The Corporate Role in Accelerating Advanced Clean Electricity Technologies

Introduction

The world faces an unprecedented energy challenge. To mitigate the worst impacts of climate change, we must collectively work to rapidly transition today's energy system, which is responsible for nearly three-quarters of global greenhouse gas emissions, to run entirely on clean energy sources.[1] At the same time, energy systems must expand significantly to reach those who have inadequate access to energy today and to power growing industries and national economies.

Electricity lies at the heart of this transition, as it is both a significant source of greenhouse gas emissions and a key tool for decarbonizing other sectors of the economy, such as buildings, industry, and transportation, through electrification. The International Energy Agency (IEA) estimates that global electricity generation will need to reach net zero emissions globally by 2040 to give the world a chance of limiting global temperature rise to 1.5 °C, while the total amount of electricity generated is expected to nearly triple by 2050.[2]

Variable renewable energy (VRE) technologies such as wind and solar, along with lithium-ion battery storage, will be core contributors to electricity grid decarbonization in many regions around the world. In 2021, wind and solar power together provided 10% of global power generation for the first time,[3] and the world is expected to add a record 440 gigawatts (GW) of new renewable capacity in 2023.[4] Grid-scale lithium-ion batteries are also being deployed at a growing scale, supporting the integration of variable wind and solar power into electricity grids.[5]

While we must continue to rapidly scale these technologies, we must also develop and commercialize new technologies to fully decarbonize electricity systems quickly and cost-effectively while maintaining reliability. According to leading energy system modelers, clean firm generation technologies and advanced energy storage systems are needed to reliably serve load during gaps in wind and solar energy production at minimum cost.[6,7] These technologies include, among others, geothermal, nuclear, power generation with carbon capture and storage, clean hydrogen, and long-duration energy storage (LDES) technologies. Beyond decarbonization, these new technologies will be needed to ensure that rising demand for electricity is met with new clean and affordable capacity while maintaining a high level of grid reliability, a critical foundation of economic development and industrial growth.[8]

In 2020, Google set a goal to run on 24/7 carbon-free energy (CFE) on every grid where we operate, which means matching our electricity demand with clean energy generation where and when our electricity consumption occurs. A core motivation for our efforts to achieve 24/7 CFE by 2030 is to accelerate the decarbonization of entire electricity grids and demonstrate that it is possible to operate major electricity-consuming facilities on reliable, affordable, and clean electricity every hour of every day.[9] Research from leading academic and international organizations shows that energy buyers pursuing local and hourly matched procurement leads to greater grid decarbonization and that procurement costs are reduced by the inclusion of clean firm generation technologies and LDES.[10] This finding is consistent with our own internal modeling of pathways to achieving our 24/7 CFE goal, which shows that advanced technologies will reduce both the cost of deeply decarbonizing our electricity consumption and market risks associated with procuring a portfolio consisting only of VRE technologies.

In our 2022 Policy Roadmap for 24/7 Carbon-free Energy, we discussed the importance of public investment in supporting the rapid development and commercialization of these next-generation clean energy technologies. Excitingly, significant new public investments have recently been committed that promise to accelerate clean technology innovation.[11] But public investments are not enough to drive the commercialization and deployment of these technologies at the speed and scale required: clean energy buyers also have a key role to play in helping to address financing, commercial, and other barriers that many of these technologies face today.

In recent decades, Google and other corporate clean energy buyers have played a critical role in scaling wind and solar deployment. We have done this through a combination of approaches, including forward purchasing renewable energy, standardizing corporate PPA contracts, working with utilities and policymakers to create pathways to scaling voluntary procurement, and joining together to form new clean energy purchasing associations.[12] As a result, in 2022, companies signed agreements for 36 GW of renewable energy projects, a new record and nearly ten times the level from just six years ago.[13] But while corporate procurement has been a valuable driver of scale for these VRE technologies, it has not played a similar role in supporting the other advanced carbon-free electricity technologies that we know will be important to achieving deep decarbonization of electricity grids worldwide.

This paper discusses the importance of advanced clean electricity technologies for grid decarbonization, and argues that companies can play a catalytic role in unlocking their potential by directing some of their clean energy purchases and investments to support their commercialization. The paper is organized in four sections:

Section One discusses how clean firm generation and advanced energy storage technologies complement wind and solar power in deeply decarbonized power systems, drawing on leading academic research. It also discusses lessons learned from Google's own internal modeling of cost-optimal technology portfolios for achieving our 24/7 CFE goal, which is consistent with this research.

Section Two profiles five different advanced clean electricity technologies that Google is considering for its own portfolio and that we believe are important for electricity decarbonization by 2030 and beyond.

Section Three describes a number of barriers to scaling these advanced clean energy technologies.

Section Four discusses how clean energy buyers can help advanced technologies overcome these barriers.

1. The Role of Advanced Clean Electricity Technologies in Electricity System Decarbonization

Rigorous studies of pathways for the deep decarbonization of electricity systems have coalesced around a number of key findings. The first is that wind and solar power generation technologies, currently the lowest-cost sources of electricity in many parts of the world, will play large roles in decarbonizing many electricity grids.[14] Second, electricity systems must expand significantly as demand that has historically been met by fossil fuels shifts to electricity. A significant expansion in transmission grids will be required in many regions to deliver low-cost wind and solar power from where it is generated to where it is consumed.[15] A third key finding is that a diverse portfolio of carbon-free electricity generation technologies is important to create an affordable and reliable carbon-free electricity sector.[16]

Firm generation and clean peaker resources (defined in section two) are particularly important complements to variable wind and solar technologies because they help maintain reliability in deeply decarbonized electricity systems. These technologies can provide electricity around the clock, if required, or ramp up flexibly when needed to fill gaps in VRE production. They also typically have a smaller land footprint than VRE per megawatt-hour (MWh) delivered and could reduce the amount of new transmission needed to be built.[17] A diverse portfolio of firm and variable clean generation technologies with balancing resources like energy storage will reduce system costs and ensure electricity systems' robustness to uncertainties and future constraints that may limit any particular technology pathway.[18]

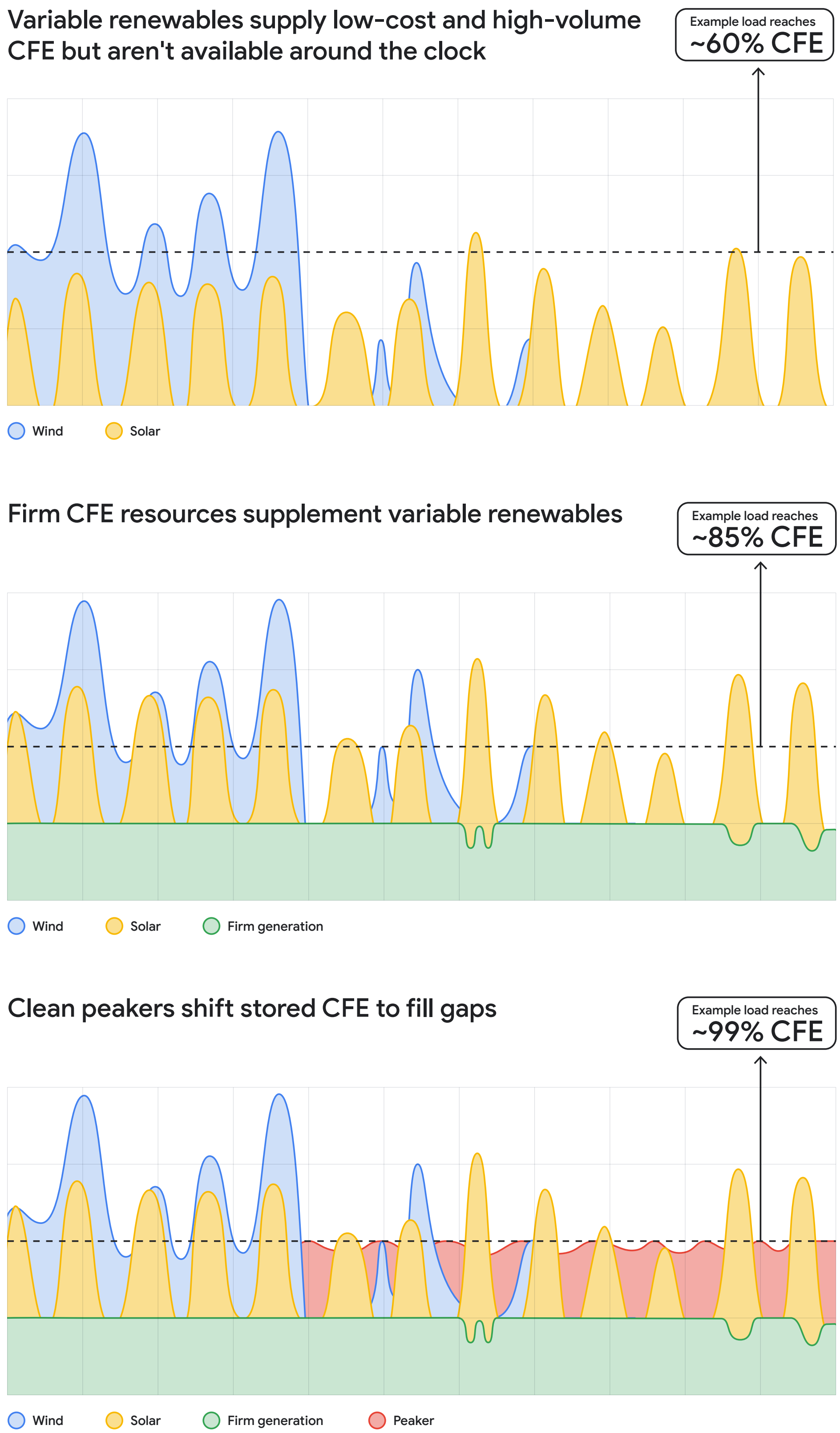


FIGURE 1: Firm generation technologies and clean peakers complement variable renewables to enable around-the-clock clean power (image shows sample portfolio over a two-week timespan).

At Google, we have set out to decarbonize our electricity consumption at all hours of the day in every region where we operate, with the aim of eliminating our electricity-related emissions footprint. We set this goal out of a desire for our clean procurement efforts to drive the greatest system-level impact as our electricity demand grows and to accelerate the decarbonization of electricity grids where we and others operate. We have performed internal modeling of the technologies that can help us meet our 24/7 CFE goal cost-effectively within every grid that serves us. Consistent with the leading academic literature on grid decarbonization, our modeling finds that a diverse portfolio of technologies reduces the cost of decarbonizing our global electricity consumption.

To inform our procurement planning, we developed a CFE optimization model to build a procurement roadmap for each of Google's owned and operated data centers around the world (See Figure 2).[19] Inputs into the model include anticipated growth in our electricity demand, projections of grid carbon intensity and wholesale power market prices, expected contract prices for different carbon-free electricity technologies, and technology-specific operating parameters (such as ramp rates) that need to be taken into account to ensure performance and reliability. Using these inputs, our optimization model defines the lowest-cost, high-CFE portfolio on each grid by 2030. A detailed list of model inputs and assumptions is included in Appendix A.

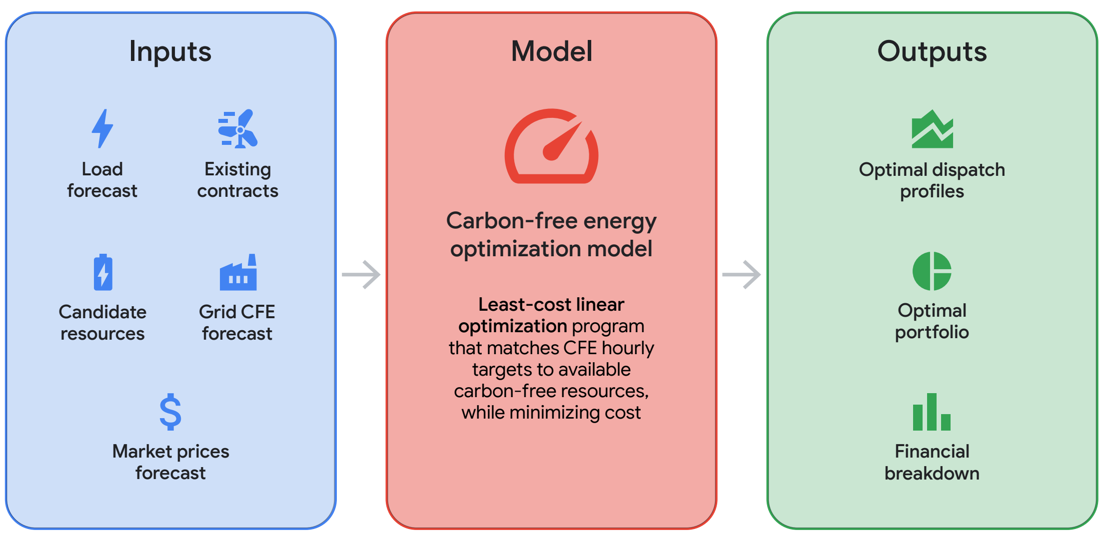


FIGURE 2: High-level overview of Google's CFE Optimization Model

In our modeling, we run two main technology scenarios. The first is a "Mature Technologies" scenario, which limits candidate technologies to wind, solar, and four-hour lithium-ion[20] storage to reach a range of target CFE levels.[21] The second "Advanced Technologies" scenario includes the Mature Technologies but also allows for the selection of a wider range of advanced clean electricity technologies (discussed in the next section) that are or could become available in particular markets to supply our electricity demand.

Three clear findings emerge from our modeling:

1. Advanced clean electricity technologies are essential to reducing the cost of 24/7 CFE portfolios. While priced at a premium per unit of energy relative to average wholesale electricity prices, the inclusion of advanced CFE technologies reduces the overall cost premium of achieving high CFE Scores.[22] For example, our modeling finds that including advanced CFE technologies would reduce the cost of achieving a 90% CFE Score across Google's globally owned and operated data center portfolio by approximately 40%, relative to a "Mature Technologies" portfolio in 2030.[23] These cost savings are realized because the inclusion of advanced technologies significantly reduces over-procurement of VRE and storage relative to demand, which would otherwise be needed to cover periods of low output from VRE sources. Moreover, firm technologies can produce electricity during the most expensive hours when wind and solar are unavailable. Taking these factors into account, our modeling finds that a cost-optimal portfolio includes a diverse mix of VRE, clean firm generation, and flexible balancing resources, including energy storage of varying durations.[24]

2. Advanced clean electricity technologies can reduce market risks in clean energy portfolios. Buyers of VRE are exposed to multiple market risks, including mismatches between hourly generation profiles and electricity demand (known as "shape risk") and the risk that market prices for renewable generation decline over time (known as "cannibalization risk").[25] These risks can be reduced through the inclusion of firm and flexible technologies in CFE portfolios. In addition to hedging against these risks, a diverse portfolio can also hedge against uncertainty in future technology cost and deployment trajectories and the possibility of over-reliance on any single technology that ultimately fails to deliver hoped-for improvements.

3. Some regions cannot reach high CFE concentrations without new technologies. In some regions, limitations on land availability, land use restrictions, poor renewable resource availability, transmission constraints, or other development challenges for VRE mean that advanced clean electricity technologies will be critical to achieving 24/7 CFE. Other areas with significant VRE availability and adequate infrastructure may require relatively smaller contributions from advanced technologies to achieve high CFE Scores.

To reflect a variety of variables and potential outcomes, we model multiple scenarios for achieving CFE Scores ranging from 70-100%. Figure 3 summarizes cost and capacity outputs from modeling scenarios targeting 90% CFE across Google's owned and operated data center portfolio by 2030. The Mature Technologies scenario results in a portfolio with a combined capacity three times the size of our average load, which is necessary to fill gaps in VRE generation. On the other hand, including advanced technologies in our portfolio results in our needing approximately 40% less capacity than in the Mature Technologies scenario, as fewer VRE and lithium-ion resources are needed to meet our demand. The net spend for theAdvanced Technologies scenario is also significantly lower—nearly 40% below net spend in the Mature Technologies scenario.[26]

We show modeling for a 90% CFE scenario in this example because the inclusion of advanced technologies has a particularly significant impact when our global CFE scores approach and exceed 90%. Our modeling of 100% CFE shows that including advanced technologies can reduce portfolio net spend even further, up to 70% or more, with some variation across regions.

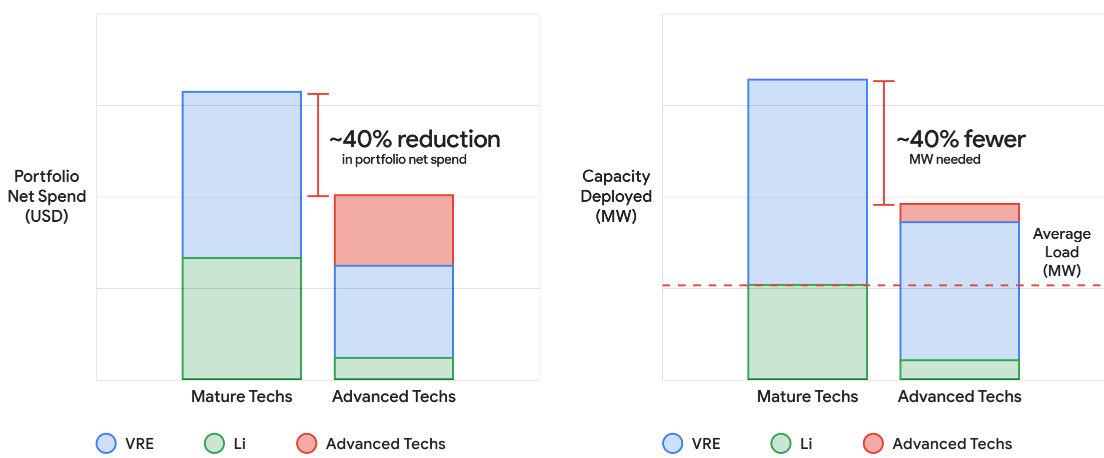


FIGURE 3: Cost (left) and capacity (right) comparison between Mature Technologies and Advanced Technologies scenarios in Google's CFE Optimization Model for 90% CFE across global portfolio.

Google's internal modeling aligns with the findings of other studies that have modeled local-and hourly-matched procurement, such as those by the International Energy Agency,[27] Princeton University,[28] and Technical University of Berlin.[29] These studies find that the cost premiums associated with high CFE Scores are significantly reduced with the inclusion of advanced clean electricity technologies. They also find that location-and hourly-matched procurement leads to lower system-wide electricity emissions compared to annually matched procurement, even at CFE Scores of less than 100%. The next section discusses the characteristics of these technologies and describes five specific technologies that we believe have the potential to scale to be key contributors to grid decarbonization and corporate clean energy portfolios.

2. Categorization of Advanced Clean Electricity Technologies

The advanced clean electricity technologies discussed in this paper fall into two general categories: **firm generation** or **clean peakers**.

Firm generation resources are "technologies that can be counted on to meet demand when needed in all seasons and over long durations (e.g., weeks or longer)."[30] These include but are not limited to nuclear, fossil generation with carbon capture and storage, geothermal, reservoir hydro, and bioenergy and biogas plants. These resources typically operate at capacity factors of 50% to 90% or more, filling similar roles in electricity systems as unabated fossil-fueled plants do play today. Flexibility, or the ability to vary generation in response to changing net demand for the resource, is a beneficial characteristic that can enhance the value of firm generation in energy systems.

Clean peaker resources are resources that can be called upon in times of peak net demand (load minus VRE), a role often played today by fast-ramping natural gas plants. These include lithium-ion batteries, hydrogen power generation, and the suite of long-duration energy storage technologies defined below. They typically operate at capacity factors of 10% to 40% and can dispatch for at least ten consecutive hours and, in some cases, up to 100 hours or more.

By definition, these technologies are dispatchable or able to be called upon when needed. How and when these technologies generate electricity is influenced by their cost, their response capabilities, and the needs of the electricity system. Thus, the same technology could operate as a firm resource in some regions and a peaker in others. In Appendix B, we include a taxonomy, originally published by Sepulveda, Jenkins, et al. (2018), of different carbon-free electricity resources mapped to their optimal roles in decarbonized electricity systems.

Top five technology categories

In our modeling, we prioritize five technologies within the two categories listed above. Several factors inform this prioritization, including forecasted pricing and potential for cost declines, global scalability, and environmental considerations. The most important factor for inclusion in our portfolio is forecasted future pricing, which is typically expressed in $/MWh net of grid electricity prices for a given load shape. We are most interested in technologies that have potential for significant cost declines through repeated deployment so that our efforts can spur further technological progress. Global scalability is thus important to capture maximum economies of scale and deploy projects across multiple regions. As outlined further below, environmental impacts must be well understood and mitigated, and close engagement with the communities where such plants operate is key.

Below, we profile five advanced clean electricity technologies that we believe could play a critical role in grid decarbonization by 2030 and beyond. While not an exhaustive list of clean dispatchable technologies (see Appendix A), we believe these technologies demonstrate the clearest path to meeting the criteria above and strongly overlap with findings from other leading researchers. Google is actively considering these technologies as part of the technology portfolio that will enable us to achieve our 24/7 CFE goal in multiple regions around the world.

Firm generation resources			Clean peaker resources	
1. Next-generation geothermal	2. Carbon capture and storage	3. Advanced nuclear	4. Hydrogen	5. Long-duration energy storage

Firm generation resources

Many variables influence the potential of firm technologies in different regions: local factors, including resource availability, infrastructure, supply chains, and policy and regulatory regimes, are important determinants of whether a particular technology is prioritized in a given region. For example, subsurface resource availability is an important regional driver for geothermal (heat and/or permeability) and carbon capture and storage (saline and other repositories for storage), while new nuclear is often favorable in regions with established supply chains, skilled workforces, and/or few alternatives.

Next-generation geothermal resources use new technological approaches to unlock geothermal potential in places where traditional geothermal systems are not technically or economically feasible. These approaches may also provide other benefits, such as a reduction in levelized cost or drilling risk compared to conventional techniques. Resource types can be broadly classified into in-field, near-field, and deep, and key next-generation extraction methods include closed-loop and enhanced.[31]

Many of today's newer technologies draw on recent technological progress in oil and gas drilling with a goal to lower drilling costs and increase success rates. Some also promise new features such as in-reservoir energy storage and load-following capabilities. Improved subsurface mapping and data can help accelerate deployments through improved site selection and potentially reduced drilling risk. Finally, new approaches to accessing superhot rock geothermal, if successful, could unlock high-quality around-the-clock renewable energy generation in many more places.

Carbon capture and storage (CCS) power generation is defined as thermal power generation using fossil or renewable fuels while capturing and storing associated carbon emissions to prevent them from entering the atmosphere. Broad technology classes include pre-combustion, post-combustion, and oxy-fuel types.

While CCS has had a mixed historical record,[32] the large unabated global fossil fuel asset base, along with new capture technology innovations and infrastructure advancements, support the case for considering CCS as a climate mitigation technology.[33] Advancements in next-generation sorbents or emerging approaches, including oxy-fueled technologies, may bring capture levels to over 95% of point source CO_2 emissions in the near term with a technical potential exceeding 99% in the future,[34] while the use of sustainable biogenic feedstocks can provide net carbon removal, subject to the sourcing of appropriate biomass feedstocks.[35] Upstream emissions (such as methane emissions) must be considered and minimized. Enabling infrastructure deployment, including CO_2 pipelines and permanent geologic storage wells, will also be required to ensure permanent storage. Eligible projects must demonstrate high capture rates and permanent sequestration of the captured carbon into safe, secure geologic storage wells.

Advanced nuclear refers to a suite of new fission reactor designs with significant improvements compared to traditional designs.[36] While commercial nuclear plants have operated since the 1950s and today generate a substantial 9% of global electricity,[37] long development timelines and safety and economic concerns have slowed deployment in many markets. Fission reactors can be categorized broadly into Gen III+ (generally water-cooled), Gen IV (other coolants), and microreactors (generally 20MW or less).[38]

The next generation of advanced fission reactor companies is pioneering new innovations across the nuclear value chain through a combination of simplified system designs, new coolants, smaller modular size ranges, and waste recycling. Many advanced nuclear technologies are being designed to enable more flexible operations and address legacy concerns relating to waste, safety, cost, and schedule certainty.

Clean peaker resources

Traditional peaker plants operate during times of peak net demand and include technologies such as natural gas turbines, pumped hydropower, and, increasingly, batteries (primarily lithium-ion types). The flexible siting potential, high efficiency, and falling cost of lithium-ion batteries make the technology well-suited to scale with growing VRE penetration for diurnal shifting applications, but the technologies below have the potential for superior cost and performance for use cases including inter-day shifting (10-36 hours) and multi-day to seasonal shifting of 100 hours or more. Such technologies, if commercialized and deployed at sufficiently low cost, will play a key role, alongside other firm carbon-free electricity technologies, in deep decarbonization.[39]

Hydrogen power generation refers to the use of hydrogen or hydrogen-based fuels in thermal generators or in electrochemical fuel cells. While hydrogen is positioned to play a more significant role in the decarbonization of other sectors, such as fertilizer and heavy industry, it may also be used as a peaking generation resource in deeply decarbonized electricity systems. While clean hydrogen is an expensive fuel source today, governments around the world are providing policy support to stimulate early markets and encourage manufacturing scale-up and technology cost declines, which will enhance its economics.[40] Hydrogen can be considered a firm power source, but our modeling and that of others suggest its best power generation use case will be meeting peak demand, effectively operating as long-duration energy storage when the hydrogen is created via electrolysis.[41] Power generation options include combustion turbines, reciprocating engines, fuel cells, and linear generators.

To ensure that the build-out of clean hydrogen delivers climate benefits, the carbon intensity of hydrogen systems should be as low as possible, with a preference for ultra-low carbon hydrogen.[42] To produce ultra-low carbon hydrogen via electrolysis, the electricity supply used to power electrolyzers should comply with three important criteria: additionality, deliverability, and temporal matching on an hourly basis.[43] Scaling clean hydrogen and linking sources to end users will also require enabling infrastructure such as pipelines and geologic storage, the costs of which can be shared across many users, thereby improving the economics for each participant in these systems. Since hydrogen is a greenhouse gas, emissions along the value chain must also be monitored and mitigated.[44] To utilize hydrogen directly, combustion technologies such as turbines must also progress to utilize 100% hydrogen while preserving existing efficiency and NOx targets.

Long-duration energy storage (LDES) includes electrochemical, chemical, thermal, and mechanical energy storage technologies with a continuous discharge duration of at least ten hours.[45] These systems are able to provide critical generation capacity in the hardest-to-decarbonize hours of the grid by shifting carbon-free energy from periods of high generation to periods of low generation across weeks and even months.

While we group storage technologies with durations above 10 hours into the category of LDES for the purpose of this paper, technologies with the capability to store energy for 100+ hours can serve a unique role in decarbonization. Technologies that may economically reach this threshold include a number of thermal and electrochemical energy storage types. This extended duration allows for the shifting of energy between periods as long as seasons, which is especially relevant in regions where solar and wind generation varies significantly by season. Advanced grid modeling shows that in addition to smoothing extended multi-day downturns in renewable energy generation, 100+ hour-duration energy storage can replace the greatest quantity of firm generation compared to shorter-duration technologies and may also help address reliability and transmission concerns.[46]

These advanced electricity technologies, alongside renewable energy technologies like wind, solar, bioenergy, hydropower, short-duration batteries, and other important grid resources like demand response, can all play critical and complementary roles in a portfolio of technology solutions working together to enable deep grid decarbonization. Google is committed to supporting the advancement of these technologies. In section four, we discuss how we and other corporate clean energy buyers can do so.

3. Barriers to Advanced Clean Technology Commercialization

Advanced clean electricity technologies must contend with a number of barriers to successful commercialization and widespread commercial deployment. Many advanced clean electricity technologies are unable to move beyond what is known as a "technology valley of death," which refers to the stage between initial demonstration and large-scale commercialization and deployment where technologies struggle to gain a market foothold (see Figure 4). A core challenge is that significant capital expenditures are required to develop and deploy these technologies compared to traditional fossil generation assets. De-risking projects so that they can secure the financing needed for widespread deployment is thus key to commercialization. This section discusses the various barriers facing advanced clean electricity technologies, including technology, financing, development, regulatory, and ecosystem barriers. These are described further below.

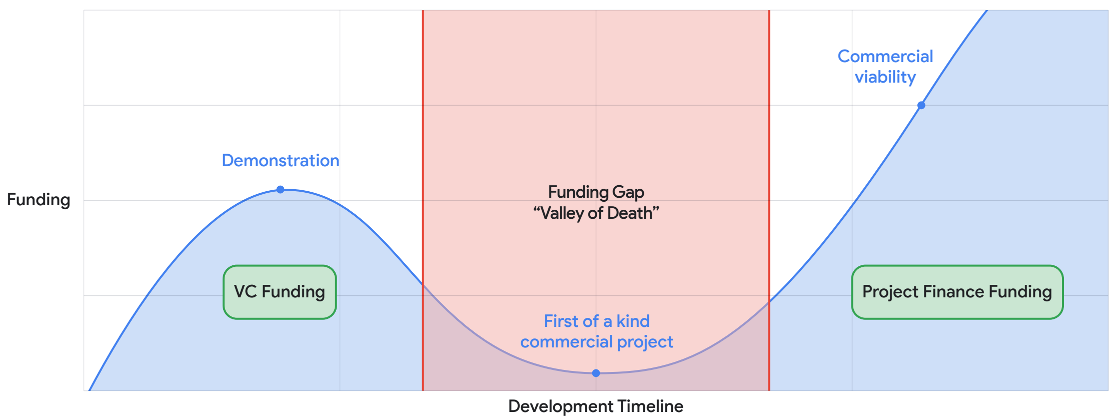


FIGURE 4: Development capital is key to overcoming the clean energy "technology valley of death"

Technology, financing, and development barriers

Technology and financing risk: One key barrier is limited access to the capital needed for new technologies to achieve commercial scale. While there has been significant investment into new "climate tech" ventures, enabling startup companies to undertake early-stage technology development, much of this investment has come in the form of R&D grants and venture capital funding that is not sufficient in either size or duration to support companies through the valley of death.[47] On the other hand, capital from institutional investors has flocked to the steady, derisked returns generated by mature, sustainable infrastructure assets such as wind and solar projects.[48] Between these two stages of funding, companies are struggling to bridge the financing gap between demonstrating a new technology and deploying it commercially at scale.

Put simply, the forms of capital available today do not match the technology and financing needs of innovative but still nascent clean energy technologies.[49] Next-generation geothermal is an illustrative example. New commercial projects require significant capital expenditures for geophysical surveys, subsurface and resource mapping, exploration drilling, and other up-front investments–often totaling tens of millions of dollars–all before a single MWh of electricity is produced. As a result, startup developers are required to manage significant investment and working capital burdens at a high cost of capital. However, when it comes to financing a promising project, traditionally risk-averse investors such as tax equity are often hesitant to invest in projects with remaining technology risk, preventing promising projects from securing the capital they need to move forward.

First of a Kind project development challenges: When it comes to developing First of a Kind (FOAK) projects, technology innovators often struggle to move from smaller-scale demonstration projects to large industrial facilities and commercial-scale power plants. In Google's experience working with advanced carbon-free energy technologies, the innovators holding the technology intellectual property often do not have the project development and engineering, procurement, and construction (EPC) expertise to build the FOAK project themselves. Given the early stage of these technologies, a broader consortium of stakeholders is needed to bring a project to fruition, which often increases the project's complexity as well as risks for a potential offtaker. For example, multiple stakeholders are needed to develop a successful CCS project, including the underlying power plant operator, the CCS technology provider, the CO_2 transport partner, and the sequestration well operator. The complexity and coordination requirements to realize success can be an obstacle to securing the financing necessary to pursue the project.

Securing long-term offtake agreements for FOAK projects can also be a challenge. Advanced clean electricity technologies will often enter the market at a significantly higher cost than more mature technologies like wind or solar. These technologies are still in the early days of their commercialization trajectory and face added financing premiums and higher project costs to compensate for their technology risk and limited economies of scale in their manufacturing and supply chains. There is a limited pool of utilities, companies, and governments willing to pay for the "green premium" associated with the projects.

Moving beyond FOAK projects: Many of the challenges that FOAK projects face persist even for subsequent plants. Technologies require repeated deployments to incorporate learnings and develop supply chains that help them realize economies of scale and move down the cost curve. This requires a level of demand in the hundreds of MW. Unfortunately, procurement for new technologies tends to be for single plants, not larger portfolios, with many observers wanting to "wait and see" how the FOAK plant performs before committing to underwrite additional plants. As a result, development costs are concentrated on the first project because none of the contractors know with certainty that another will follow. This can cause the FOAK project to be so costly that its developers abandon the technology after the FOAK deployment, never making it past the first project. The U.S. Department of Energy has identified this exact dynamic as a historic barrier for nuclear power to achieve scale: multiple reactor designs were tried once and never repeated because of cost overruns or challenges with the first deployment.[50] According to the DOE's analysis, advanced nuclear technologies will require a committed order book of "5-10 deployments of at least one reactor design" in order to enable commercial liftoff in the U.S.

Commercial structuring challenges: In addition to cost premiums, there may be challenges to structuring commercial agreements due to the unique operating characteristics of these technologies. For example, the contract form for green hydrogen for power generation more closely mirrors a fully dispatchable tolling agreement than an as-delivered solar or wind power purchase agreement. Contract components such as how and when an electrolyzer will be operated to produce compliant green hydrogen and how and when the downstream power generation technology will be operated to fill in the gaps of the broader system's carbon-free energy profile are material to the commercial structure. Over time, such contracts will become more familiar to offtakers, but in the near term, aligning on these details among counterparties for FOAK projects requires significant time and effort.

Demand bankability: A single offtaker may not be able or willing to underwrite offtake for a single large-scale plant, given the technology risks and the offtaker's desire for diversity in their procurement portfolios. Even if customers are willing to underwrite an offtake contract, an "if you build it, we will buy it" approach may not be sufficient to make a project bankable. A traditional PPA with standard termination rights, liquidated damages, and availability and performance guarantees works well for a proven commercial technology like solar, but can be challenging as the basis for financing a FOAK technology project, as it requires other project stakeholders to bear the risk of project underperformance, cost overruns or delays.

Regulatory and ecosystem barriers

Lack of enabling infrastructure: The pace of clean energy deployment depends on the availability of infrastructure to transport and deliver clean energy from where it's generated to where it's consumed. However, many important forms of enabling infrastructure projects face significant challenges, such as funding, permitting, or other institutional barriers that delay or prevent their timely completion. For example, the widespread scale-up of CCS and green hydrogen technologies will require proactive planning and coordination of multiple types of infrastructure, including storage, pipeline, and transmission systems, without which technology deployment will slow.

Electricity market design: While modeling indicates that firm carbon-free electricity technologies are critical to achieving deeply decarbonized grids cost-effectively, today's electricity markets are not designed to fully value these resources for the services they provide to the grid, including capacity, reliability, and, in some cases, the deferment of infrastructure investment. Many electricity markets are designed around the lowest-cost marginal dispatch of electricity, which makes it challenging for advanced technologies that are initially more costly to find an economic foothold. Capacity markets can be a source of remuneration, but capacity contracts are typically awarded to lower-cost fossil fuel plants. Clean firm resources will need market mechanisms or incentives in place to ensure they are sufficiently remunerated in electricity systems to achieve economies of scale and cost declines.

Ultimately, these and other barriers to the commercialization and deployment of advanced clean energy technologies mean that projects may incur financing challenges, cost overruns, and schedule delays that increase the risk of abandonment after the first project without an opportunity to achieve economies of scale and cost reductions associated with wider deployment. As the experience of the solar industry shows, repeated deployment is critical to driving learning-by-doing, process improvements, the maturation of supply chains, and the training and upskilling of workers, all of which contribute to cost reductions that can enable an industry to reach cost competitiveness.[51] Solar power took over 30 years to reach today's scale and cost competitiveness, and could have done so sooner if not for a lack of capital investment during the early scale-up phase of the industry (see Figure 5). We need much greater capital investment in the next generation of advanced clean electricity technologies today to move them down their own cost curves and toward cost competitiveness and widespread market adoption.

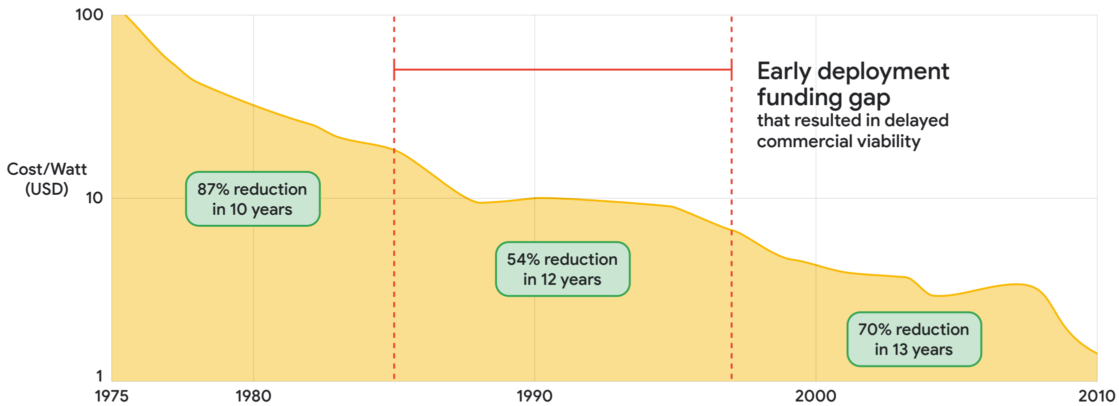


FIGURE 5: Deployment funding gap slowed cost declines of solar PV.[52]

4. How Corporates Can Accelerate and Benefit From Advanced Clean Electricity Technologies

To date, clean energy buyers have purchased electricity almost exclusively from wind and solar technologies. This has allowed companies to benefit from low-cost clean electricity when these technologies are generating and has spurred the deployment of significant quantities of new renewable energy on electricity grids. Now that wind and solar technologies have become the lowest-cost clean electricity sources in many markets around the world, corporate buyers should aim to play a similarly significant role in accelerating the commercialization of advanced clean energy technologies.

Such engagement, despite a higher initial price premium, would also provide benefits to corporate buyers:

- With rising penetrations of wind and solar, portfolios reliant on these technologies alone will experience increasing market risks and price volatility, while advanced technologies with complementary production profiles would help hedge against these risks.
- Advanced clean energy technologies provide reliable and dispatchable electricity, supporting new capacity needs and grid reliability as corporate electricity demand grows.

As we advance toward our 24/7 CFE goal, we have observed gaps in the corporate clean energy ecosystem with respect to support for advanced clean electricity technologies. Clean energy buyers can play a catalytic role in accelerating the commercialization of these technologies this decade. They can do this by directing some of their procurement and investment toward these technologies and advocating for policies that support advanced technology deployment.

Procurement

In recent years, we have seen an encouraging expansion of mechanisms to create demand for nascent technologies. Google is proud to be a Founding Member of Frontier Climate, an advanced market commitment for carbon removals, as well as a champion of the carbon dioxide removals pillar of the First Movers Coalition. Clean energy buyers could create similar initiatives to send large demand offtake signals for advanced clean electricity technologies. Based on our conversations with technology developers, investors, and other stakeholders seeking to commercialize these technologies, we believe that some particularly helpful actions could include:

- Signing long-term and bankable offtake contracts, which can help technologies bridge the “valley of death” and enable financing and construction of initial commercial plants. As an example, Google entered into an agreement with Fervo Energy, which is building a next-generation geothermal plant that will add carbon-free energy to the electric grid that serves our data centers and infrastructure throughout Nevada. Offtakers can assume an appropriate portion of project risks in order to advance bankability. This could be done, for instance, by developing a contract that has increased flexibility around termination and damages, underperformance, or other contractual guarantees.

- Developing replicable contract templates that reflect and value the unique attributes of emerging technologies. Many advanced clean electricity technologies have features that differentiate them from solar and wind and call for different contract structures than today’s standardized wind and solar PPAs. Clean energy buyers and sellers can work together to create template contracts for these technologies that balance offtaker needs with those of advanced technology developers.

- Contracting for multiple plants at a time. This could give project contractors, financiers, and the broader market confidence that the technology will not be a one-off project. By spreading costs (and risks) across a series of projects instead of a single one, these technologies could be more attractive to lower-risk financiers, unlock lower-cost financing, and de-risk EPC and operations for the technology developer going forward.

Investment

In addition to procurement, companies can invest directly in technologies and projects to help fill capital gaps. From 2010 to 2022, Google entered into agreements to invest nearly $2.9 billion in renewable energy projects with an expected combined generation capacity of approximately 4.2 GW. Deploying similar investments into advanced clean technology projects can support their commercialization. This could include:

- Providing development capital directly into projects early in the development lifecycle, and in particular first-of-a-kind projects, to help advance project development and reduce project risks. For geothermal, for example, corporate buyers could finance activities such as geophysical surveys, subsurface and resource mapping, and exploration drilling.
- Investing in advanced technology projects by monetizing tax credits, such as the 45Q tax credit for carbon capture and sequestration projects or 45V for clean hydrogen in the United States.
- Investing directly in companies working to develop and commercialize advanced clean electricity technologies to provide innovative companies with the capital they need to prove and scale their technologies and business models.

Policy and advocacy

Companies can support advanced clean electricity technologies by publicly articulating the importance of these technologies, promoting supportive policies, or working with others to develop market structures that support their commercialization. This could include:

- Working with utilities and regulators to develop new approaches to green tariffs that enable large industrial customers to support utilities' clean energy transitions and focus additional procurement on advanced technologies that are needed to accelerate full decarbonization. These "Clean Transition Tariffs" can buy down the cost of the utility transition for all ratepayers while appropriately crediting the participating customer for the value these new resources bring to the grid.
- Working with utilities and market operators to establish market rules and products that correctly value and remunerate the services that advanced clean electricity technologies provide. One example is the introduction of time-based energy attribute certificates (T-EACs), which will create temporally differentiated price signals that stimulate investments into technologies that deliver carbon-free energy when it is most needed.

- Joining or supporting technology-specific trade associations that work to accelerate deployment of particular advanced clean energy technologies. For example, Google is a member of the Long Duration Energy Storage Council and sits on the Nuclear Innovation Alliance's Advisory Committee, in addition to supporting a variety of working groups at other organizations.

- Actively advocating for government policy measures that help scale the deployment of these technologies and maximize their contribution to decarbonization. For example, Google has supported rules in Europe and the U.S. that would ensure that grid-connected hydrogen electrolysis projects are scaled up in a way that doesn't significantly increase emissions. We also outline many other clean energy policies we support in our Policy Roadmap for 24/7 CFE.

Just as corporate clean energy buyers played a key role over the past decade in building voluntary clean energy markets that helped accelerate the cost declines and scaled deployment of wind and solar power, we believe that leading companies have an opportunity to do the same for a broad suite of advanced technologies that the world needs to build resilient, secure, cost-effective, and fully decarbonized electricity systems in the coming decades.

We are interested in working with other companies to send a strong demand signal for nascent advanced clean energy technologies and accelerate their commercialization and deployment. **If you are a project or technology developer, corporate or energy offtaker, or other stakeholders interested in partnering with Google on advanced clean electricity technologies, please get in touch here.**

Appendix A: Methodology for 24/7 CFE Optimization

To inform our resource procurement planning, our CFE optimization model provides, for each grid where we have an owned and operated data center, the least-cost portfolio of technologies and hourly dispatch for future years (e.g., 2030) that achieves Google's CFE goals. Our 2021 methodology paper outlines how we calculate our CFE scores and measure our progress.

Key inputs include hourly forecasts for data center load, contracted carbon-free energy, grid carbon intensity, forecasted wholesale market prices, and forecasted carbon-free generation and prices. These variables are combined to calculate forecasted CFE scores and expected cost premiums for each data center region. Cost premium, otherwise referred to as "net spend," refers to the cost of procured carbon-free energy, less the price of the baseline market energy forecast over the same period.

The optimization model solves for the least-cost portfolio of carbon-free resource generation that matches Google's forecasted data center load on an hourly basis in a given year. The model is subject to a series of constraints that ensures portfolios meet a specified CFE target given resource availability, limits overgeneration of carbon-free resources, and enforces operational limitations such as ramping and cycling constraints. Key outputs include the portfolio of resource capacities, optimal hourly dispatch, and net premium spend.

Technologies considered

We use the following technologies in the model, with input assumptions as noted (ranges represent regional variation across the geographies where we operate).

	2030 Price assumptions	Heat rate (mmbtu/MWh)	Capacity factor	RTE/Duration
Variable Renewables	$/MWh			
Solar	26 - 79		8 - 36%	
Onshore Wind	25 - 80		23 - 49%	
Offshore Wind	46 - 120		38 - 53%	
Energy Storage	$/kW / $/kWh incremental capex			
Li-ion	240 - 400/ 140 - 230			90%/4h
Generic inter-day ESS	1,100 - 1,800/ 66 - 110			64%/12h
Generic multi-day ESS	1,200 - 1,700/ 11 - 16			43%/100h
Firm generation	$/kW (capex) / $/MWh (variable)			
Hydrogen	890 - 1,400/ 97 - 220	6.1		
CCS	2,000 - 2,900/ 27 - 85	6.8		
Nuclear	6,900 - 10,000/ 10 - 14			
Geothermal	5,500 - 13,000/0			

The 2030 forecasts are derived from a wide variety of academic, governmental, and other sources.[53] There is significant intra-regional variation stemming from resource availability and market differences. For VRE, the price is input in $/MWh. The renewable generation profiles used come from third-party data and represent a range of weather years. For dispatchable technologies (lithium-ion and advanced techs), the price is input as a combination of capacity payments ($/MW-mo) and variable costs ($/MWh).

All technologies have region-specific maximum contractible capacities that are enforced in the model. The maximum contractible capacities reflect internal projections for feasible CFE procurement by 2030 and limit the amount of technology available for selection in the optimal portfolio. In many cases, there is no foreseeable contractible capacity, so the technology is not modeled as a candidate resource for the relevant region.

Technologies omitted

The above technologies are included in our modeling for the reasons noted in the main paper. There are a number of other technologies that have the potential to play a significant role in grid decarbonization but are not considered in our modeling for a variety of reasons—from scalability challenges to difficulties with modeling in all global regions. Notable technologies omitted from our modeling include, but are not limited to:

- **Biomass and biogas:** These technologies already contribute significant global generation capacity and are poised to grow further. Competing uses for limited feedstock is one challenge for this market. Robust standards for feedstock quality are key to ensure that these resources contribute to climate mitigation in a sustainable way.

- **Hydropower:** This is the largest source of renewable energy today and will continue to be a major contributor to grid decarbonization. Approaches include run-of-the-river and reservoir hydropower. Certifications such as those from the Low Impact Hydropower Institute can provide science-based criteria on environmental impact. One reason for excluding this asset type is a relative lack of dispatch data across global grids, as well as significant uncertainty in future forecasts.

- **Demand response:** Demand flexibility is critical for reducing emissions and helping to meet 24/7 CFE matching goals more cost-effectively.[54] While the optimization modeling results in this paper don't explicitly include demand response, we are actively working to expand our demand response capabilities through our carbon-aware computing platform.

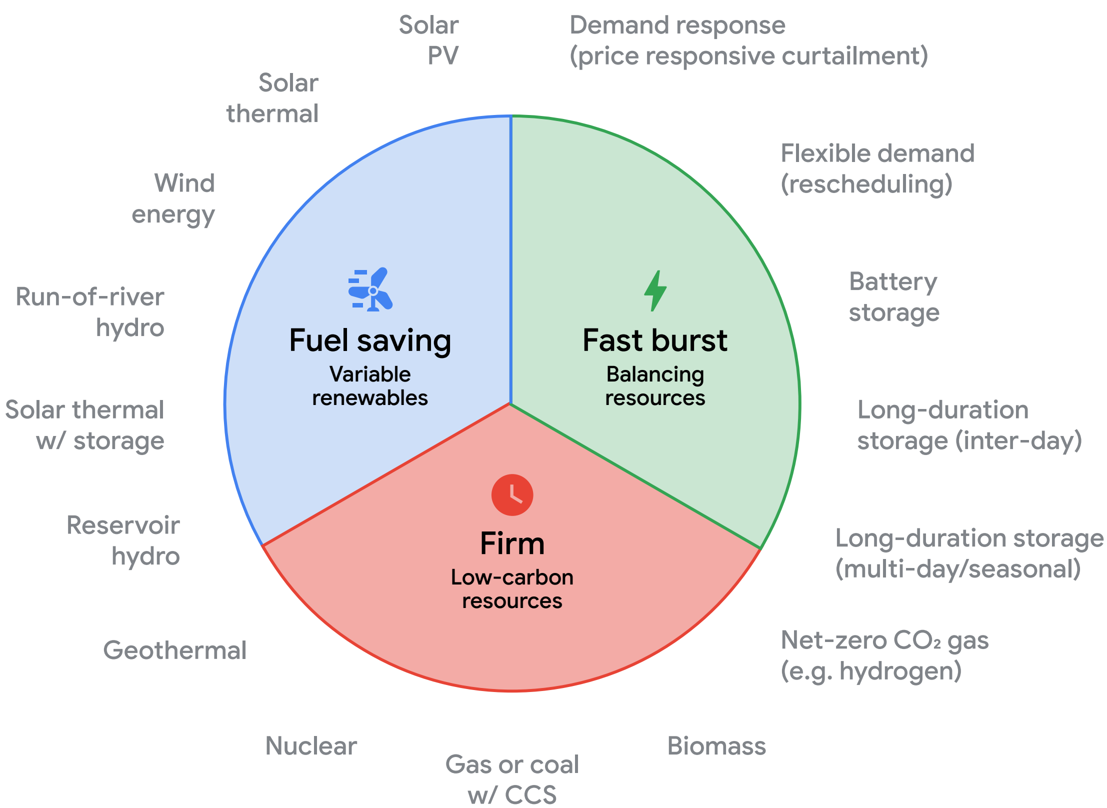
- **Energy Efficiency:** Energy efficiency remains a critically important resource for decarbonization. Google operates some of the most energy-efficient data centers in the world and continues to invest in this area.

Appendix B: A Complete Clean Technology Portfolio

Sepulveda, Jenkins, et al. (2018) introduced a taxonomy (reproduced below) that divides low-carbon electricity technologies into three subcategories and describes how these technologies play different and complementary roles in decarbonized electricity systems.[55]

A key finding of this research is that diverse technology portfolios that include different types of technologies (variable renewables, firm low-carbon technologies, and balancing resources) are needed to achieve deep decarbonization at the least cost.

The taxonomy they use is different from that used in our paper but helps to clarify the role that each technology plays in the system. The “clean peakers” discussed in our paper are generally a subset of “fast burst” resources in the taxonomy below, while the others discussed in this paper fall into the category of “firm low-carbon resources.” The distinction between these two classes of resources is sometimes blurred, as optimal dispatch profiles can be determined both by a technology's economic profile and by the needs of the system.



Endnotes

Click the source number to return to the relevant page in this paper.

1. Hannah Ritchie, Max Roser, and Pablo Rosado, "CO_2 and Greenhouse Gas Emissions" (2020). Published online at OurWorldInData.org.

2. International Energy Agency, Net Zero by 2050: a Roadmap for the Global Energy Sector (2021).

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4. International Energy Agency, Renewable Energy Market Update - June 2023.

5. Energy storage added a record 16 gigawatts. 35 gigawatt-hours in 2022, 68% more than in 2021. Bloomberg New Energy Finance, 1H 2023 Energy Storage Market Outlook (2023).

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7. Denholm et al., 100% Clean Electricity by 2035 Study, National Renewable Energy Laboratory, (2022).

8. Tong et al., Geophysical constraints on the reliability of solar and wind power worldwide, *Nature Communications*, (2021).

9. For more on how we are approaching this goal, see 24/7 by 2030: Realizing a Carbon-free Future (2020). For our detailed 24/7 CFE methodology, see 24/7 Carbon-free Energy: Methodology and Metrics (2021).

10. Q. Xu, A. Manocha, N. Patankar, J. Jenkins, System-level Impacts of 24/7 Carbon-free Electricity Procurement, Princeton University Zero-carbon Energy Systems Research and Optimization (ZERO) Laboratory (2021); I. Riepin and T. Brown, System-level impacts of 24/7 carbon-free electricity procurement in Europe, Technical University of Berlin (2022); International Energy Agency, Advancing Decarbonisation through Clean Electricity Procurement (2022).

11. For example, the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA) in the United States will invest hundreds of billions of dollars into clean energy, including the advanced clean electricity technologies discussed in this paper.

12. These include the Clean Energy Buyers' Association in the U.S., the Re-Source Platform in Europe, and the Asia Clean Energy Coalition.

13. Bloomberg New Energy Finance, Corporations Brush Aside Energy Crisis, Buy Record Clean Power (2023).

14. The IEA estimates that putting the global economy on the path to net-zero emissions by 2050 would require over 1,000 GW of new wind and solar to be deployed every year starting in 2030, a 400% increase over today's annual rates of deployment. Princeton University estimates a similar rate of increase for wind and solar deployment in the United States. See: International Energy Agency, Net Zero by 2050: a Roadmap for the Global Energy Sector (2021); E. Larson et al., Net-Zero America: Potential Pathways, Infrastructure, and Impacts (2021).

15. As an example, leading modeling of the U.S. electricity system finds that transmission capacity needs to expand to more than three times its current level to integrate renewable energy and serve increases in electricity demand. See: E. Larson, et al., Net-Zero America: Potential Pathways, Infrastructure, and Impacts (2021).

16. Sepulveda et al., The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation, *Joule* (2018); Baik et al., What is different about different net-zero carbon electricity systems? *Energy and Climate Change* (2021).

17. A recent study of California found that relying exclusively on VRE would triple the amount of transmission lines required vs. a system that includes firm clean power. See: Jane C.S. Long et al., "Clean Firm Energy is the Key to California's Clean Energy Future," Environmental Defense Fund (2021).

18. Baik et al., What is different about different net-zero carbon electricity systems? *Energy and Climate Change* (2021).

19. This is akin to the way many utilities conduct their generation planning through Integrated Resource Plans (IRPs), which are common in vertically integrated utility service territories in the United States.

20. While lithium-ion batteries continue to be installed at gradually higher durations, the Mature Technologies scenario assumes 4 hours which matches common durations installed today.

21. There are other mature CFE technologies, such as existing nuclear and hydro power assets, which are not included in our procurement modeling. Appendix A provides the rationale for this decision.

22. Our CFE percentage, otherwise known as a "CFE Score," measures the degree to which our electricity consumption on a given regional grid is matched with CFE on an hourly basis. This is calculated using both CFE under contract by Google as well as CFE coming from the overall grid mix. CFE coming from the overall grid mix is based on data obtained from a third party, Electricity Maps, and has not been assured. For more information, see our 2021 white paper, "24/7 Carbon-Free Energy: Methodologies and Metrics."

23. The costs for advanced technologies used in this modeling assume continued improvements and scale up of these technologies on the path to commercialization. Section three discusses various barriers that must be overcome for this to occur. Detailed cost assumptions are provided in Appendix A.

24. While important tools like energy efficiency and load flexibility are not explicitly modeled here, Google is actively working in these areas. One example is our carbon-aware computing platform, which can move shiftable computing tasks to times and places when electricity grids are cleanest.

25. Many corporate PPAs are structured such that the purchased renewable energy is resold into the market at the prevailing market price. As more VRE is deployed on a grid with similar production profiles, the market price will decline and the revenues earned by VRE will be reduced.

26. The "net spend," otherwise known as the cost premium, refers to the cost of procured carbon-free energy, less that of the baseline market energy forecast over the same period. The size of this premium differs by technology and grid.

27. International Energy Agency, Advancing Decarbonisation through Clean Electricity Procurement (2022).

28. Xu. et al. find that including advanced technologies reduced premiums for 90-100% CFE of between 20-60% in California and PJM in the United States. See: Q. Xu, A. Manocha, N. Patankar, J. Jenkins, System-level Impacts of 24/7 Carbon-free Electricity Procurement, Princeton University Zero-carbon Energy Systems Research and Optimization (ZERO) Laboratory (2021).

29. Riepin and Brown find that including advanced technologies reduces premiums for 90-100% CFE of between 40-90% in Ireland. See: I. Riepin and T. Brown, System-level impacts of 24/7 carbon-free electricity procurement in Europe, Technical University of Berlin (2022).

30. Sepulveda et. al., The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation (2018).

31. For more detail on next-generation geothermal technologies, see U.S. Department of Energy, GeoVision: Harnessing the Heat Beneath Our Feet (2019).

32. See for example: U.S. Government Accountability Office, "Carbon Capture and Storage: Actions Needed to Improve DOE Management of Demonstration Projects," (2021).

33. There were 4,460 GW of unabated fossil (coal, natural gas, and oil) power plants operational in 2021. International Energy Agency, World Energy Outlook 2022 (2022).

34. National Energy Technology Laboratory, "Cost And Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity," Appendix C (2022).

35. This is termed bioenergy with carbon capture and sequestration (BECCS), a technology pathway deemed important in deep decarbonization scenarios from IEA, the Intergovernmental Panel on Climate Change (IPCC), and others. See: IPCC Special Report on Climate Change on Land, Chapter 6 (2019).

36. Advanced reactors are defined in the United States Energy Act of 2020 (42 USC 16271).

37. International Energy Agency, Electricity Market Report 2023 (2023). Data for 2022.

38. Separate from nuclear fission technologies, nuclear fusion is another technology category that, while at an earlier development stage, has potential for significant deployment beyond 2030. Fusion features significant potential benefits in terms of relative fuel abundance, safety, and radwaste management.

39. Sepulveda, et al., The Design Space for Long-duration Energy Storage in Decarbonized Power Systems. Nature Energy (2021).

40. For instance, the U.S. Inflation Reduction Act provides significant tax subsidies for clean hydrogen production based on different carbon intensity thresholds. EU governments have also announced price support for renewable hydrogen. India, Japan, and many other countries are developing national hydrogen strategies to support the industry.

41. Due to its low round trip efficiency and high variable costs, hydrogen is dispatched at low capacity factors (often 10 to 30%) in our modeling. As a more practical matter, it is uneconomical to dispatch hydrogen power generation when electrolyzers connected to the same system are operating.

42. "Ultra-low carbon hydrogen" is defined by WBCSD as emissions below 1 kg/CO_2e/kgH_2.

43. These criteria have been set out in the European Union's Renewable Hydrogen Delegated Act, and electricity system modeling from Princeton University, TU Berlin, Evolved Energy Research, and others show that all three criteria are key to minimizing the emissions from grid-based H2 production.

44. I. Ocko and S. Hamburg, "Climate Consequences of Hydrogen Emissions," Atmospheric Chemistry and Physics (2022).

45. The U.S. Department of Energy segments LDES into inter-day (10-36 hours), multi-day/week (36-160+), and seasonal balancing (time shifting across seasons). See: U.S. Department of Energy, Pathways to Commercial Liftoff: Long-Duration Energy Storage (2023).

46. Sepulveda, et al., The Design Space for Long-duration Energy Storage in Decarbonized Power Systems. Nature Energy (2021).

47. There was over $70 billion of venture capital investment into the climate sector in 2022. Bloomberg New Energy Finance, "How the World is Spending $1.1 Trillion on Climate Technology," (2023).

48. Bloomberg New Energy Finance, "A Record $495 Billion Invested in Renewable Energy in 2022," (2023).

49. Karine Khatcherian, "Barriers to Timely Deployment of Climate Infrastructure," Prime Coalition (2022).

50. United States Department of Energy Pathways to Commercial Liftoff: Advanced Nuclear (2023).

51. Gregory F. Nemet, How Solar Energy Became Cheap: a Model for Low-Carbon Innovation (2019).

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53. Selected sources include NREL Annual Technology Baseline (ATB); reports from the IEA, U.S. Department of Energy, other U.S. National Laboratories, LDES Council, and others.

54. Recent research shows how demand flexibility can achieve 24/7 CFE procurement at lower cost, driving electricity grid decarbonization more cost effectively. See: Riepin and Brown, "The value of space-time load shifting flexibility for 24/7 CFE procurement," Technical University of Berlin (2023).

55. Sepulveda et al., The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation, *Joule* (2018).