# Increasing Electric Power System Flexibility

## THE ROLE OF INDUSTRIAL ELECTRIFICATION AND GREEN HYDROGEN PRODUCTION

A Report of the
Energy Systems Integration Group's
Flexibility Resources Task Force

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ESIG
ENERGY SYSTEMS INTEGRATION GROUP

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# Increasing Electric Power System Flexibility: The Role of Industrial Electrification and Green Hydrogen Production

**A Report of the Flexibility Resources Task Force of the Energy Systems Integration Group**


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# Evolving Reliability Needs for a Decarbonized Grid

As electric power systems continue to decarbonize and levels of renewable energy continue to rise, sources of system flexibility will become increasingly important. As flexibility from traditional resources may be reduced with the retirement of conventional coal-and natural gas–fired generation, other sources such as demand-side flexibility will become much more important. Concurrently, the increased electrification of the overall energy system will create new loads on the electric power system, which will have the potential to contribute to such system flexibility.

A key issue for electricity system operations and planning is to what extent the new loads may contribute to system flexibility: whether and how these loads can shift electrical energy demand from periods when renewable electricity is less abundant to periods when there is a large amount available.

## A Critical Need for New Sources of Flexibility

Many decarbonization studies demonstrate the increasing importance of this flexibility as clean energy, particularly variable renewables such as wind and solar, becomes a larger portion of the resource mix (EPRI, 2021; Larson et al., 2020; Williams et al., 2021). For example, hydrogen production and the electrification of industrial loads are often cited as important sources of flexibility as levels of renewables surpass 80 or 90 percent of total electricity (EPRI, 2021). At such high levels of renewables, the need to shift energy across time (and potentially space), as well as the expected retirement of existing sources of flexibility, means that electric power system flexibility from the typical sources today—conventional natural gas plants, batteries, interconnection with neighboring grids, and renewables themselves—may need to be supplemented with new sources.

The need for flexibility stems from two issues related to supply and demand balancing of electricity systems that are reliant on variable renewable electricity generation: oversupply of generation, and structural energy deficits due to the variability associated with renewable generation (EPRI, 2016). The first issue arises from the limited capacity factors of wind and solar. High electrical-energy penetration of naturally variable sources such as wind and solar photovoltaics could result in substantial *overcapacity* compared to the peak load of the electrical power system, which, in the absence of dedicated measures, would lead to negative net, or residual, load in

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many hours.[1] While the instantaneous excess power generation could always be curtailed, an alternative is to divert that electric power to sectors outside the classical electric grid system. This would involve using flexible electric loads to increase demand to maintain the supply/demand balance.

The second issue, energy deficits, can occur in systems where there are long periods with relatively little wind or solar power compared to system demand, due to prevailing weather conditions. (This is likely to be particularly important for wind energy, as demonstrated recently in the UK and EU region where wind was relatively low for a long period of time.) In such circumstances, resources that are not often used will need to be available to provide energy when called upon. The ability to shift demand from periods of energy deficits to periods with more renewables available could therefore be a significant source of flexibility. The need for this flexibility will be region-specific and depend on the particular mix of generation, transmission, and load on the electricity system.

The absolute quantity of flexible capacity (however defined) that is required to manage oversupply of renewable energy appears low, giving opportunity for flexibility via industrial electrification, including hydrogen production, to play an important role. Currently, the electrification of industrial loads is happening slowly, and hydrogen production is still relatively expensive. However, cost declines are predicted for both of these resources, similar to what has been achieved in recent years for wind, solar photovoltaics, and battery storage. In 2021, the U.S. Department of Energy, for example, set a goal of reducing the cost of electrolytic hydrogen by 80 percent to $1 per kilogram in one decade.[2]

## Services Provided by Industrial Electrification and Electrolytic Hydrogen Production to the Electricity System

This report lays out viable ways that industrial electrification and hydrogen production may play a role in providing flexibility in the future electric power system. Whereas most analysis in this space focuses on the overall energy system and aspects such as the cost reduction required to enable more industrial electrification and hydrogen, the focus here is on describing how these technologies may impact and provide services to the electric power system. The underlying assumption is a future where levels of electricity-generating renewables are high, at 70 percent annual energy penetration or higher, as this is the point at which the electrification of industrial processes and the economic production of hydrogen will both be needed and be ready to serve this need. The intent of this report is to discuss the electric power systems perspective for these new electrical loads. Building on the Energy Systems Integration Group's work on renewable integration over the past decades, this report lays out how very high levels of renewable energy could be supported by leveraging opportunities in the industrial sector.

The report first discusses sources of industrial electrification and the potential flexibility that could be derived from the resulting large electrical loads in energy-intensive industries (EIIs). It then examines the potential role of hydrogen production in providing flexibility to the future high-renewables system, with a focus on green hydrogen. The report concludes by summarizing high-level operations and planning issues for power systems and identifying key areas needing further work.

1 Net load, or residual load, are defined as the total load minus the instantaneous generation of solar photovoltaics and wind. "Net" and "residual" can be used synonymously.

2 See https://www.energy.gov/eere/fuelcells/hydrogen-shot.

# Industrial Electrification and Electric Power System Flexibility

EIIs are at the foundation of the broader economy and enable a vast amount of other industrial activity. They provide the basis for many chemicals used in industry, produce construction materials, support agriculture and paper industries, and far more. They link to all other economic sectors, are themselves extensively interlinked, and are deeply connected within the broader energy system (see Figure 1, p. 4). EIIs are often very carbon-intensive, and they can be harder to decarbonize than other sectors such as the electricity sector. One option for their decarbonization is to electrify these industrial loads and rely on clean electricity to power the loads. This is not simple, however. Any significant change in the provision of energy in these industries, their operation, and their cost structure will have profound and systemic ramifications across the broader economy (Lovins, 2021a; 2021b).

## Electricity Use in Industry Today

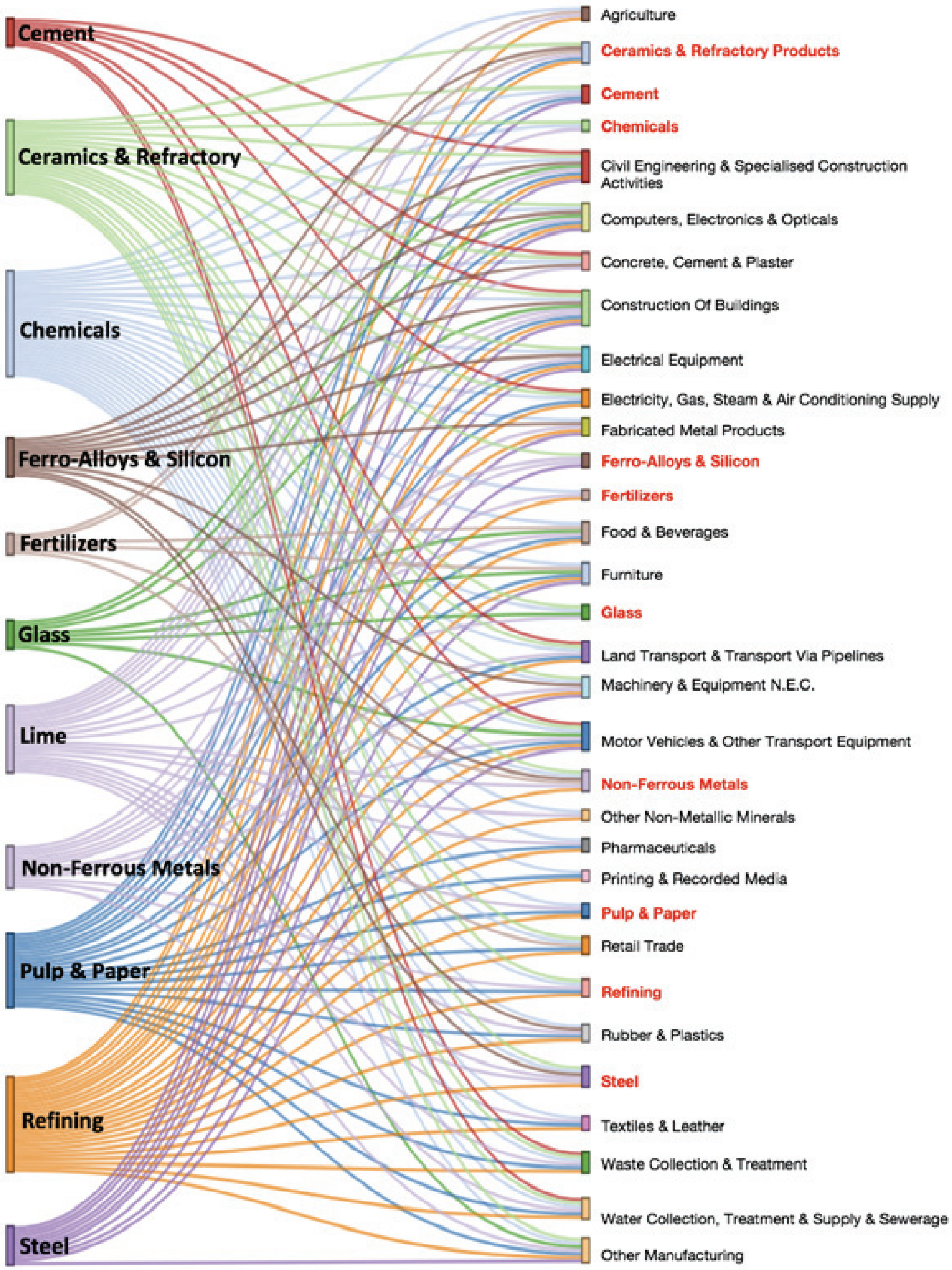
The share of electricity among all energy inputs in the industrial sector varies widely, with a general shift toward increased electricity use in the industrial sector expected in the near to medium term. The lowest share, at 14 percent, is in non-metallic minerals (mostly cement, glass, and ceramics industries), and the highest share of 65 percent is in non-ferrous metals, composed mostly of primary aluminum production that uses electrolysis to reduce aluminum from aluminum oxide. Electricity is mostly used for machine drives, to provide electrical control of industrial processes, and for some means of electric heating (including electric arc, infrared radiation, electron beam, and plasma heating). Some industrial electric technologies use electricity as an alternative to directly providing heat, for example, using mechanical work in mechanical vapor recompression heat pumps or separating materials using selectively permeable membranes rather than using heat. Other means of material separation use electric potential gradients (e.g., electrodialysis) or electrolysis (e.g., electrolytic refining of alumina and copper). The increasing demand for renewable energy technology will itself lead to a general shift toward higher electricity use in the industrial sector due to the increased production and refining of rare earth elements and potential increase in the recycling of metals.

## Pathways for Contribution of EIIs to Decarbonization

Currently, industry accounts for more than one-third of the global final energy use, making it an essential sector to decarbonize. However, EIIs, owing to their heterogeneity and the need for high-quality heat to transform raw materials into more refined materials, are particularly challenging to decarbonize. In contrast to the electric power sector, where low-carbon electricity is used by

FIGURE 1

## Connections Between Energy-Intensive Industries and the Rest of the Economy




Note: The red text refers to the EIIs discussed in this report.

Source: Wyns, Khandekar, and Robson (2018).

loads in exactly the same way as fossil fuel–based electricity, the concept of a baseline or "archetypal" industry facility is difficult to define. Facilities' electrical and non-electrical loads, operating procedures, and practices vary from location to location and have a significant time dependence regarding when they are used. In addition, many facilities within a given sector use multiple fuel sources and have multiple point sources of carbon dioxide ($CO_2$).

It is important to note that EIIs have already played an important role in emissions reductions. Between 1990 and 2015 in Europe, EIIs reduced their greenhouse gas emissions by 36 percent, representing approximately 28 percent of economy-wide reductions, despite the fact that EIIs were responsible for only 15 percent of total greenhouse gas emissions in the European Union in 2015. To date, EII emissions reductions have come about through a combination of improvements in energy efficiency, fuel switching, and plant closures or reduced output, largely as a result of the 2008 financial crisis.

There are many pathways to further emissions reductions, as shown in Table 1. In addition to further energy efficiency improvements, process integration, and the use of carbon capture, utilization, and storage technologies (Wei, McMillan, and de la Rue du Can, 2019), electrification has the broad potential to contribute across all sectors, through both heat and mechanical processes and through electrolysis for hydrogen production.

## Heat

A large proportion of industrial emissions arise from the provision of heat (or thermal power). Given the rapidly improving economics of renewable/low-carbon electrical power and energy storage, the electrification of EII heating needs is becoming more attractive as a means to decarbonize this sector. High to very high temperatures (above 500°C) account for over half of industrial heat demand, and very high temperatures (above 1000°C) account for 33 percent of demand. Electrification of heat demand can be applied across most basic materials industries, and it is a particularly promising approach for emissions mitigation in industries such as ceramics, glass, and paper. Low-temperature heat (defined here as lower than 300°C) can be provided relatively easily via electric boilers and electric arc, infrared, induction, dielectric, direct resistance, microwave, and electron beam heating. However, to economically achieve temperatures approaching

**TABLE 1**

Emissions Reduction Approaches for Various Energy-Intensive Industries

| | Electrification (Heat and Mechanical) | Electrification (Processes: Electrolysis/ Electro-chemistry Excluding $H_2$) | Hydrogen (Heat and/ or Process) | Carbon Capture and Utilization | Biomass (Heat and Feedstock)/ Biofuels | Carbon Capture and Storage | Other (Including Process Integration) |
|---|---|---|---|---|---|---|---|
| Steel | **xxx** | xx | xxx | xxx | x | xxx | Avoidance of inter-mediate process steps and recycling of process gases: xxx<br>Recycling high-quality steel: xxx |
| Chemicals and fertil-izers | xxx | xxx | xxx | xxx | xxx | xxx (in particular for am-monia and ethylene oxide) | Use of waste streams (chemical recycling): xxx |
| Cement Lime | xx (cement)<br>x (lime) | o (cement)<br>o (lime) | x (cement and lime) | xxx (cement and lime) | **xxx** (cement)<br>x (lime) | xxx (cement and lime) | Alternative binders (cement): xxx<br>Efficient use of cement in concrete by improving concrete mix design: xxx<br>Use of waste streams (cement): **xxx** |
| Refining | xx | o | xxx | xxx | xxx | xxx | Efficiency: **xxx** |
| Ceramics | xxx | o | xx | x | x | o | Efficiency: **xxx** |
| Paper | xx | o | o | o | **xxx** | o | Efficiency: **xxx** |
| Glass | xxx | o | x | o | xxx | o | Higher glass recycling: xx |
| Non-ferrous metals/ alloys | **xxx** | **xxx** | x | x | xxx | x | Efficiency: **xxx**<br>Recycling high quality non-ferrous: xxx<br>Inert anodes: xxx |

o = Limited or no significnat application foreseen
x = Possible application but not main route or wide-scale application
xx = Medium potential
xxx = High potential
**xxx** = Sector already applies technology on large scale (can be expanded in some cases)

Note: Even after decarbonizing heat for cement, reaction-based emissions remain.

Source: Wyns, Khandekar, and Robson (2018).

1,000°C, modifications of electric furnace technology are needed. It is technically possible to electrify high-temperature process heating using, for example, electric arc furnaces or electric calciners. To achieve temperatures beyond 1,000°C, as is required in the production of cement and glass, significant additional research, development, and demonstration is required.

Given the deeply integrated nature of these processes, any alteration to a particular element of a process will necessarily induce changes to other aspects. Electrification of the furnace therefore necessitates adjustments to other stages of production and will have capital cost implications. In some sectors, such as the refining, steel, chemicals, and cement sectors, the electrification of heat can be at best a partial solution and will likely have to be used in combination with other technologies to achieve full decarbonization.

## Industrial Processes

Process electrification is already quite widely applied in, for example, secondary steel, non-ferrous metals, ferro-alloys, and silicon production. The electrification of iron and steel production can take several possible routes and is an area of active interest for many in the industry (Edie, 2021). One route is to increase the circularity of the product flow in the economy by increasing recycling rates and the use of secondary steel, which is produced in electric arc furnaces. In general, steel retains a significant overall recycling rate. In 2014, this rate stood at 85 percent (Tata Steel, 2021); however, when demand for steel is high, this proportion drops significantly—in 2016 it was 35.5 percent—owing to a mismatch between demand for steel and availability of scrap (BIR, 2020). Looking beyond iron and steel, several other metals are produced through electrolysis, including aluminum, nickel, and zinc. The economic viability of electrolytic approaches to metal refining is, of course, a function of the cost and carbon intensity of electricity and the cost of electrolyzers (Allanore, 2014).

Another option for indirect decarbonization via electrification, as discussed in more detail in the next section, is electrolytic hydrogen. Hydrogen can play a key role in industrial decarbonization when the hydrogen is produced using zero-carbon electricity or from natural gas with carbon capture and storage. It can be used as an energy carrier, as industrial feedstock for products and fuels, or for long-duration energy storage.

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Key to continuing to decarbonize industries through increasing the electrification of industrial processes will be the progression of technologies to technology readiness levels (TRL) above 7 and the further decarbonization of the electricity grid.[3] Sufficient technological maturity is not expected until the 2030s, due to the need to demonstrate these technologies and mobilize capacity to deploy them, but by then they may provide a fruitful way to decarbonize the system. Economic incentives or technological breakthroughs may make these technologies relevant even sooner; however, 2030 is already well within the planning time frame for the electric power industry.

The move toward fuel-switching from natural gas to electricity will be driven by energy and environmental policies (EPRI, 2018); however, electrification benefits for industrial processing also include non-energy benefits such as product quality and yield; process time, controllability, and flexibility; and safety. For example, potential non-energy benefits in induction heating include faster start-up, enhanced process controllability and flexibility, reduced space required for fuel storage and handling, an improved working environment for workers due to the elimination of combustion emissions, and less waste heat.

3 The TRL scale runs from 1 through 9, with 1 being related to (fundamental) research and 9 referring to full technological maturity.

# Provision of Flexibility from Energy-Intensive Industries

The electrification of industry, a critical component of industrial decarbonization, provides opportunities for the sector to offer much-needed flexibility to electricity grids with high levels of variable renewable energy. This flexibility can be provided via low- or zero-carbon generation resources (including hydrogen, discussed below); grid-scale energy storage; or, as discussed here, demand response. Importantly, the absolute quantity of currently available flexible capacity that is required on a very-high-renewables grid appears to be low in comparison to the total installed capacities of supply and demand resources; hence, flexibility through industrial electrification could in theory play an important role.

As the electrification of the industrial sector proceeds, the increased demand for electricity is likely to require significant expansion in clean electricity generation technologies such as wind and solar photovoltaics. The variability of these resources, in turn, increases the need for flexible loads that can respond to the changing output of renewable generation on the grid. If highly electrified industries are incentivized to do so, some will be in a position to provide significant flexibility through flexible loads and the provision of energy storage that supports grid reliability and flexibility. Given the highly coupled way in which the EIIs and electricity system will co-evolve, understanding how EIIs can contribute to the flexibility and reliability of the power system is key.

## Increased Demand as a Result of Increased Electrification of Industry

The large-scale electrification of EIIs will, directly or indirectly, require significant amounts of electricity to

operate. In Europe, for example, EIIs are projected to become the largest electricity consumer by 2050, consuming an additional 3,000 to 4,400 TWh compared to 2016 levels (a 120 to 180 percent increase) (Eurostat, 2021). Many such loads would be expected to have a relatively constant demand, as the underlying industrial processes are designed to operate at steady state, at least in their current form.

In a study by the Electric Power Research Institute evaluating the impact of industrial electrification on the electricity grid, the scenario with the highest levels of electrification showed the electricity share of industry final energy demand increasing from 27 percent in the reference scenario to 45 percent in 2050 (EPRI, 2018), demonstrating that industrial electrification could provide opportunities for closer integration and optimization of the U.S. energy system. Another study looking at China found that maximizing electrification using commercially available technologies in industries including steel, food and beverages, glass, and pulp and paper could increase its industrial sector's share of electricity consumption in 2050 from about 30 percent under business-as-usual assumptions to nearly 40 percent (Khanna et al., 2017).

Completely electrifying the industrial sector would require a significant amount of new electricity generation capacity, even when electric technologies provide improved energy efficiency. One study examined a scenario in which electro-thermal technologies for heating and electrolysis for material separations replaced all energy requirements of eight EIIs in the European Union and estimated a four-fold increase in electricity demand by 2050 (Lechtenböhmer et al., 2016). It found that the replacement of petroleum-derived fuels and feedstocks with $H_2$, $CO_2$, and syngas would involve nearly 10 times more electricity by 2050. The carbon required to produce replacement hydrocarbons could either be captured $CO_2$ from power plants, captured from the $CO_2$/CO portion of syngas ($CO_2$/CO + $H_2$), or obtained from direct air capture.

Switching from fossil to non-fossil industrial feedstocks also greatly increases the electricity consumed. For example, one study analyzed the switching of feedstocks for the production of common industrial chemicals from fossil to non-fossil feedstocks using electrolytic technologies, and estimated that to transition the entire European Union production of ethylene and propylene to electrolytic processes by 2050 would require roughly the equivalent of one-fourth of the European Union's electricity production in 2012 (Palm, Nilsson, and Åhman, 2016). Similarly, transitioning all plastics in the European Union to electrolytic production would increase electricity consumption by 1400 TWh to 1900 TWh (Palm, Nilsson, and Åhman, 2016), compared to the current consumption of about 2,800 TWh (across the European Union, including the United Kingdom). The electrification of other industries would likely show similar levels of increased demand. These are significant additional demands that provide an opportunity for new sources of energy and flexibility while also requiring significant build-out of generation, transmission, and distribution in a relatively short amount of time.

**One important way in which the EIIs can provide flexibility to the electricity grid is through demand-side management via energy efficiency and demand response.**

## Provision of Demand Response via Industrial Loads

One important way in which the EIIs can provide flexibility to the electricity grid is through demand-side management via energy efficiency and demand response. The task of the system operator (or other entity, such as a utility) is to set up programs with appropriate financial incentives such that electricity consumers are encouraged to participate, reducing their load when needed to help balance supply and demand on the grid. The system operator must consider consumers' perspectives in this picture of system needs, as their availability to provide flexibility is an important factor, and their incentives to participate are key drivers of the availability of demand-side management.

The two main types of demand response, as defined from a utility perspective, are dispatchable (controlled by the utility to reduce costs or provide grid services) and price responsive (and therefore not directly dispatched by utility/ISO). Various programs are used under each; for example, direct load control or ancillary services are examples of dispatchable demand response, while time-of-use or critical peak pricing are examples of price-based demand response. Both types are applicable to industrial situations, and, depending on the design of programs, certain loads may contribute to both. Because electric power consumption in the EIIs is very high, this has the potential to motivate and facilitate EIIs' participation in demand-side management programs, providing either type of response.

**In most cases, advanced metering infrastructure is already in place; therefore, the capital investment required to implement demand-side management in industry is close to zero. In addition, industrial processes operate in isolated environments in which human comfort is usually not an issue.**

This may be particularly true for certain types of demand response, where the use of the demand-response resource lines up well with the end use, for example, requiring flexibility during periods of the day or the year where the end use may have such flexibility. Aluminum production, for example, has an energy intensity of 71 gigajoules (GJ) per ton, and a typical aluminum plant produces hundreds of tons of aluminum on a daily basis. Such loads providing ancillary services or responding to critical peak pricing to avoid very high prices could provide significant potential revenue or cost savings. While there may be limits in terms of how often such resources could be called upon, facilities could leverage the relative difference in time for thermal diffusion compared to power system needs—for example, by pulsing or interrupting aluminum smelter electricity demand. The impact on the overall process can be minimized due to the high thermal mass of molten aluminum, while providing valuable flexibility to the grid.

In most cases, advanced metering infrastructure is already in place; therefore, the capital investment required to implement demand-side management in industry is close to zero. In addition, in contrast to the residential and commercial sectors, industrial processes operate in isolated environments in which human comfort is usually not an issue. However, industrial processes are often highly complex and subject to strict safety and efficiency requirements. Start-up and shut down can be very involved, and the underlying process chemistry may be delicate, allowing limited room for process variation. In industrial demand-side management, it is therefore crucial to carefully evaluate and design the flexibility of each process in order to avoid detrimental disruptions caused by sudden changes in the plant operation.

## Provision of Grid Services

Throughout the world, ancillary services, sometimes called grid services, have been defined to support reliable system operations.[4] EIIs have the ability to provide a variety of ancillary services, particularly those related to supply-demand balancing, as discussed below. Frequency regulation services can be provided by variable-frequency drives, induction furnaces, and electrolysis processes, and event-based reserves can be provided by electrolysis, electric arc furnaces, mechanical pulp production, and cement milling (Dorreen et al., 2017; Shoreh et al., 2016). Most of these services come from resources (supply or demand side) having capability to respond when called upon. They can be further divided into event-based and non-event-based:

- **Event-based reserves** are held to respond to large events such as the loss of generation. Typically, reserves are held that can respond across different time frames, from quick response directly after an event (fast frequency response, primary frequency response) to slower-responding reserve that replaces the quick response (e.g., non-spinning reserves, tertiary reserves). The size of these reserves is based on the size of the largest generation resource as well as other factors such as the inertia on the system, which acts to arrest the rate of change of frequency after an event.

4 The definitions of ancillary services and grid services vary from place to place, but in general they consist of a variety of different types of support to maintain system reliability. Those most relevant to this discussion are related to active power balancing services.

- **Non-event-based** reserves are used to maintain continuous supply-demand balance in response to smaller changes in load and generation output. These types of reserves include automatic generation control, frequency regulation, manual control of spinning or non-spinning reserves, and balancing reserves that might be held to manage intra-hour variability and uncertainty.

The provision of these grid services by industrial facilities has been demonstrated for certain types of services, particularly for the event-based reserves. However, facilities' ability to provide grid services depends on factors related to both the demand itself as well as the electric power system needs. The ability of industry to implement and benefit from a more dynamic or "smart" interaction with the grid and provide grid services is determined by such factors as the specific production processes used, their tolerance for variable process conditions, and the degree to which they may be interruptible while maintaining their electricity usage within desired limits. It should also be noted that many of the markets for grid services, while expected to grow over time as renewables are added, are still likely to be relatively small, with requirements often a small percentage of total load. While this may limit the attractiveness of market participation to all but the most suitable loads, it is also true that the total requirement for grid services is relatively small, so even a small quantity of responsive industrial load may provide significant value to the grid.

## Barriers to the Provision of Flexibility by Newly Electrified Loads

In general, barriers to industry electrification are similar to those associated with the adoption of energy efficiency measures, including equipment costs, low (or relatively lower) fuel costs in the absence of the new measure, and uncertainty in investments (Deason et al., 2018). However, increasingly stringent decarbonization targets, as well as the prevalence of variable renewable resources that could provide low-cost electric energy during certain times of the year, may drive overall electrification in industry as well as the increasing use of flexible loads. It should be noted that some industries can more easily adapt to electrification and provision of flexibility than others, with more work needed to arrive at more comprehensive capabilities.

The electrification of EIIs will add a substantial demand to the existing power systems that, in its current form, is typically constant (varying only slightly over the year) and has deliberately infrequent start-up and shut-down cycles for scheduled maintenance. In order for industrial loads to take advantage of low-cost power and/or demand charges, or provide flexibility, equipment usage may need to decline or additional investment in energy storage may be required to maintain current run times. More flexible modes of operation will potentially require modified equipment designs and increased inventory supply to ensure the demand for product can still be met.

Lastly, even if all of the above barriers are overcome in a given region, a critical additional barrier for regional industry decarbonization is the competitive disadvantage of moving to potentially higher-cost production methods for materials or products which are served by a global market. Thus, additional support and policies for this transition may be needed to ensure domestic competitiveness, such as consideration of carbon in importing practices. This is being considered in many regions as decarbonization policies are set (EC, n.d.).

# Role of Hydrogen Production in Grid Decarbonization and Flexibility

Another important way in which the industrial sector can contribute to both the flexibility of the electricity grid and the decarbonization of the sector—as well as the decarbonization of other sectors—is through the production of hydrogen. Hydrogen can be manufactured or extracted from hydrogen-rich materials such as coal, natural gas, biomass, or water. Currently, the primary means of manufacturing hydrogen is to strip it from methane found in natural gas via steam methane reforming. However, where exclusively renewable power is used, electrolytic $H_2$ production can have a substantially lower carbon footprint than blue hydrogen (Mac Dowell et al., 2021).

Hydrogen has received significant attention in recent years, with numerous studies and reviews examining the potential role in the decarbonization of the electric power system of electrolyzers (Buttler and Spliethoff, 2018; Schmidt et al., 2017), fuel cells (Staffell et al., 2019), and hydrogen gas turbines (ETN Global, 2020), as well as combinations thereof (IEA, 2019). As economies aim for full decarbonization by mid-century, and as costs continue to decline due to increased research and development around hydrogen technologies (EC, 2020b), these technologies are likely to play an increasingly relevant role in power and energy systems planning.

Power systems planning and operations will need to incorporate a thorough understanding of the capabilities and contributions of these resources. In particular, hydrogen may very likely be the key to reaching a 100 percent net-zero electric power supply. Electrolytic hydrogen has the potential to electrify various end uses and provide grid flexibility as the power system decarbonizes, with its specific roles in different countries and regions depending on existing assets in the electric power system, meteorological conditions, market structures and government policies (mandates, subsidies, emission caps, or $CO_2$ levies), and levels of potential hydrogen demand in heavy industry and transportation. It is therefore important to consider where and how a hydrogen economy would develop and what role it could play in the electric power sector of a particular market (Wang et al., 2018).

Electrolytic hydrogen produced from renewable electricity, or "green" hydrogen, has recently seen significant research and demonstration (see H2 Bulletin (2021) for definitions of the colors associated with hydrogen fuel). Electrolyzers have begun to be installed in the 10s to 100s MW range (Shell, 2021). Further research and development is expected to improve the performance and reduce the cost of such resources. Europe (EC, 2020a), the United States (HFCTO, n.d.), Australia (ADISER, 2021), China, Japan, and South Korea, among others, have developed significant research programs and roadmaps, while private companies, particularly large energy companies (Brooks, 2021), are also demonstrating hydrogen production technologies at increasing scale.

## Potential Applications of Hydrogen in the Power System

Hydrogen can play important roles in the power system on both the demand and supply side. On the demand side, its production can be a flexible load that aids in balancing the grid; low-carbon electricity can be used to power electrolyzers, whether dedicated to a specific renewable plant or as part of the overall power system. Hydrogen can provide a significant amount of demand flexibility if the systems used to produce hydrogen are designed such that they can respond to power system signals such as market pricing signals, power system events, or renewable curtailment. Demand can be turned up or down to produce hydrogen when costs or emissions are low. This hydrogen can then be utilized for other end uses or stored for later use. Flexibility in this context can come from provision of grid services over minutes or hours, or from shifting energy across days or weeks. Hydrogen can be used in industrial applications (including heating) to reduce the electrical load during periods of low power production by renewables. This use of hydrogen avoids the roundtrip efficiency loss in converting hydrogen back into electricity.

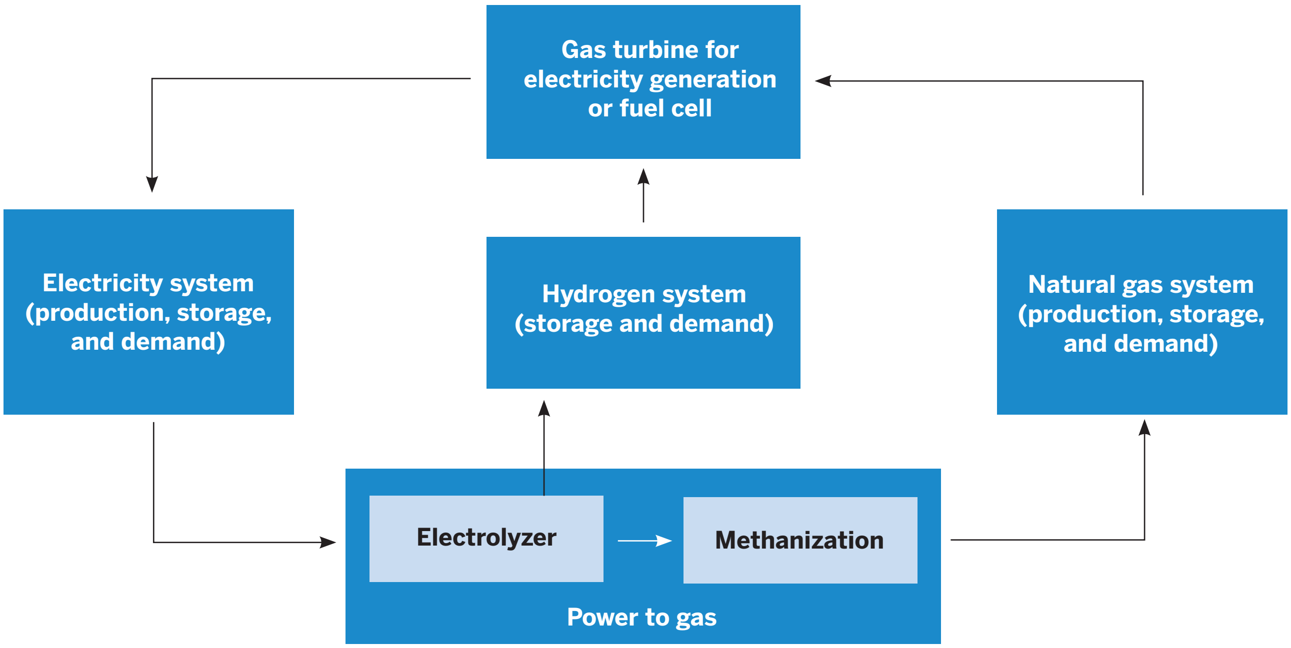
In addition to the use of hydrogen electrolyzers as flexible loads, which are expected to be developed and implemented first to help manage times of overgeneration, there may eventually be a need for electric power–generating technologies such as fuel cells or gas turbines fueled by pure hydrogen or hydrogen-derived fuels. Hydrogen will be particularly important to help manage the structural deficits that are likely to occur when levels of variable renewable energy on the grid become very high. Such hydrogen resources could provide energy, capacity, and grid services to the system. These may contribute substantially on the supply side of a fully decarbonized electric power system to cover periods with very little wind or sunshine, whereby hydrogen would provide long-term or seasonal storage for the electricity grid (see, for example, Denholm et al. (2021), Strbac (2020), Blanco and Faaij (2018), Blanco et al. (2018a), and Blanco et al. (2018b), among others). Indeed, in several regions worldwide there are sometimes periods of up to two or three weeks during which there is hardly any wind or sunshine. For example, in northwestern Europe, there are several historic examples of such "cold spells" in winter. Hydrogen fuel cells or gas turbines powered by stored hydrogen could be used to serve load during such long-duration shortfalls in renewable generation. Fuel cells have high capital costs, but progress in reducing electrolyzer costs should also have some spillover effects in improving fuel cell costs.

While most studies show a limited use of hydrogen-based fuels for electricity production, these fuels may still play an important role in the ultimate decarbonization of the electricity system and energy systems overall. For example, the International Energy Agency's net-zero-by-2050 scenarios show less than 5 percent of total global electricity supply coming from hydrogen by 2050 (IEA, 2021). While this is a relatively small number for the global supply, some regions will be more reliant on hydrogen than others to fully decarbonize. Additionally, although they are a small percentage of total energy use, such resources may provide much-needed capacity and flexibility to the system during periods when other carbon-free resources are not available, analogous to gas peakers today.

Figure 2 (p. 14) depicts a power-to-gas system in which hydrogen electrolysis produces hydrogen and/or synthetic methane, which are then utilized either for end uses (one-way coupling to the hydrogen or gas system) or for grid flexibility by generating electricity during periods when demand is high or production from renewables is low (two-way coupling through gas turbines or fuel cells). Synthetic methane produced by electrolyzers that are powered by low-carbon electricity can be injected into the gas network and used to power gas plants, or hydrogen can be used in fuel cells. The advantage of the synthetic methane route is that no new large infrastructure (such as networks or storage) is needed, since all existing natural gas infrastructure could be used, though in some situations the fuel cell route may still make more sense.

FIGURE 2

## The Main Elements of a Power-to-Gas System




Notes: The colors have no relationship to the conventional colors typically assigned to hydrogen. This figure is simplified to provide general context and as such misses some more detailed aspects of the system, including $CO_2$ streams to and from the gas system and steam methane reformers, and other technologies that are likely to accompany these systems such as carbon capture, utilization, and storage and direct air capture. While important in the overall context, they are less relevant to the interactions between green hydrogen, the electric power system, and the gas system that is the focus of this report. See Belderbos (2019) for a more detailed example of the full interactions.

Source: Energy Systems Integration Group.

The premise is that in the long run, conventional natural gas would disappear from the picture, and synthetic methane would fill the original natural gas network (merging with the hydrogen network). The electric power–generating devices can also be used for balancing and even provide ancillary services. For a decarbonized grid, this may mean that only the electric and hydrogen systems would remain, with all of the gas system being hydrogen-fueled.

## Considerations for Obtaining Flexibility from Green Hydrogen in a Future High-Renewables Grid

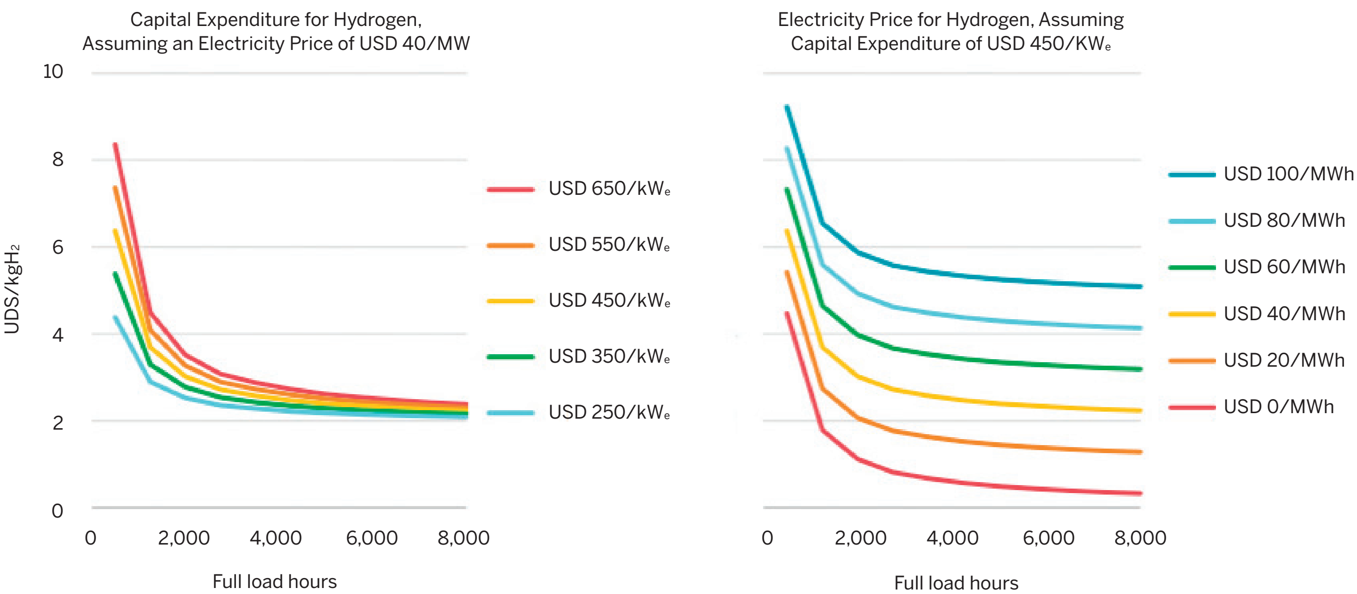
The ability of hydrogen to support power system decarbonization and provide flexibility to a system with high levels of renewables will depend on how the system evolves, with various factors including costs, specific uses of hydrogen, and the development of different technologies all playing a role.

### Effect of Load Hours on Financial/Economic Viability of Hydrogen Production

The feasibility of using hydrogen to support the power system will depend on multiple factors, including the relationship between the cost of electricity, the cost of electrolyzers (capital cost), and the capacity factor of the electrolyzer (or availability of curtailed electricity) (see Figure 3, p. 15). When electrolyzers are operating for more hours of the year (toward the right in both graphs), electricity costs are more important than capital costs, whereas at lower usage (toward the left in the graphs), both capital and electricity costs are important. Thus, as operating hours go up, the impact of capital costs on the cost of hydrogen goes down (Mazloum, 2020).

FIGURE 3

## Relationship Between Costs of Hydrogen, Costs of Electricity, and Full Load Hours




**In the left figure, as full load hours increase, the electricity price declines.**

Note: CAPEX = capital expenditure

Source: International Energy Agency (2019), The Future of Hydrogen: Seizing Today's Opportunities. 

While the specific numbers used in Figure 3 are likely to vary, the trend shows how important the number of hours at full load will be to determining the costs of hydrogen. Ideally, one would be using a hydrogen electrolyzer more than 25 percent of the time; if powered only by otherwise curtailed (surplus) renewables, that is a significant amount of time for curtailment to be taking place. An implicit issue in using electrolyzers to reduce curtailment of renewables is that the cost savings from low-cost electricity might be offset by the higher capital expenditure–related charges associated with lower equipment utilization. This again points to hydrogen as a potential source of flexibility mainly for very high renewable cases, unless electrolyzers' capacity factors are sufficiently high and the costs of renewables sufficiently low to achieve economic production under lower levels of renewables. Additionally, more hydrogen storage may be needed, and the costs of hydrogen storage can be significant, particularly if suitable geological conditions are not present nearby.

Given current decarbonization targets, electrolyzers may become more prevalent in the 2030s and 2040s to support renewable resources. It is likely more promising for hydrogen production to first be used to support decarbonization of industrial sectors as a feedstock for certain industries (e.g., fertilizers) or as a fuel for certain processes (e.g., treating metals), particularly compared to two-way coupling, as discussed in the next section.

### Relative Costs of One- and Two-Way Coupling

Conceptually, a two-way coupling is appealing in which water electrolysis is used to generate hydrogen during periods of peak renewable generation, and hydrogen-derived power (via fuel cells or gas turbines) is contributed to the grid during periods of low generation (as seen in Figure 2). However, while this may represent the optimal, long-term role of hydrogen in supporting grid flexibility, there are two reasons to believe that the path to this end state may evolve in an uneven manner and take time.

### Unidirectional Versus Bidirectional Hydrogen Use

First, cost structures and the expected changes in the structure for each direction are not the same. The capital costs of electrolyzer systems and fuel cell systems are currently high, but the potential for cost reductions is uneven. Specifically, reductions in fuel cell costs will lag behind reductions in electrolyzer costs, due to lower investment levels observed today. In a bidirectional energy storage system, the fuel cell contribution to the cost roll-up accounts for about 40 percent of the total capital expenditure of a current two-way system (Mongird et al., 2020), but would grow to 60 percent of the total capital expenditure due to smaller expected levels of improvement in costs for fuel cells over electrolyzers. Fuel cells' cost reduction is expected to be around 50 percent; in contrast, a unidirectional system that only withdraws electricity from the grid during peak production periods for use in hydrogen production via electrolyzers could see cost reductions of 70 percent (although this comparison ignores some of the downstream integration costs for the use of unidirectional hydrogen production).

Second, the value of hydrogen in the energy system extends beyond its ability to store electrical energy, as hydrogen can be used for transportation (heavy duty as well as light duty), industrial decarbonization, and, in some cases, residential heating, sectors that can be challenging to decarbonize. As such, green hydrogen may provide more value to a decarbonized energy system if used in one or more of those sectors.

The use of hydrogen to provide flexibility does not immediately have to be either unidirectional or bidirectional. A dynamic arrangement could exist in which pockets of unidirectional flexibility develop as separate localized operations that coordinate via market signals, with electrolysis during peak production (to reduce curtailment of renewables) and system-level demand response options. This might provide a more achievable path toward the use of hydrogen for flexibility services.

### Appropriately Located Production of Hydrogen-Derived Fuels, with Transport to Load Centers

While hydrogen-derived fuels may eventually be needed worldwide in many regions with insufficient renewable resources to complete the future decarbonization picture, there is no need to produce these fuels near where they are needed. For example, a system with global market structures that enable cross-border trade by internalizing external costs consistently would support renewables-based production of (green) hydrogen in high-insolation and high-wind places. Locating hydrogen production in this way would mean more hours of use for electrolyzers and lower per-kW cost as described above. Promising production regions would therefore include the Middle East and North Africa region, Australia, Central and South America, and parts of North America, China, and India (IEA, 2021; Frontier Economics, 2018; Agora Energiewende, 2020).

Higher-density hydrogen-derived liquid fuels would then be transported by ship or pipeline to load centers. For many countries, import of hydrogen or hydrogen-derived fuels will become the final puzzle piece for achieving decarbonization. This may involve the use of existing gas networks or the development of new hydrogen transmission systems, as envisioned by the European Network of Transmission System Operators for Gas (ENTSO-G) (Jens et al., 2021). As an example, there are currently 1,600 miles of dedicated hydrogen pipelines in the United States—such infrastructure would need to be significantly expanded to enable a wider use of hydrogen, but is a good starting point. In comparison, the United States has over 320,000 circuit miles of gas transmission.

In some cases, high-insolation or high-wind regions may commonly experience water scarcity or have only salt water available. For example, ensuring local water availability for hydrogen production requires advance consideration in desert-like regions, while feeding electrolyzers with seawater (in the case of offshore wind farms) requires extra measures and causes some (albeit small) efficiency loss (IRENA, 2020). It may therefore be necessary to first transport the renewables-generated electric power via high-voltage direct current (HVDC) transmission lines to distant regions where the electrolyzers (and perhaps other further processing technologies) are installed. These transmission lines may be simply dedicated lines or could be part of the overall electricity grid; this distinction is important for the price formation of the input electricity to the electrolyzers and for the role that electrolyzers can play as a flexibility tool for the grid.

### Implications for Market Outcomes

One aspect to note when it comes to the price of electricity is that electrolyzers would increase the load during low-priced periods, and thus mitigate some of the challenges related to the merit order effect of renewables. During periods when high renewable generation results in very low or even negative prices, a predictable increase in load to power electrolyzers would provide additional revenue certainty, which may help the development of both renewable resources themselves and potentially other flexibility resources. At the same time, market designs will continue to evolve, with capacity and flexibility potentially being a large part of the overall revenues for electricity sector participants. Thus, all told, the implications of hydrogen for the market remain hard to determine at this stage.

## Provision of Grid Services

One key topic from an energy systems integration perspective is whether the electrolyzers expected to be deployed—whether to provide hydrogen to other energy sectors or to shift energy during times of high renewable production and charge long-duration storage—can provide grid services. The specific characteristics of different technology types are important considerations when assessing how hydrogen may provide services such as frequency regulation or spinning reserves. While the potential for electrolyzers to provide grid services will be present only in certain locations, since the bulk of electrolyzer investments are expected to occur in meteorologically favorable regions, electrolyzer use in those locations will hold substantial potential for grid support.[5] In addition, in many regions lithium ion batteries are expected to have even more substantial capacities (in terms of overall summed-up nominal power capacities), and these batteries will also participate in ancillary services, leading to competition for provision of services. Therefore, it will be important to understand electrolyzers' capabilities, how they can substitute or complement batteries and other providers of grid services, and how they will be used to provide flexibility in other ways such as seasonal shifting of energy.

### Electrolyzer Characteristics and Configurations

For provision of grid services, the most important factors are the electrolyzer's speed of response (whether it can provide frequency response or provides slower-acting balancing services), the notification time required (whether it can respond immediately or needs to be notified in advance), and whether it is able to continuously respond to small changes or has a step response after an event (thus whether it can provide event-based or non-event-based reserves). After hydrogen technologies are characterized in such a manner, they can then be classified for the different types of reserves used across the world. Rather than catalog each reserve type here, we will identify electrolyzer capabilities and discuss generally how these may be used to support the reliability of a high-renewables grid.

In regions where large amounts of installed electrolyzer capacities may be present in the future, four main configurations are possible, depending on whether the electrolyzers are connected to an electricity grid and whether the hydrogen side is connected to a hydrogen grid.[6] Regarding the hydrogen side, in order to allow the electrolyzer to provide system services without compromising the end use needs for hydrogen, a temporal and flexible hydrogen storage buffer may be needed, to be sized according to the end use of hydrogen and its load profile.

Several types of electrolyzers are under development, having different characteristics and capabilities which affect their suitability for providing different types of grid services. The most mature are of the alkaline type, although in the future, polymer electrolyte membrane (PEM) electrolyzers, though currently somewhat less mature, are expected to make more progress (IRENA,

5 A few aspects of electrolyzer specifications, as currently given, complicate an analysis of their potential to provide grid services. There is currently no standard industrial definition of the rated or nominal capacity of an electrolyzer unit or of what precisely is meant by the overload capacity; these characteristics are solely defined by the vendors. Investment cost is usually expressed in currency per unit electrical power input (kWe), meaning that the overall capital cost is obtained by multiplying the cost of the equipment by the nominal (input) electrical power. However, it is not always clear whether this cost only applies to the electrolyzer cell stack or also includes the auxiliary equipment of the balance of system or balance of plant. In fact, even the concept of electrolyzer "unit" is ambiguous. The same is true for the efficiencies cited, as it is often unclear whether quoted efficiencies apply to only the stack or the whole system (Belderbos, 2019).

6 As an additional configuration, units connected (or disconnected) under "normal" circumstances may perhaps be automatically disconnected (or connected) in emergency situations.

2020). Solid oxide electrolyzer cells (SOECs), which operate at very high temperatures and therefore require more energy, are still in the research phase, but may enter commercial operation over the next 10 to 20 years. PEM electrolyzers seem to have the lowest efficiencies of the three types (although some sources indicate similar ranges for alkaline and PEM electrolyzers), while the potential electrical efficiency of the SOECs could be in the range of 80 to 90 percent. Selected characteristics are summarized in Table 2 (p. 19).

The cost trajectories and potential for cost reductions associated with these different technologies are also relevant. Large-scale adoption of PEM fuel cells in vehicles for transportation might spur cost reductions in PEM electrolyzers. Similarly, breakthroughs in solid oxide fuel cells might result in cross-over improvements in SOEC costs, especially if they are related to manufacturing aspects of high-temperature ceramic components. Conversely, material competition could come into play. For example, PEM fuel cells in transportation could compete with PEM electrolyzers for platinum.

**Load Range**

The ability of different electrolyzers to provide system balancing and related grid services depends on their load range—the range over which load can vary as percentage of maximum load. Alkaline electrolyzers can operate in a range of 10 to 110 percent of nominal load, and SOECs operate in a range of 20 to 100 percent. PEM electrolyzers can cover the broadest operating range, from zero to 160 percent, or from no load to overload by 60 percent (for limited amounts of time). Clearly, such overload is only possible if the balance of system (or balance of plant) equipment, especially the power electronics, is also designed for such overload. This is a very strong point of PEM electrolyzers since, for system stability services (e.g., regulation and contingency reserve) and when running at nominal capacity, they can react both ways: they are able to virtually inject power into the electricity system by reducing load or shutting down, and can increase demand by increasing their operation into the overload range.

TABLE 2

## Technical and Economic Parameters for Different Types of Electrolyzers under Development

| | Alkaline Electrolyzer | | | PEM Electrolyzer | | | SOEC Electrolyzer | | |
|---|---|---|---|---|---|---|---|---|---|
| | Today | 2030 | Long Term | Today | 2030 | Long Term | Today | 2030 | Long Term |
| Electrical efficiency (%, LHV) | 63–70 | 65–71 | 70–80 | 56–60 | 63–68 | 67–74 | 74–81 | 77–84 | 77–90 |
| Operating pressure (bar) | 1–30 | | | 30–80 | | | 1 | | |
| Operating temperature (°C) | 60–80 | | | 50–80 | | | 650–1,000 | | |
| Stack lifetime (operating hours) | 60,000–90,000 | 90,000–100,000 | 100,000–150,000 | 30,000–90,000 | 60,000–90,000 | 100,00–150,000 | 10,000–30,000 | 40,000–60,000 | 75,000–100,000 |
| Load range (%, relative to nominal load) | 10–110 | | | 0–160 | | | 20–100 | | |
| Plant footprint ($m^2/kW_e$) | 0.095 | | | 0.048 | | | | | |
| CAPEX (USD/$kW_e$) | 500–1,400 | 400–850 | 200–700 | 1,100–1,800 | 650–1,500 | 200–900 | 2,800–5,600 | 800–2,800 | 500–1,000 |

Note: LHV = lower heating value; $m^2/kW_e$ = square meter per kilowatt electrical. No projections made for future operating pressure and temperature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning, and balance of plant. CAPEX ranges reflect different system sizes and uncertainties in future estimates.

Source: International Energy Agency (2019), The Future of Hydrogen: Seizing Today's Opportunities. 

### Start-Up Times and Ramp Rates

Table 3 (p. 20) shows the start-up times and ramp rates of the three major types of electrolyzers, including the electrolyzer itself and the balance of system or balance of plant (Buttler and Spliethoff, 2018).

Electrolyzers can contribute to operating reserves (frequency regulation) as well as contingency reserves by rapidly reducing their load (i.e., voluntary load shedding) or increasing their load (for all types when operating a partial load, but also for PEMs when functioning at nominal load). A hydrogen buffer is important to ensure that hydrogen delivery to users is not interrupted during periods when hydrogen production is temporarily halted for the provision of load flexibility. In addition, the performance of an electrolyzer depends on the system architecture: whether the electrolyzer is grid-connected or in island mode, both on the electrical and the hydrogen sides. If it is in island mode, the use of the electrolyzer is based purely on the production source (on the electrical side) or demand (on the hydrogen side), and therefore operations are dictated purely by one resource or demand. If electrically coupled, an electrolyzer can provide flexibility in a broader fashion, with production based on overall system needs, whereas being coupled to a hydrogen grid allows for more variable operations where it is not the only way to meet demand.

Electrolyzers capable of a quick response can also potentially provide fast frequency response, possibly utilizing a hydrogen buffer so as to mitigate the transient effects on the hydrogen side (Ghazavi Dozein, Jalali, and Mancarella, 2021). In this way, grid-scale electrolyzers could support the more secure and resilient operation of low-carbon systems for both credible and extreme outages.

**TABLE 3**

## Start-Up Times and Ramp Rates of the Three Main Electrolyzer Types

| Electrolyzer Type | Cold Start | Start-Up from Warm/Hot Standby | Ramp Rate |
|---|---|---|---|
| Polymer electrolyte membrane (PEM) electrolyzer | 5 to 10 minutes | Seconds | Able to vary full operating range within seconds if at operation temperature |
| Alkaline electrolyzer | 1 to 2 hours | 1 to 5 minutes | Able to vary full operating range within seconds if at operation temperature |
| Solid oxide electrolyzer cells (SOEC) | 7 to 8 hours | Several minutes | Able to vary full operating range within seconds to several minutes |

Note: These time ranges pertain to the capabilities of the electrolyzer itself together with those of the balance of system or balance of plant.

Source: Energy Systems Integration Group.

Some electrolyzers could also be capable of providing ramping/active power control (Hovsapian, 2017).

### Ability to Operate in Reversible Mode

SOECs' ability to operate in "reversible" mode, hence also as fuel cells, opens up interesting possibilities for generating electric power and injecting it into an electricity grid if necessary.[7] The solid oxide fuel cell operational mode could also be fed with synthetic methane instead of hydrogen, since the high temperatures allow internal reforming of the methane into hydrogen (Guan et al., 2006; IEA, 2019; Mogensen et al., 2019), which would offer even more options for the system. PEM electrolyzers may also be able to operate in reversible mode as PEM fuel cells (Escobar-Yonoff et al., 2021; Paul and Andrews, 2017; Rabih et al., 2008). Possible configurations include reversible operation in a single unit (Paul and Andrews, 2017; Rabih et al., 2008) or a combination of two units, one as electrolyzer and the other as fuel cell, with an integrated balance of system or balance of plant (Escobar-Yonoff et al., 2021). This is an area where additional research and development is needed to identify the best approaches and move to deployment.

### Hydrogen-Fueled Gas Turbines

A final potential role for hydrogen in providing flexibility to the grid is its ability to provide balancing services. In regions with long-duration undesirable meteorological circumstances (such as long periods with little wind or sunshine, and/or water shortages in regions reliant on hydro power), the electric power system must have a minimal required amount of dispatchable capacity, which can include gas turbines—single open-cycle or combined-cycle gas turbines, fed with (synthetic) natural gas, biogas, or hydrogen. Current gas turbine technology can be fueled by hydrogen with relatively minor changes, and therefore possesses the classical flexibility for system-balancing assistance. Open-cycle gas turbines are typically very quick-starting but less efficient than the more efficient but slightly less flexible combined-cycle turbines (ETN Global, 2020).

**Current gas turbine technology can be fueled by hydrogen with relatively minor changes, and therefore possesses the classical flexibility for system-balancing assistance.**

7 When a electrolyzer operates in reversible mode, it can provide energy back to the grid instead of using energy to produce hydrogen.

# Advances Needed in System Planning, Operations, and Market Design

Decarbonizing the energy system will result in increased emphasis on both industrial electrification and the production of hydrogen in the electric power system, as well as interactions between them. More attention is needed on the decarbonization of industrial facilities (especially the most energy-intensive) and hydrogen production, as well as on their ability to provide flexibility and other grid services for a high-renewables grid. Industrial load types differ with respect to the ease with which they can be electrified, but in general there are significant opportunities for substantially higher electrification in this sector. As more renewable resources are deployed to meet decarbonization policy goals—thus increasing the need for flexibility in the system—these electrified loads will be in a position to provide substantial amounts of that flexibility.

In addition to providing demand-side flexibility to support renewable integration, the electrification of EIIs and the production of hydrogen can support decarbonization in other sectors, such as transportation and heating. These contributions can take the form of demand-shifting (timing hydrogen production and other industrial processes to coincide with periods of low demand); providing grid services such as fast frequency response, operating reserves, ramping, and other services, and providing other flexibility measures such as balancing supply and demand over hours, days, and weeks; or, in the case of hydrogen production, directly providing capacity and energy. Certain types of electrical loads, particularly when linked to seasonal storage, may be extremely beneficial to support grid operations as conventional sources of flexibility are retired. Electricity markets and system

operations are evolving to better reflect the need for and value of services, some of which may be able to be provided by the technologies discussed here. Questions remain as to the timing, type, and location of these industrial resources, but an understanding of key developments will allow system planners to account for them in planning studies.

**Electrified industrial loads and hydrogen production should also be considered in transmission planning activities, where there may be trade-offs and complementarities between these flexibility resources and the electricity transmission system.**

Importantly, the approaches presented here are at varying technology readiness levels, with some close to deployment and others significantly further away. For example, delivering high-temperature heat via electricity is still at a relatively low technology readiness level, and many other electrification routes have not yet reached the demonstration stage, although active research is underway. In all cases, cost and decarbonization potential via electrification are a function of the cost and carbon intensity of the underlying electricity grid.

A number of things need to happen for EIIs and hydrogen to play a major role in supporting a high-renewables future. Research, development, demonstration, and deployment efforts are needed to address core challenges to widespread industrial electrification, including the need to move toward commercialization of novel industrial electric technologies (especially for high-temperature processes), reduce the high capital costs of commercialized electric technologies, and provide real-world examples to reduce the impacts of risk aversion in the industrial sector.

Key needs include the following:

- **Electrified industrial loads and hydrogen production need to be more deeply integrated into power system planning processes.** Greater detail should be included when modeling the industrial sector in electric power system resource planning, including hydrogen production specifically. New electricity forecasting approaches and resource models will be needed to adequately characterize the loads and the potential for generating capacity to come from low-carbon fuels, including hydrogen. This includes further analyzing the flexibility characteristics described here.

  Electrified industrial loads and hydrogen production should also be considered in transmission planning activities, where there may be trade-offs and complementarities between these flexibility resources and the electricity transmission system. For example, hydrogen could be used to replace the need for transmission in moving clean energy from wind- or solar-rich areas to areas of high demand. Instead, the hydrogen would be transported and used to generate electricity at its destination. Alternatively, increased transmission build-out may allow for the use of more flexibility resources, including hydrogen and industrial electrification, to make better use of an expanded electricity grid.

- **Additional work is needed to understand the implications of new sources of flexibility for electricity system operations and market operations.** Questions include how these resources should be considered in unit commitment and economic dispatch, how long-duration storage and shifting of demand across longer periods will need to be managed in operational planning processes, how these flexible resources can participate in markets, and whether new market services are needed to incentivize entry. Lessons learned from the integration of battery storage and hybrid power plants into the electric power system and markets can be applied to the integration of industrial electrification and hydrogen production.

  For example, market redesign has been needed in these cases to ensure that the characteristics of these resources are adequately represented, and changes have been needed in order to reflect energy-limited resources in resource planning. This work should also be done in the context of very high levels of renewables, as this is when industrial electrification and hydrogen production will be both technologically ready and of greatest benefit to the electricity grid. The specific system services required at very high levels

of variable renewables and those provided by other resources are likely to differ from those in use today.

- **Improved performance and lower costs in industrial electric technologies are needed, especially for high-temperature processes.** Significant cost declines or changes to process design and implementation (e.g., accommodation of more variable load for some processes) may be required before EIIs can be integrated into electric power system operations and planning in a deep way. Many industrial loads tend to be relatively constant, at least in their current form, and incentives and policies will need to align to ensure that such loads can provide the flexibility that may be required. This may come in the form of policies more explicitly rewarding flexibility, or could come as standards developed in this regard.

- **Policies are needed that support low-carbon and renewable heating in industry.** Such policies would play an important role in industry decarbonization and electrification efforts.

- **Pilot and demonstration projects should be done to assess the impacts of electrification on process performance, cost, and output.** These projects could support technology development and risk mitigation for industries, to ensure that any concerns about implications for the production of the final product are addressed.

One means to address these challenges would be to develop a relatively small analytical exercise based on one or more of the current decarbonization pathway studies done by organizations such as the International Energy Agency, National Renewable Energy Laboratory, U.S. Department of Energy, Electric Power Research Institute, and others. A desktop-style study could take results from studies showing a role for industrial electrification and hydrogen and link these to more detailed planning and operational studies, allowing the identification of key challenges and gaps. Work could then begin to develop modeling, metrics, and practices to better account for these new flexibility resources in power systems. Such a study would provide a useful springboard to develop more detailed analyses of how flexibility can be obtained from new resources, the value of such flexibility, and the ways in which these resources can be procured and operated. This could lead to the development of improved planning methods and tools that can ensure that the flexibility of these new resources—and their benefits for the electricity grid—can be more fully realized when needed in the future stages of electricity system decarbonization.

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# Increasing Electric Power System Flexibility: The Role of Industrial Electrification and Green Hydrogen Production

**A Report of the Flexibility Resources Task Force of the Energy Systems Integration Group**

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The report is available at https://www.esig.energy/reports-briefs.

To learn more about the recommendations in this report, please send an email to info@esig.energy.

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. More information is available at https://www.esig.energy.

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