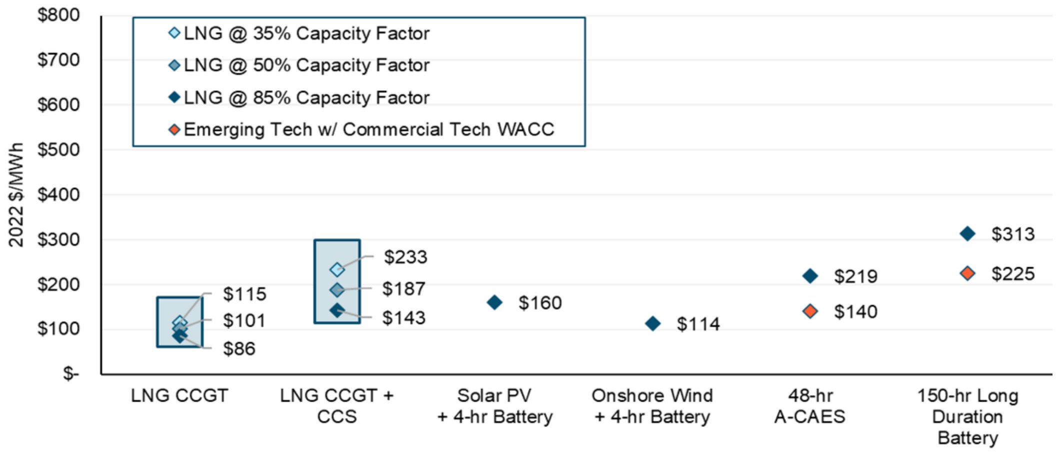


Figure 17: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Vietnam



In addition to wind-battery hybrids proving economically competitive vs. LNG-fired generation, we find that commercialized A-CAES (without technology risk included in the cost of capital) is cost-competitive with LNG in Germany and solar-battery hybrids in Vietnam. Long-duration energy storage is cost-competitive with an LNG-fired CCGT with CCS in all three countries, but only if the cost of capital is reduced to equal commercialized technologies (e.g. wind, solar, batteries). Power produced from green hydrogen combustion is the highest cost resource in each country due to the significant infrastructure investment costs and relatively low round-trip efficiencies of producing hydrogen from electrolysis, storing the fuel, and generating power from combustion turbines.

Due to the significant capital investment needs for all of these technologies—and the corresponding impact of the cost of capital on LCOE—we also present a sensitivity in which the cost of capital in Pakistan and Vietnam is reduced to equal the cost of capital in Germany (similar the energy-only analysis above).

In these sensitivities, emerging technologies are presented with Germany's cost of capital for emerging technologies (baseline) and also with Germany's cost of capital for commercial technologies to illustrate the impact of these technologies being de-risked at commercial scale in a low-cost investment climate.

Figure 18: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Pakistan – Low Cost of Capital

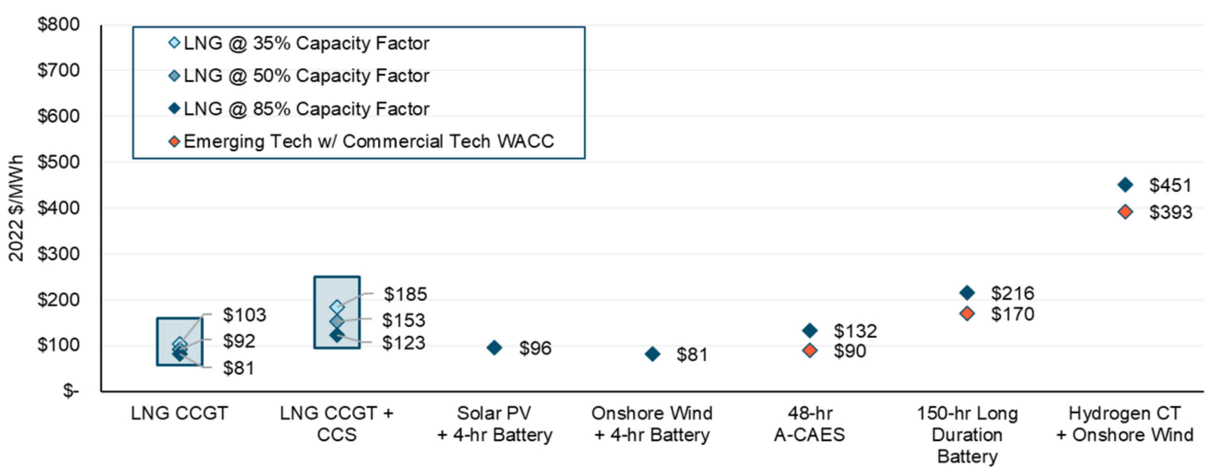
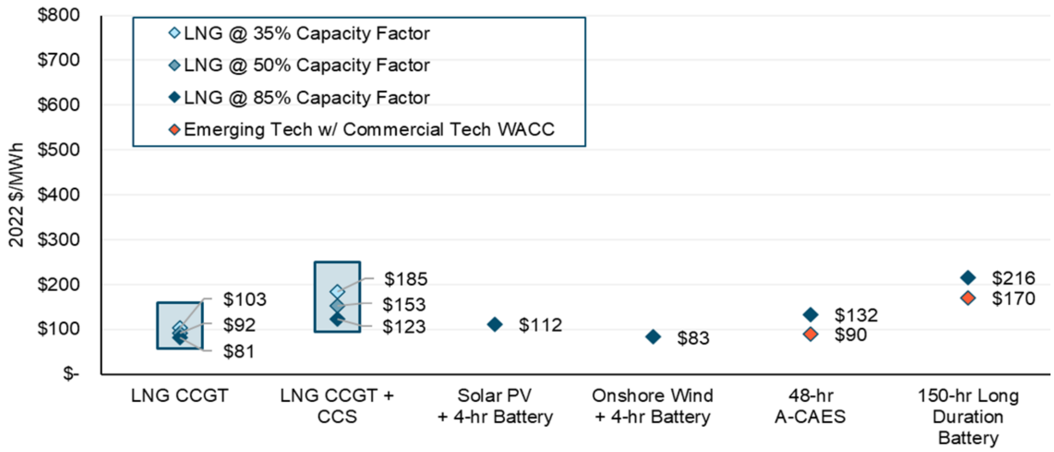


Figure 19: 2030 LCOE of LNG vs. Low Carbon Firm Generation in Vietnam – Low Cost of Capital



We find that solar-battery and wind-battery hybrid resources are quite cost-competitive with LNG-fired generation in a low-WACC scenario, and 48-hour A-CAES also becomes cost-competitive with a commercialized cost of capital. LDES remains less competitive even with lower costs of capital, and hydrogen combustion remains much more expensive relative to all other options evaluated.

Conclusions

The analysis presented in this report illustrates that commercially available renewable energy resources—solar PV and onshore and offshore wind—offer lower-cost and lower-emissions alternatives to LNG-fired power generation to meet energy demand in different countries, from Germany to Pakistan and Vietnam. Renewable energy resources also offer greater price stability and energy security compared with electricity generation from imported LNG. Renewable energy resources have significant potential to meet future demand for electricity in each of the countries studied, with renewable energy potential exceeding projected electricity demand in 2050 by factors of 2x (Germany), 5x (Vietnam), and 12.5x (Pakistan).

Pairing renewable energy resources with shorter-duration Li-Ion batteries can also provide substantial grid reliability benefits at similar costs to LNG-fired generation. Assessing and realizing the capacity contributions of renewable resources and short-duration batteries can reduce the need for fossil-fueled resources for grid reliability while also reducing reliance on high-cost imported fuels such as LNG. Additional demand-side management measures such as energy efficiency and demand response can provide effective, low-cost contributions to grid reliability which can similarly reduce the need for fossil-fueled generation and reduce dependence on imported fuels.

Several emerging technologies also have the potential to offer cost-competitive, low carbon firm generation if the costs (and cost of capital) of these technologies can be lowered. This can be accomplished through commercial scale-up of these technologies (reducing investment risk and capital costs as the technology is proven at commercial scale), and other forms of financial support such as preferential lending, loan guarantees, tax incentives, technology grants, or other financial interventions.

The cost of capital is also a critical issue for the economic competitiveness of commercialized renewable energy and battery storage technologies in Pakistan and Vietnam. Renewable and other low-carbon technologies have higher upfront investment costs but very low lifetime operations and maintenance costs compared with fossil-fueled resources. The repayment of investment costs (including the interest on debt and return to equity investors) is the single most significant factor in the lifetime costs of power from these resources. Reducing investment risk and borrowing costs in Pakistan, Vietnam, and other countries with higher costs of capital is one of the most impactful measures to lower the costs of electricity, reduce power sector emissions, and reduce reliance on imported fossil fuels.

Our findings largely align with results from decarbonization studies performed in the U.S. and elsewhere, which affirm that the least-cost way to decarbonize an electricity grid is to deploy low-cost renewable resources to displace fossil fuel use. We recommend that policymakers and planners take care to identify and evaluate a full range of resource options available and feasible within each country prior to making major investment or procurement decisions.

In order to apply these findings more broadly, we suggest following a similar methodology of what is driving LNG use in a particular country, assessing which resources can be added locally to provide energy and capacity to the electricity grid, and assessing the relative competitiveness of various technologies. Additionally, we recommend the application of optimization and reliability modeling (with loss of load probabilities) to inform power system planning and procurement decisions regarding the optimal resource mix to meet reliability, energy, and environmental goals in a particular country or service area.