Assessing the Flexibility of Green Hydrogen in Power System Models

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

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

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Contents

Executive Summary

As decarbonization goals advance for both electric power systems and the broader economy, it is clear that the energy grid of the future will look vastly different from today's. Power systems will increasingly require different types of flexibility to balance supply and demand and maintain reliability as levels of wind and solar rise. Hydrogen production has the potential to provide such flexibility. ESIG's 2022 report *Increasing Electric Power System Flexibility: The Role of Industrial Electrification and Green Hydrogen Production* identified the need for green hydrogen production to be more deeply integrated into power system planning processes and the need for additional work to understand the implications of green hydrogen production for electricity system operations and market operations.[1]

As a versatile energy carrier, hydrogen produced via electrolysis is likely to be used across many sectors. Although providing flexibility services to the electric power sector may not be a hydrogen production facility's primary objective, there is substantial interest in understanding the ways that hydrogen can provide flexibility to the electric power system. Stand-alone hydrogen production that behaves as a flexible load is well suited for providing balancing and operating reserve–type services, whereas other services, like seasonal energy arbitrage, require the production of electricity through a fuel cell or combustion engine. Many studies suggest that, as the electricity system and broader economies decarbonize, hydrogen might be used to provide grid services instead of conventional dispatchable

1 Energy Systems Integration Group, *Increasing Electric Power System Flexibility: The Role of Industrial Electrification and Green Hydrogen Production*, a Report of the Flexibility Resources Task Force (Reston, VA, 2022), https://www.esig.energy/increasing-electric-power-system-flexibility/.

resources, such as coal-fired turbines, natural gas, and pumped hydro.

Potential grid services include:

- **Regulation:** To manage, on a second-to-second basis, uncertainty from forecast errors and generator responsiveness
- **Balancing (also known as ramping or load-following):** To manage variability and uncertainty within an hour and across hours
- **Operating reserve:** To manage contingencies or operational events—such as any combination of forced outages and periods of low wind or solar
- **Seasonal energy arbitrage:** To manage the mismatch of resource availability and load across seasons

This report explores the modeling needs and data requirements to integrate hydrogen into power system studies and evaluates the role of hydrogen production via electrolysis as a source of system flexibility. While other emerging technologies, such as coordinated charging of electric vehicles or stationary battery storage, may also provide similar flexibility, green hydrogen is of special interest due to its ability to store energy for use in many time frames (from seconds to seasons), its rapid response time, and its potential for large-scale deployment. The possibility of large centralized hydrogen production facilities is a key aspect of hydrogen's flexibility and predictability.

This report discusses several challenges and gaps in existing power system modeling tools and methods and is intended as a starting point for modelers to consider how to evaluate the benefits and implications of using green hydrogen production to provide flexibility in their systems.

Four Main Technologies for Green Hydrogen Production

The components and processes of an electrolysis system affect the performance and costs of using green hydrogen production for flexibility. The four main types of electrolysis technologies are alkaline, polymer electrolyte membrane (PEM), solid oxide electrolysis cell (SOEC), and anion exchange membrane (AEM), and each has advantages and disadvantages in terms of cost and performance. Electrolysis systems that perform with higher operating ranges and faster response times are best suited for providing operational flexibility/ancillary services. Systems with higher efficiencies/capacity factors are better suited for providing longer-duration flexibility, such as seasonal storage.

Electrolysis systems with higher operating ranges and faster response times are better suited for providing operational flexibility, and systems with higher efficiencies/capacity factors are better suited for providing longer-duration flexibility, such as seasonal storage.

Alkaline systems are the most mature technology and have the lowest capital costs and the longest life. While these characteristics are encouraging, alkaline electrolysis has drawbacks in terms of performance. Alkaline systems have a narrower operating range than other types. Further, it is best for them to operate continuously to reduce issues from short-circuiting or slow start-ups, making them potentially more suitable for continuous baseload rather than balancing services.

PEM systems are well suited for providing balancing services due to their faster ramp rates and start-up and shut-down times. Additionally, the costs and efficiencies of PEM electrolysis are expected to improve over the next decade, making it competitive with alkaline electrolysis.

SOEC and AEM systems are the least mature technologies. While their costs and performance are less certain, they have the potential to provide flexibility benefits. Of note, SOEC systems of the future have the potential to operate across the widest load range (from -100% to 100%) by reversing their mode of operating and acting like a fuel cell.

Modeling the Flexibility of Hydrogen

Modeling the flexibility of hydrogen introduces new considerations beyond what power system models have typically incorporated. Modeling hydrogen's potential to provide grid flexibility is a complex effort: there are many options and permutations of potential electrolysis systems, operating regimes, and grid services to target. Modelers may consider the following questions to assist in selecting appropriate data inputs to incorporate:

- What grid services are needed in this geographical area?
- What tools are best suited for assessing these grid services?
- What time horizon is being studied?
- What operating regime and other end uses might a given hydrogen facility provide?
- What electrolysis system is best suited for providing the grid service(s) being studied?
- What inputs are most critical for the grid service(s) being studied?
- How can the availability and uncertainties of supporting infrastructure be considered?
- How can the dynamics between hydrogen and electric power markets be considered?
- What data sources are available to develop modeling inputs?

Modeling hydrogen may require the use of multiple planning tools, such as capacity expansion, production cost, and multi-energy system models. It will be important to capture the technical characteristics and costs of different electrolysis technologies, the locational aspects of transmission and hydrogen networks, a range of assumptions around renewable energy sources and hydrogen prices, and the interactions between the electricity system and other sectors and markets. Modelers will need to incorporate and evaluate the benefits and implications of green hydrogen in their systems by using multiple planning tools, capturing the characteristics and behavior of electrolysis technologies and systems, sourcing high-resolution data, and considering different scenarios and sensitivities.

Moving Toward Best Practices

Given that hydrogen is still an emerging resource for power system applications, there is as yet limited consensus on best practices for modeling. However, organizations can continue to study the role of hydrogen in providing grid flexibility by developing initial models and can monitor improvements in the cost and performance of hydrogen to continually update their models. In parallel, ongoing research and software improvements may improve modeling techniques for future studies. And as the industry matures, knowledge and experience obtained from academia, other research institutions, software developers, hydrogen technology developers, and system modelers can be shared and used to move toward best practices. Several areas for further research and development can also be advanced, including improving the availability and quality of data for hydrogen production and demand, enhancing modeling capabilities and resolution to better represent hydrogen's potential role in providing flexibility to the system, and exploring the value streams and trade-offs of hydrogen production for different end uses and scenarios. Both the electric power sector and hydrogen facilities benefit from such exploration and collaboration around the use of hydrogen production facilities as a source of flexibility in power systems.

Modeling Potential Power System Flexibility from Hydrogen

As decarbonization goals advance for both electric power systems and the broader economy, it is clear that the energy system of the future will look vastly different from today's. Ensuring reliability will require a deep understanding of the characteristics and behavior of emerging technologies, and power system planning practices will need to evolve rapidly to better characterize reliability needs.

As levels of wind and solar rise, power systems will increasingly require different types of flexibility to balance supply and demand and maintain reliability. Today, flexibility is largely provided by fossil-fueled power generators; however, several emerging technologies may be able to supplant this current source of flexibility. Hydrogen is an emerging technology of special interest, being both versatile and able to be built at a large scale.

The potential of hydrogen production to provide such flexibility was examined in the Energy Systems Integration Group's (ESIG's) report *Increasing Electric Power System Flexibility: The Role of Industrial Electrification and Green Hydrogen Production*, which identified the need for green hydrogen production to be more deeply integrated into power system planning processes, as well as the need to better understand the implications of green hydrogen production for electricity system operations and market operations (ESIG, 2022). The present report extends that analysis by looking at integrating hydrogen into power system planning studies—specifically, exploring what planners and modelers will need to know about hydrogen production to model it as a potential source of flexibility.

This report focuses primarily on green hydrogen produced by electrolysis, whereby electricity from renewable sources (and in some cases a heat source) is used to split water into hydrogen and oxygen. Much of the discussion of this report can be generalized to other types of electrolytic hydrogen production, including pink hydrogen (produced using nuclear power) and yellow hydrogen (produced using grid electricity). There are two ways in which this hydrogen can be used for flexibility in the electric power sector:

- **Stand-alone hydrogen production**: Hydrogen production is used as a flexible load that adjusts its electricity consumption in response to signals from an electricity system operator.
- **Hydrogen production to generate electricity**: Previously produced hydrogen or its derivatives are used to produce electricity through fuel cells or combustion engines.

Hydrogen production can be a flexible load responding to signals from an electricity system operator, or previously produced hydrogen can be used to produce electricity through fuel cells or combustion engines.

Flexibility in this report is defined as the ability to change either resource output or consumption, on time scales from several seconds or minutes to provide grid services, to hours, days, and even seasons to provide balancing to the system.

ESIG convened a task force to examine the need for various types of data—for hydrogen production, the broader electricity system, and adjacent sectors—and modeling needs to estimate the flexibility that hydrogen production can potentially provide to the system. There are several approaches to producing hydrogen, typically

described by their "color" based on the energy source used. This report focuses on green hydrogen—produced using renewable energy—and two major roles it can play. The first is as a flexible load whereby variability and uncertainty within an hour or across hours are managed and compensated by the power markets, with hydrogen-producing electrolyzers providing balancing or ramping services. The second is the ability to provide seasonal energy arbitrage, whereby hydrogen (or hydrogen derivatives) is used as a fuel to manage the mismatch of resource availability across seasons.

An essential first step for incorporating hydrogen into planning and market operations is to effectively integrate hydrogen production and electrified industrial loads into operational and capacity expansion models. While there are significant gaps in techniques for incorporating hydrogen into models, here we explore what data and capabilities are needed to model the potential for green hydrogen to offer flexibility that today is commonly provided by conventional dispatchable resources, such as coal-fired and natural gas–fired turbines and pumped hydro. This report is intended to be a starting point for modelers to incorporate and evaluate the benefits and implications of green hydrogen as they plan their systems for a high-renewables future.

While there are significant gaps in techniques for incorporating hydrogen into models, here we explore what data and capabilities are needed to model the potential for green hydrogen to offer flexibility that today is commonly provided by conventional dispatchable resources, such as coal-fired and natural gas–fired turbines and pumped hydro.

Green Hydrogen in Potential Energy Futures

Various net-zero and other pathways studies have been done that describe futures with very high levels of renewable generation and electrification to meet decarbonization goals, and many cite a potential role for hydrogen.

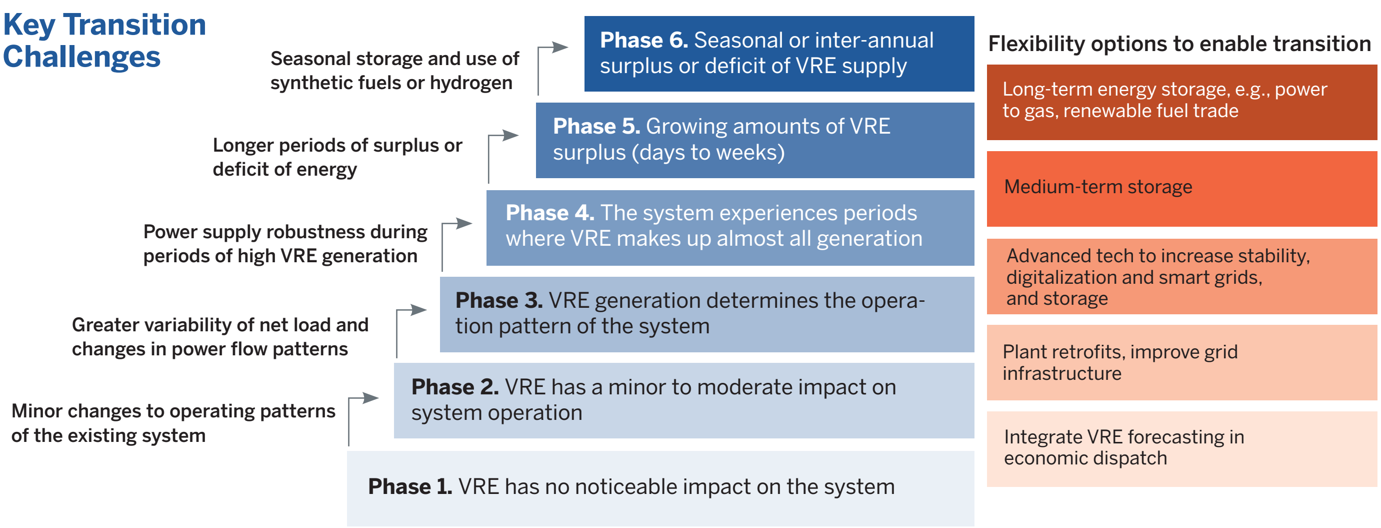
Pathways Studies

At a global level, the International Energy Agency's net-zero scenario demonstrates that hydrogen and hydrogen-based fuels may have an important role to play in the global energy system. In the last two years, the agency reports that the total global installed electrolyzer capacity doubled, reaching nearly 700 MW in 2022 (IEA, 2023). In the International Energy Agency's Power System Flexibility campaign, which highlighted different flexibility options at different phases of system integration of variable renewable resources (Figure 1), hydrogen was identified as helping integrate more renewables and enhancing energy security by diversifying the fuel mix, in addition to providing dispatchability and balancing services (IEA, 2018).

EPRI's report *Net Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis* identified the need for more clean, readily dispatchable (or "firm") electricity

FIGURE 1

The International Energy Agency Identified Key Transition Challenges in Different Phases of System Integration of Variable Renewable Energy

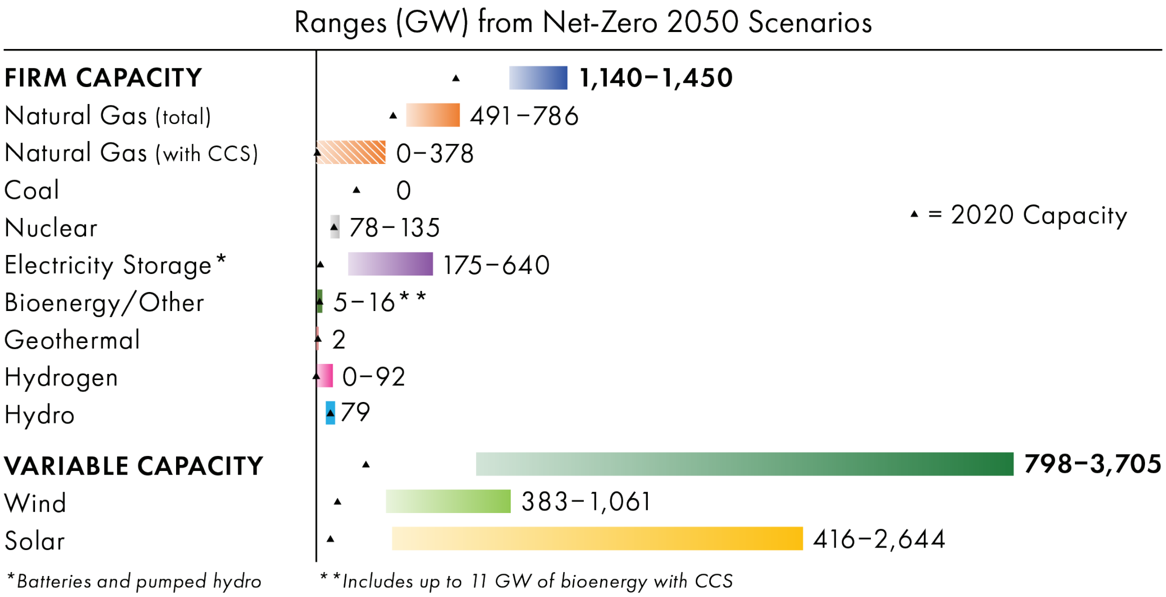


Regarding the integration of variable renewable energy, the International Energy Agency posits that additional flexibility options will be needed to enable transitions. In the later stages of the energy transition, flexibility options like power-to-gas (such as hydrogen) will likely be needed to accommodate seasonal deficits of renewable energy supply, and periods of deficit may be longer.

Source: Kristiansen (2021).

FIGURE 2

Critical Role for New Gas and/or Hydrogen-Fuel Electric Generating Capacity in Providing Flexibility



EPRI's Net Zero 2050 study found that in the United States hydrogen can play a role in a net-zero system as a low-carbon fuel, whether in fuel cell vehicles, blended with the natural gas supply, or used directly for process heating in industry. In cases where geological storage of carbon dioxide is not available, hydrogen's role is significantly expanded. The use of electrolysis potentially drives increases in electricity demand and increases investments in power generation accordingly.

Source: EPRI (2022c).

generation capacity to balance the growth of variable resources, and in all the scenarios studied found that "new gas- and/or hydrogen-fueled electric generating capacity plays a critical role in providing resource adequacy and flexibility for reliable power generation" (Figure 2) (EPRI, 2022c).[2]

The National Renewable Energy Laboratory's report *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035* discussed stored hydrogen as a possible source of reliable electricity for multiple days during periods of lower wind and solar generation, extreme heat, and extreme cold (Denholm et al., 2022). In such conditions, achieving very high levels of clean electricity requires firm resources, like hydrogen, during net load peaks. The amount of hydrogen projected in future systems is sensitive to the level of adoption of other low-carbon technologies and the amount of transmission grid expansion. For example, in scenarios that do not allow direct air capture, the study saw significant growth in hydrogen-fueled combustion turbine capacity. It also identified the need for seasonal storage, potentially from green hydrogen, on a large scale.

Princeton University researchers found similar results in their report *Net Zero America* (Larson et al., 2021). To ensure reliability, all scenarios studied maintained some firm generating capacity that is capable of providing flexibility services, and while the source of this capacity varies by scenario, the study posits that hydrogen is a key carbon-free intermediate and final fuel.

A common observation across these pathways studies, regardless of underlying assumptions, is that hydrogen production will need to grow to support a decarbonized economy. Scenarios with a highly decarbonized electric

2 This study incorporated negative emissions technologies to offset the use of natural gas by buildings and industry.

power sector can lean on hydrogen to provide an essential role as a new source of flexibility.

Types of Flexibility Potentially Provided by Hydrogen Production

"Flexibility" describes several grid services, distinguished by time scale. Hydrogen has the technical potential to provide flexibility to the electricity system for the following:[3]

- **Regulation:** On a second-to-second basis, manages uncertainty from forecast errors and generator responsiveness
- **Balancing (also known as ramping or load-following):** Manages variability and uncertainty within an hour and across hours
- **Operating reserve:** Manages contingencies or operational events—such as any combination of forced outages, periods of low wind, or periods of low solar
- **Seasonal energy arbitrage:** Manages the mismatch of resource availability and load across seasons

Stand-alone hydrogen production that behaves as a flexible load is well suited for providing balancing and operating reserve–type services, whereas other services, like seasonal energy arbitrage, require the production of electricity through a fuel cell or combustion engine.

Although other emerging technologies, such as coordinated charging of electric vehicles, may also provide similar flexibility, green hydrogen is of special interest due to its ability to store energy in many time frames, its rapid response time, and its potential for large scale. The possibility of large centralized hydrogen production is a key aspect of its flexibility and predictability; for example, green hydrogen relies on fewer agents' decision-making compared to coordinated charging of electric vehicles, which requires managing thousands of individual decision-makers (Wang et al., 2018).

Although other emerging technologies, such as coordinated charging of electric vehicles, may also provide similar flexibility, green hydrogen is of special interest due to its ability to store energy in many time frames, its rapid response time, and its potential for large scale.

A common finding in decarbonization pathways studies is that balancing will be initially provided by natural gas and that, over time, this reliance on natural gas will shift to other resources, with green hydrogen being one option (EPRI, 2022c). However, the cost of employing resources to provide balancing services is uncertain and likely to increase in areas with high levels of variable generation. To assess their various options, system planners and utilities will need to better understand the role green hydrogen can play, particularly in providing flexibility to the electricity system, by incorporating green hydrogen into their power system models.

3 While outside the scope of this report, hydrogen in combination with inverter-based resources may also contribute to system stability, similarly to batteries and DC tie lines. The need for primary frequency response is assessed using transient simulation, and it will be important to account for these services in capacity expansion modeling since a lack of primary frequency response can lead to solar and wind curtailment.

Moving from Pathways to Detailed Models

Technology pathways models, such as those used for the studies above, involve trade-offs in model fidelity. Because they look at a large geographical area over a long period of time, these models use reduction techniques and limit some details. The simplification, however, reduces the accuracy of the model in its representation of hydrogen as a source of flexibility, as well as under-estimates the value of flexibility in general.[4] For example, without information about ramp rates in a particular system with particular conditions, resources, and loads, it is not possible to quantify the intra- and inter-hour load-following needs that hydrogen could potentially address.

Common simplifications in these models include:

- **Temporal aggregation:** While some models look at full 8,760 hour annual chronology, many use some form of temporal aggregation, such as selecting segments or time slices. These models typically ignore sub-hourly operations.
- **Aggregation of generating units:** Many models aggregate generating units in blocks that are dispatched together and/or simplify commitment decisions.
- **Dispatch constraints:** Many models do not consider ramp rates, start-up costs, load limits, and other operational type of constraints.
- **Perfect operational foresight:** Most models do not consider short-term variability and uncertainty, nor do they consider periods of extreme conditions (e.g., "doldrums" during which renewable energy generation is low).
- **Simplification of the transmission network:** Most models treat transmission as a simplified pipe and bubble between regions and thus do not fully consider the deliverability of resources.

A comparison of various roadmaps to net-zero emissions found temporally and spatially aggregated studies to be less useful for evaluating power sector options because they do not effectively describe the strong link between variable renewables and balancing operations (Bistline, 2021). Detailed models provide greater insight into the role of new resources and can better support the system planners analyzing the needs for flexibility in the future and where it will come from.

The Implications of the Time Horizon for Modeling Choices

In general, the level of detail increases and the level of uncertainty goes down in models with shorter time horizons. The time horizon for a study is often the first decision to be made and ought to be informed by the types of decisions that need to be made. Factors like contract horizons and permitting and construction timelines may dictate how soon decisions must be made. Therefore, system planners may use detailed models in early planning stages to support the designers and developers of the flexibility resources, helping them to understand the value streams available and inform them about design choices and research and development to support future power system needs that hydrogen may be able to address—in the next few years or up to a couple of decades in the future. Furthermore, models that look further into the future should consider structural changes to the electric power system as well as the potential for technological maturity, decreases in cost, greater availability of supporting infrastructure, and improvements in performance of hydrogen technologies.

4 For more context on the importance of ensuring flexibility adequacy in deeply decarbonized electricity systems, please see *Enhancing Energy System Reliability and Resiliency in a Net-Zero Economy* (epri.com).

Tools and Methods for Modeling the Flexibility of Hydrogen

Multiple modeling tools may be required to fully characterize the flexibility of green hydrogen and can help to overcome the insufficient resolution found in pathways modeling. To effectively model flexibility needs and their costs requires having access to the necessary data and selecting models with sufficient resolution (both temporal and spatial) to consider flexibility needs at various time scales—whether it's minute-to-minute balancing, diurnal energy arbitrage, or seasonal energy arbitrage. Given potential uncertainties—such as the availability of renewable energy sources, the future cost of electricity, policy decisions, techno-economics of hydrogen facilities, or the performance of electrolyzers—modeling efforts may include multiple scenarios or probabilistic techniques to capture the range of possibilities. These efforts may also include modeling of upstream or midstream processes such as the transportation of hydrogen (initially through the natural gas system and over time through hydrogen-specific pipelines), water systems, and other users of hydrogen, in order to fully understand the implications of a broader hydrogen economy and market dynamics.

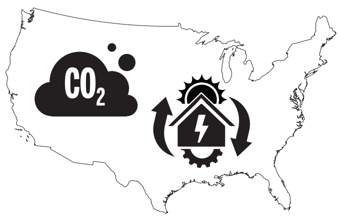
Given potential uncertainties—such as the availability of renewable energy sources, the future cost of electricity, policy decisions, techno-economics of hydrogen facilities, or the performance of electrolyzers—modeling efforts may include multiple scenarios or probabilistic techniques to capture the range of possibilities.

Figure 3 (p. 8) describes an ecosystem of planning tools that could be used to characterize and assess the impacts of generation resources including hydrogen. Regional decarbonization technology pathways models provide a starting point to understand where, when, and how emerging technologies, such as hydrogen, are likely to be used. Capacity expansion models take these pathways models a step further, facilitating siting and investment decisions for utilities or other electric power companies. Bulk system reliability, production cost, and power flow and stability models can be used to confirm that the investment plan is reliable and identify additional reliability needs. Often, flexibility needs are discovered in these latter models.

For example, chronological hourly or sub-hourly modeling is beneficial for estimating the value of system balancing. This resolution is common in production cost models, many of which can simulate dispatch up to a 5-minute granularity and incorporate operational constraints of individual resources, and some of which can replicate day-ahead decisions (EPRI, 2022a). As a result, they are used to assess balancing needs and diurnal energy arbitrage. Production cost models describe most of the variability of wind and solar generation and the resultant balancing services needed, some of which could be met by hydrogen production as a flexible load or hydrogen as a fuel. However, this high temporal resolution is not always available in capacity expansion or pathways models. In such cases, using time steps coarser than hourly can under-estimate the benefits of using hydrogen to respond to hourly or sub-hourly changes in the grid's supply demand balance. Coarse time steps may also limit a fulsome understanding of how non-constant electricity supply affects hydrogen production. Capacity expansion models typically have a reduced representation of operational detail in favor of reduced computational complexity. But given increased flexibility needs of future power systems, this model decision may need to be revised, by finding alternative ways to reduce the

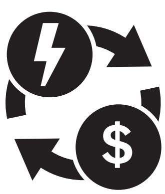
FIGURE 3

Using Multiple Planning Tools to Value Resources Appropriately



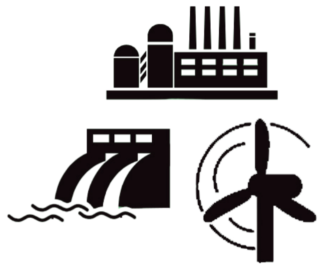
Regional Decarbonization Technology Pathways Modeling

- Is national, regional, or state focused
- Ensures the system can meet decarbonization and technology targets and policies
- Includes a detailed representation of customer heterogeneity across end-use sectors, and end-use technology trade-offs
- Includes a detailed analysis of electrification and efficiency opportunities



Production Cost Model

- Examines detailed operating costs, and market, environment, and revenue impacts

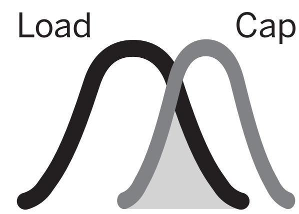


Bulk System Capacity Expansion Model

- Has a selected geographical area of focus
- Includes nodal generation and transmission capacity expansion
- Includes detailed unit-level costs and engineering constraints

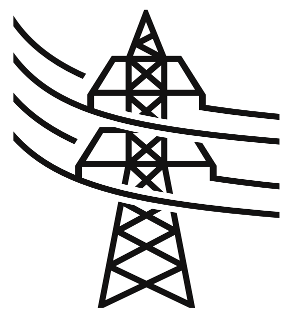
Distribution Grid Model

- Incorporates distribution infrastructure needs and better understanding of DER share of resources



Bulk System Reliability Model

- Ensures steady-state reliability (reduce load shed, meet reserves)
- Ensures the system has adequate capacity



Power Flow and Stability Model

- Ensures the system is stable; the system has sufficient reactive resources, voltage control, frequency response, inertia, and system strength; and the transmission system is robust

EPRI's Integrated Strategic System Planning initiative identified the importance of an ecosystem of planning tools, each with feedback loops that inform decision-making and value resources appropriately. While the planning models listed here pertain mostly to the power sector, going forward, these models may need to either be able to endogenously account for hydrogen demand and potential reutilization or be linked to designated hydrogen market models, given the dependence of hydrogen price on electricity prices going forward.

Source: EPRI.

computational burden in favor of technical detail, to appropriately value the benefit of these services.

Looking at longer-horizon flexibility needs, such as seasonal energy arbitrage, existing capacity expansion and production cost models both have limitations. These tools often apply reduction techniques, such as rolling horizon optimizations and temporal aggregation, which limit planners' ability to identify operational detail and seasonal effects.

Many state-of-the-art modeling techniques may be required to accurately capture the flexibility provided by hydrogen production and utilization. Modeling requirements and granularities may differ depending on the flexibility service of interest and the study scope.

Modeling Grid Services from Hydrogen Production via Electrolyzers

The production of hydrogen via grid-connected electrolyzers, regardless of the intended end use, lends itself to providing grid services operating as a flexible load. Depending on the electrolyzer type and ancillary components (compressor, buffer, inverter, etc.), this technology may qualify for energy and/or ancillary services.

Modeling Hydrogen as a Flexible Load

With more and more operational uncertainties in the power sector because of increasingly variable and/or weather-driven supply and demand, there is an increased need for operational flexibility. Demand response is often considered as a possible source of additional flexibility. Flexible loads (often used interchangeably with demand response) can, for example, provide grid services to balance a stressed system by reducing offtake. Hydrogen production via electrolysis can also be a flexible load, and can contribute to system flexibility in two ways.

When the system is experiencing a positive imbalance (a surplus of energy), electrolyzers that are not operating, or are operating below their maximum capacity, can provide flexibility as downward reserves. When the system is experiencing a negative imbalance (a lack of energy), electrolyzers operating above the minimum operating point may provide flexibility by reducing their hydrogen production as upward reserves.

To accurately capture the flexibility of electrolysis-based hydrogen production as a flexible load, modelers need to accurately represent (1) the operating characteristics of hydrogen production, and (2) the flexibility of hydrogen end uses, which also depend on the availability of hydrogen storage buffers.

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Hydrogen's Operating Characteristics

First, regarding operating characteristics, the level of detail representing the electrolytic hydrogen production may vary a great deal from model to model. It is important that the level of detail is appropriate for the scope of the respective study. In the simplest case, hydrogen production is represented as an additional electrical load without considering the actual electrolysis and associated technical constraints. The advantage of this approach is its simplicity, although its inability to capture all technical details about hydrogen production can be a problem.

Alternatively, hydrogen production can be modeled in more detail, taking into account the operation of the electrolyzer and also the balance of plant as necessary. Depending on the grid service(s) provided (e.g., ancillary services), it might be more or less relevant to capture operating constraints appropriately (such as ramping constraints of electrolyzers, hydrogen buffer, etc.). More detail on the technical characteristics of electrolyzers is presented below in the section "Characteristics of an Electrolysis System."

For electrolyzers, we need to be able to accurately incorporate operating conditions, including operating states, efficiencies, and ramping constraints. Power system planners should be aware that existing studies modeling electrolyzers in detail are often designed to maximize the utilization or revenue of hydrogen from a plant perspective, and they should take this into account when using such studies for other purposes.

Details that may need to be included in these models going forward may include non-linear efficiency curves and different operating points. Mathematical models of the non-linear efficiency curve of electrolyzers may be presented through piecewise-linear approximation or a conic model (Raheli, Werner, and Kazempour, 2023) or may be represented similarly to piecewise similar heat rates for thermal generators. The implications of incorporating multiple operating points (on, off, standby) (Baumhof et al., 2023) need to be explored in the context of production cost models and expansion planning models. When modeling the use of electrolyzers for ancillary services, ramping constraints should reflect the lag time of the electrolyzer and the balance of plant. For example Zheng, Bindner, and Münster (2022) considered ramps for electrolyzers and efficiencies for compressors, though they did not address potential ramping constraints of the compressor.

While many studies on hydrogen production and electrolyzer operation are designed to maximize the utilization or revenue of hydrogen from a plant perspective, the impact of these detailed operating constraints in production-cost or capacity expansion models needs to be identified to accurately capture flexibility performance requirements. Operational constraints are often represented at a low level of detail in capacity expansion planning models in particular. The omission of these constraints can result in under- or over-estimating the flexibility value of hydrogen production and thus an under- or over-estimation of technology investments in hydrogen and other related technologies (e.g., solar, wind, batteries). Therefore, more research is needed to determine the appropriate level of modeling detail. Further, representing hydrogen production at a higher or lower level of detail than other system components (such as thermal generators) may lead to an over- or under-estimation of electrolyzers' technical limitations in comparison to other technologies—for example, hydrogen from steam-methane reforming in combination with carbon capture, utilization, and storage.

The omission of hydrogen production's operating constraints from models can result in under- or over-estimating its flexibility value and thus under- or over-estimating technology investments in hydrogen and other related technologies.

The Flexibility of Hydrogen End Uses

Second, when considering electrolytic hydrogen production serving as a flexible load, we need to represent flexibility limitations on the hydrogen receiving end—how responsive hydrogen demand may react in times of renewables surplus or shortage. Models may assume an exogenous price for hydrogen, which in turn means that hydrogen is only produced if electricity prices are competitive or when incentives from balancing markets are sufficient. For simplicity, many studies assume a fixed price for hydrogen throughout the study horizon. However, the projected price of hydrogen is highly uncertain and will strongly depend on which sectors are going to rely on low-carbon hydrogen for decarbonization in the future. Model sensitivities to these assumptions may be large and need to be accounted for, for example, through scenario analysis. Further, prices for electrolytic hydrogen may become more volatile on a shorter time scale, depending on the availability of hydrogen storage buffers, given its dependence on fluctuating electricity prices.

While this approach may be simple from a modeling perspective, it may be difficult to come up with hydrogen-price data, and it may fail to represent technical limitations on the hydrogen demand side, such as the flexibility of downstream chemical processes, availability of hydrogen storage buffers, and physical and financial contracts. Alternatively, the flexibility on the hydrogen demand side could be modeled in a manner analogous to other flexible load models, incorporating, for example, restrictions on time of use, frequency, etc.[5] Similar to other forms of demand response such as large data centers or electric vehicles, it remains to be seen how visible price signals are between electricity markets and hydrogen markets and how responsive these assets will be in reality. When available, the use of historical performance and correlated market data may inform model assumptions.

More advanced models may represent the hydrogen sector and corresponding demand explicitly, for example, using multi-energy system models further described in the section "Modeling End Use Demand."

Modeling Hydrogen as Seasonal Storage

As we move toward highly decarbonized energy systems with high shares of variable renewable energy sources, it will become more challenging to serve electrical load during times of low availability of renewables, sometimes called a "dunkelflaute," or "dark doldrums." Various types of seasonal storage are gaining attention as a means to shift renewable energy across longer time periods, rather than relying on overbuilding of renewables to meet load during these times. Hydrogen and hydrogen-based synthetic fuels may potentially serve as seasonal storage when produced through electrolysis at times of renewable surplus and utilized as firm capacity through fuel cells or turbines during prolonged periods of renewable energy deficits.

5 For more details see, for example, https://gridops.epri.com/Adequacy/technologies/flexible_demand.

When looking at hydrogen and hydrogen derivatives as a seasonal energy storage,[6] it will be important to capture the seasonal variability of load and variable renewable energy resources. Models will need to capture the entire horizon, from hydrogen production to utilization. However, production cost models often partition problems into shorter subproblems to tame computational complexity, thereby limiting optimization foresight. Similar to modeling hydropower resources, modeling seasonal energy storage will require long time series. Associated uncertainties (e.g., different seasonal projections) also need to be addressed, with stochastic programming, for example. In capacity expansion models, where representative periods are used to reduce computational complexity, novel aggregation methods can be leveraged to preserve the seasonal characteristics of the system (see, for example, Gonzato, Bruninx, and Delarue (2021)).

It is important to note that, while less pronounced than in the case of using hydrogen flexibility for ancillary services, it will still be important to capture operational detail of the storage facilities accurately enough to appropriately capture production and reutilization of hydrogen during times of surplus/shortage. Further, it will be important to take hydrogen leakage into consideration, that is, how much hydrogen is lost throughout conversion and storage processes due to hydrogen's high volatility. Leakage of hydrogen may, for example, be modeled in a similar way as self-discharge of batteries. Depending on compression and storage techniques, leakage risk may be more or less significant (Zheng, Bindner, and Münster, 2022).

Representing Uncertainties

As levels of variable renewable energy resources increase, so does the need for flexibility to accommodate their volatility. To understand what services can be provided by electrolytic hydrogen production as a flexible electrical load, it will be important to accurately capture the dynamics of overall electrical load and renewables, as well as the operational characteristics of electrolyzers and balance of plant. Technical details about electrolyzers are given in the section "Representing Hydrogen Plants and their Electrolysis Systems." For the representation of renewable resources, it will be important to capture short-term uncertainties and possibly intra-hourly variability (depending on the grid service provided). Uncertainties can be addressed by incorporating stochastic scenarios or by leveraging dynamic reserve sizing methods.

Further, when considering hydrogen as seasonal storage, models will need to take into account seasonal uncertainties: they will need to capture seasonal projections to mimic the uncertainty attached to seasonal arbitrage. Modeling this behavior may be informed by modeling other technologies with seasonal uncertainties, such as multi-stage stochastic optimization for hydro resources.

Lastly, like other emerging technologies, uncertainties are inherent in future projections of technology costs. In addition, there are large uncertainties concerning the development of the hydrogen economy overall. As this will impact the results of any study, it is essential to incorporate different trajectories with models. Operational models should therefore highlight the dependence of modeling results on the assumed hydrogen system; planning models should include uncertainties—such as through scenarios, stochastic optimization, or robust optimization—to capture a wide range of possible outcomes. Since these uncertainties do not stem only from the power sector and the electrolytic hydrogen production itself, it may be necessary to incorporate the larger hydrogen economy into models, for example, for industrial purposes and transport, as further discussed below in the section "Modeling End Use Demand."

Modeling Locational Detail and Transmission Networks

When modeling hydrogen production, it is important to consider the locational aspects of both the transmission network and the hydrogen network. In the case where hydrogen prices are exogenous inputs to the model, these price assumptions may differ by region depending on locational hydrogen demand and availability. Deliverability issues may apply to the location of hydrogen infrastructure (e.g., demand, storage, pipelines) and its connections to renewable energy resources. In this regard, the hydrogen

6 While we separate these two forms of flexibility (flexible load and seasonal storage) to disentangle specific model requirements, these services are not mutually exclusive.

network itself may need to be modeled explicitly, if hydrogen network constraints become binding. The location of hydrogen demand and availability of cheap hydrogen storage options, for example, in salt caverns, needs to be taken into account, as it may impact locational pricing (Walter et al., 2023; Kirchem and Schill, 2023). The main challenge may be to find representative data on locational hydrogen demand.

Because the cost of electricity is the largest operating expense for green hydrogen, it is vital that any model accurately and precisely incorporate the dynamics of electricity prices. Especially in systems where electric power markets exist, it is necessary to model the transmission network in detail to inform choices on siting and potential revenues. Such modeling can inform the trade-off between siting hydrogen production close to demand centers or siting it where low-cost electricity is more plentiful (often away from load centers). The model should also reflect that the price of electricity changes over time in response to supply and demand and the resulting price dynamics and variability across locations. Alternatively, in areas with regulated (and therefore often fixed) prices, the incentive for flexible loads to respond to price is often dampened.

Modeling the Transportation of Hydrogen

One pathway to use hydrogen as an energy carrier and seasonal storage is by either blending hydrogen directly into the existing natural gas network or using dedicated hydrogen networks. Apart from the various well-known modeling techniques available for modeling the gas network itself (from common collector approach assumptions to transport-based approaches to full hydraulic models), modeling the blending of hydrogen requires accurate tracking of hydrogen concentrations to comply with operating limits. Approaches to tracking hydrogen are being explored in academia (see, for example, Saedi, Mhanna, and Pancarella (2021)). Further, given that hydrogen is a volatile gas, it will be important to account for losses during transportation, similar to self-discharge for a battery.

While the focus of this subsection is on hydrogen and the natural gas network, hydrogen transport through pipelines is only one option to realize a hydrogen network. Different hydrogen storage and transportation options include the on-site storage of hydrogen or a network using road or ship transport (Zhang et al., 2024). Depending on the system being studied, these different aspects may need to be represented through transport models and multi-energy/multi-sector modeling.

Modeling Hydrogen End-Use Demand

To understand competing interests for hydrogen and identify whether hydrogen production using electrolyzers is an economically viable option for long-duration energy storage,[7] it will be important to incorporate into models different types of end-use hydrogen demand, including transportation, heating, the chemical industry, and others. Demand for hydrogen is impacted not only by the cost of production, including capital costs and electricity costs, but also by demand from other end uses. Price forecasts will need to consider the supply chain, overall electricity demand, hydrogen transportation and delivery costs, and electricity prices.

Models need to be able to represent different end uses, e.g., through respective demand time series or by endogenously modeling other sectors through multi-energy-system modeling. Many modeling tools are starting to consider multiple energy vectors in their systems to link different energy sectors. The choice of which energy vectors to represent will depend on the system investigated and alternative end uses considered. While multi-energy-system modeling is not the main focus of this report examining flexibility from electrolytic hydrogen, it is important to acknowledge the interdependence of the many elements of the overall hydrogen economy. Ignoring this interdependence could lead to unrealistic assumptions about the need for electrolytic hydrogen beyond the power sector and, conversely, the availability of hydrogen to the power sector.

7 Note that end uses of hydrogen from electrolysis will not have an impact on flexible load services or ancillary services, unless downstream demand adds additional lag constraints to the flexible operation of the electrolyzer.

Representing Hydrogen Plants and Broader Systems in Power System Models

Modeling electrolytic hydrogen production facilities, similar to modeling generators in electric power system models, begins with understanding the technology itself. From this foundation, detailed modeling entails representations of both cost and performance and, in the case of green hydrogen, other factors like transportation and sector-coupling.

Operating Regime

Hydrogen and its derivatives are notable because they can act as energy carriers in multiple systems. Therefore, it is crucial to take into consideration the operating regime and goals of the electrolysis plant, recognizing that hydrogen production facilities are unlikely to treat the provision of electricity and flexibility as their primary objectives.

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Blended Operations

Today, combustion turbines are capable of using blends of up to 30% hydrogen by volume with natural gas. For operations that expect to blend natural gas with hydrogen, best-in-class models may need to consider the following:

- **Emissions:** Emissions from the facility will depend on the amount of hydrogen that is blended with natural gas at any given point in time. Incorporating an emissions-to-blending ratio curve (noting that it is non-linear) can improve emissions estimates. Similarly, temperature control of the combustion process will be important for avoiding nitrogen oxide (NO_x) formation.
- **Fuel switching:** There may be decision variables that affect how much hydrogen is blended into the system, and when. These variables may include the cost of natural gas, emissions requirements, efficiency of the plant, and other considerations.

Operations That Rely on the Electricity System

While some electrolysis-based hydrogen production facilities may have dedicated electricity sources (behind the meter), many are expected to draw much or all of their required electricity from an increasingly decarbonized and renewable grid. Therefore, power system models, in considering the need for additional resources to supply hydrogen production facilities and the deliverability of electricity, will need to include projections of hydrogen facilities' electric load impacts and capacity factors.

Additional complexity ensues when considering carbon-free matching—where, as part of a procurement or contract, a facility guarantees that its electricity usage is matched to 100% carbon-free generation over a defined time scale. Matching regimes vary by contract, with the most complex requiring around-the-clock matching throughout the year. If contracts require some level of matching, the model should take into consideration the availability of renewable energy sources along with consumption data to ensure that these renewable energy sources indeed provide power at the right time to the hydrogen facility.

Provision of Hydrogen Fuel for Industrial Loads or Other End Uses

Hydrogen and hydrogen derivatives are fuels that can be used for numerous industrial loads and other end uses. The production of electrolytic hydrogen is sensitive to the cost of electricity; so, modeling the interplay between electricity price and hydrogen production can inform when hydrogen is produced, when its production is curtailed, and when a bi-directional electrolyzer (a combined electrolyzer and fuel cell that can alternate between a direct mode and reverse mode) or on-site fuel cell is used to provide peak power or exports for broader system support.

Alternatively, with hydrogen playing an important role in broader economy-wide/energy system decarbonization, many hydrogen facilities will likely treat the provision of power to the electricity system as a secondary priority. These facilities may be akin to co-generation/combined heat and power plants or other self-scheduling types of facilities. In such cases, it may be sufficient to use simplified models that treat the facility like a flexible electrical load or a self-scheduling generator that responds only under certain conditions, such as when the price of electricity exceeds a pre-determined point.

Characteristics of an Electrolysis System

It is essential to understand the electrolysis technology used in a hydrogen facility in order to model the flexibility of the plant as a whole. An electrolyzer's characteristics greatly affect its response rate and efficiency. Furthermore, plant operators need to understand the impacts of deployment strategies when providing flexibility to the grid, as these affect the electrolyzer's operation and durability.

Types of Electrolysis Technology, and Grid Services They Can Potentially Provide

The type of electrolysis technology being modeled should be defined from the outset, as each has different operational behavior. The technologies can be characterized as either high-temperature or low-temperature. Low-temperature electrolyzers operate at 50-100°C and use liquid water as an input, whereas high-temperature electrolyzers operate at 700–1000°C and use steam. These temperature differences influence performance characteristics, such as system response and dynamic range, making some electrolyzer technologies better suited than others for providing different types of flexibility services.

Electrolyzers' temperature differences influence their performance characteristics, such as system response and dynamic range, making some electrolyzer technologies better suited than others for providing different types of flexibility services.

While electrolysis technology has existed for decades, advances in cost and performance have become much more rapid in the last decade and will no doubt continue. Therefore, when assessing the ability of different types of electrolyzers to provide flexibility to the electric power system, it is important to be mindful of the time horizon being studied. If considering the next few years, studies should include only mature technologies that have reached commercial operation. But if looking at a longer time horizon, studies can include a wider range of technologies.

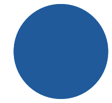
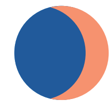
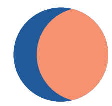
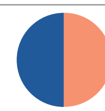
This report focuses on the four main types of electrolysis technologies, in order of the most to the least mature:

- Alkaline electrolysis
- Polymer electrolyte membrane electrolysis
- Solid oxide electrolysis cell
- Anion exchange membrane electrolysis

As seen in Table 1 (p. 16), alkaline is the most mature electrolysis technology, followed by polymer electrolyte membrane (PEM) electrolysis. For studies that look out decades, solid oxide electrolysis cell (SOEC) and anion exchange membrane (AEM) systems could be modeled, despite not being commercially ready today. Although no commercial SOEC systems are currently available (only demonstration units), SOEC systems, a type of high-temperature electrolysis, could mature in future decades, at which point SOEC could provide superior performance with comparable costs to other systems. AEM is in the laboratory phase with only a few small-scale commercial offerings.

TABLE 1

Electrolysis Technology Types

Category	Technology Type	Description	Technology Maturity
Low-temperature electrolysis	Alkaline electrolysis	Uses nickel alloy electrodes submerged in an alkaline solution separated by a diaphragm	
	Polymer electrolyte membrane electrolysis (PEM)	Uses precious metal catalysts and a solid polymer membrane without a liquid electrolyte	
	Anion exchange membrane electrolysis (AEM)	Uses a design similar to PEM, but its electrolyte conducts anions rather than protons (the same reaction as in alkaline)	
High-temperature electrolysis	Solid oxide electrolysis cell (SOEC)	Has catalyst layers separated by a gas-tight ceramic electrolyte and uses steam as an input rather than liquid water	

The four main types of electrolysis described and compared in this report. The blue indicates greater technological maturity.

Source: Adapted from EPRI (2023).

Components of an Electrolysis System

In addition to the electrolysis stack, the electrolysis system combines other processes that can also impact the performance and costs of the hydrogen production plant. These processes—taking place in the balance of plant—must also be considered when determining the flexibility the plant can offer to the electric power system. For example, the plant's response time may be impacted by compression and storage-related processes and interactions between components. The main process blocks of the process units involved are the following (EPRI, 2022b):

- Electrolysis stacks
- The balance of plant, which includes:
  - Purification system
  - Transformer and rectifier
  - Lye separators (for alkaline electrolysis)
  - Scrubber (for alkaline electrolysis)
  - Hydrogen-water separator
  - Deoxidizer
  - Dryer
  - Compressor
  - Heat exchangers
  - Recuperator and pre-heater (for SOEC)

Some hydrogen facilities may leverage on-site storage or buffers. In such cases, siting decisions may consider proximity to geological formations that could be used as cost-effective hydrogen storage, in addition to typical siting considerations for electric power generation facilities such as transmission interconnection, congestion, and distance to load centers.

Costs to Consider

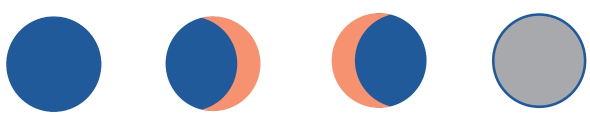
When modeling hydrogen production for provision of flexibility to the electric power system, several major types of costs need to be considered.

Capital Costs

Capital costs must of course be taken into account when considering electrolytic hydrogen production as a source of flexibility for the electric power system (see Figure 4).[8] In general, the more mature the technology, the lower the costs. When modeling hydrogen production, regardless of what services are being provided to the electricity system, it is important to consider the time horizon. For studies with a short time horizon, current cost estimates are sufficient. The longer the time horizon, the more important it is to assume some cost reductions as well as account for uncertainties around future costs.

The relative costs between technology types can also change over time. While alkaline electrolysis is currently the cheapest option, the costs and efficiencies of PEM electrolysis are expected to improve over the next decade, making it competitive with alkaline electrolysis (ENTSO-E, 2021). However, the costs of PEM stacks are also affected by the costs of precious metal catalysts used in their design (EPRI, 2022b).

FIGURE 4
Capital Costs of Electrolysis Systems



Blue shading indicates lower cost, and orange shading indicates higher cost. Due to the early-stage development of SOEC and AEM electrolysis, their costs could remain high for the foreseeable future and remain highly uncertain. Capital costs for AEM electrolysis are not available.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

Source: Adapted from EPRI (2023).

As noted above, the electrolysis system consists of many processes. While the cost of the electrolysis stack is the largest line item, modeling of the capital costs must consider the unique process costs (consisting of hydrogen compression, water treatment, and the balance of plant), as well as additional plant costs common across any industrial facility (such as cost of facilities, contingencies, cost of debt, etc.).

Cost estimates depend greatly on location (EPRI, 2022b). When developing cost assumptions for studies, it is therefore recommended that modelers source high-resolution estimates and adjust for location. Further, modelers should be sure to scrutinize cost estimates, as the level of reported costs varies across vendors, and quotes from manufacturers differ according to the scope of components included.

The scale of production also has a significant impact on capital costs (EPRI, 2022b), as centralized production tends to be more cost-effective than distributed cases. The cost of the electrolyzer stack can vary from 24% to 44% of the total capital required.

Operating and Maintenance Costs

When modeling the flexibility of hydrogen, a critical cost consideration is operation and maintenance costs, which should include the following:

- Electricity
- Chemicals
- Raw water make-up
- Maintenance
- Replacement stack
- Insurance and local taxes
- Administrative and overhead
- Direct labor

Of these costs, electricity is the largest operational expense (EPRI, 2022b). This expense is highly dependent on location, as the cost of electricity is very sensitive to the availability of low-cost power generation, nearby demand for electricity, and availability of transmission. Accurately modeling these dynamics, using detailed transmission inputs and consideration of market revenues, is imperative for understanding the flexibility and responsiveness of hydrogen to the electric power system.

8 The cost differential between electrolytic hydrogen production and other types of hydrogen production (e.g., steam methane reformation combined with carbon capture, utilization, and storage) is a vital consideration. Additional interactions between the price of natural gas and tax structures may drive greater production of hydrogen through non-electrolytic pathways.

In a study conducted at a site in Wisconsin, excluding the cost of electricity, the most significant operations and maintenance cost was the replacement of the stack (EPRI, 2022b). While there is uncertainty around when stack replacement will be necessary, studies with longer time horizons (exceeding 10 years) should factor in the costs of replacement or refurbishment. These costs can vary by technology type. Of note, while PEM replacement costs are expected to be higher than those of alkaline electrolyzers, they are also sensitive to assumptions on precious metal salvage values.

Given how sensitive modeling the flexibility of hydrogen production is to the costs of electricity, it is essential for models to consider the interactions between operations and maintenance costs and performance characteristics of electrolysis technologies (discussed next), as both affect their ability to leverage lower electricity prices.

Performance Characteristics

The performance of electrolyzers—operating range, response time, efficiency, capacity factor—varies by technology type and can greatly affect the amount of, and value of, the flexibility they provide. Any system model must consider both the cost and performance of each technology modeled.

Electrolysis systems with higher operating ranges and faster response times are best suited for providing operational flexibility/ancillary services. Systems with higher efficiencies/capacity factors are better suited for providing longer-duration flexibility, such as seasonal storage.

Operating Range

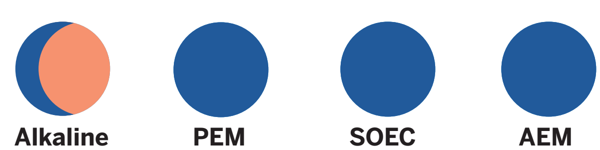
The operating range, or partial load range, describes the capacity range at which an electrolyzer can operate, and is often described relative to a rated load. Notably, electrolyzers can operate above their rated capacity for some duration of time. A wide operating range—the ability to largely or completely shut down and/or go into "overdrive"—allows for an electrolyzer to provide the most flexibility to the grid. Figure 5 compares the operating ranges of the four main electrolyzer types.

Alkaline systems have a narrower operating range than other types. At low loads (below 5%) alkaline systems have a higher likelihood of gas cross-over, a diffusion of hydrogen that creates a dangerous mixture of hydrogen and oxygen gas that can be explosive. The result is the purity of oxygen is reduced, and the production of hydrogen drops. Therefore, to ensure safety, alkaline systems require additional purification and have a smaller operating range. A 2018 study found the lowest load levels of individual alkaline electrolyzers' operation to be 20% to 25% of peak load; however, larger systems with multiple modules can switch off individual electrolyzers, which can reduce the minimum operating level to about 11% for the entire plant (EPRI, 2022b). To overcome the limitations of alkaline systems compared to other electrolyzers, these systems may improve their ability to provide operational flexibility by coupling with batteries or other technologies, at the potential expense of efficiency losses.

PEM systems operate from 0% to 160% (ENTSO-E, 2021). This wider operating range makes PEM better

Electrolysis systems with wider operating ranges and faster response times are best suited for providing operational flexibility/ ancillary services, while systems with higher efficiencies/capacity factors are better suited for providing longer-duration flexibility, such as seasonal storage.

FIGURE 5
Operating or Dynamic Range of Electrolysis Systems



Of the four main electrolyzer types, alkaline systems have the narrowest operating range. The other three technologies provide a broad operating range that can be beneficial for providing operational flexibility. Blue shading indicates a larger range and orange indicates a narrower range.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

Source: Adapted from EPRI (2023).

suited today for providing operational flexibility and ancillary services, and its market share is growing as a result.

SOEC systems of the future have the potential to operate across an even larger range. By reversing their mode of operation and acting like a fuel cell, they can have a load range of -100% to 100% (EPRI, 2022b).

Aspects of Electrolyzer Operation

Response Rate

The membrane used in the electrolysis stack influences its response rate: how rapidly the stack can respond to signals directing it to ramp its electric power consumption up or down. This response can be to either fluctuating power inputs, such as intermittent renewable energy generation, or signals from system operators. PEM, SOEC, and AEM technologies are best suited for responding quickly. Alkaline electrolyzers, in contrast, have liquid membranes with slower responsiveness. See Figure 6.

By understanding the flexibility requirements of a given system, modelers can narrow down which technologies to model. For example, it is best for alkaline systems to operate continuously to reduce issues from short-circuiting or slow start-ups, making them potentially more suitable for continuous baseload rather than balancing services. And, even though both AEM and PEM technologies can provide flexibility, PEM plants have faster ramp rates and start-up and shutdown times, making them better suited for balancing services, particularly when operating in systems with high shares of variable renewable energy and high net-load variability (EPRI, 2022b).

FIGURE 6
System Response of Electrolysis Systems

The rapid response rate of AEM and PEM systems makes them ideally suited for providing operational flexibility. Blue shading indicates faster response, and orange shading indicates slower response.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

Source: Adapted from EPRI (2023).

An electrolyzer's response is dependent not only on the electrolyzer stack, but can also be further constrained by the balance of plant. For example, SOEC systems have additional complexities relating to their high-temperature steam input that can limit their responsiveness (EPRI, 2022b).

Compression

Consideration should also be given to electrolyzers' auxiliary components, particularly compression systems for hydrogen that might be slower to respond than the electrolysis stack. While it is not feasible to model all process components in an electric power system model when considering flexibility, there is value in at least modeling both the electrolyzer and the compressor. Hydrogen must be compressed before being transported, and less compression means less electrical power consumed. When an electrolyzer operates at higher pressure, less compression is needed downstream before transportation. Most PEM and AEM systems operate at pressures of more than 70 bar, whereas alkaline and SOEC systems can operate at less than 30 bar. It should be noted, however, that while using less electrical power for compression is certainly advantageous, this high pressure can reduce the performance of the plant over time (see discussion on degradation below) (EPRI, 2022b).

Efficiency

Many power system models that focus on operational flexibility (like production cost models) currently simplify electrolyzer behavior, often using approximation methods inspired by established techniques used for thermal generator heat rate (or efficiency) curves. In particular, these models assume a constant power-to-hydrogen conversion ratio; however, the efficiency curves of electrolyzers are non-linear (Baumhof et al., 2023). Consensus does not exist in the research community about the level of detail necessary to model electrolyzer behavior. Baumhof et al. (2023) assessed the level of detail appropriate for alkaline systems. They posited that to ensure satisfactory dispatch decisions in the day-ahead time frame, the most accurate models should incorporate: (1) the non-linearity of hydrogen production curves (for tractability, piecewise linearization is necessary), and (2) three operating states (on, off, and standby), which allows the model to respect minimum loading points (see discussion on operating ranges above). Further, it can be useful to include operating temperature as an input variable for determining conversion efficiency. Conversion efficiency varies substantially between low-temperature electrolysis and high-temperature high-pressure (HTHP) steam electrolysis, where HTHP conversion efficiencies can be nearly double the efficiency of ambient temperature conversion. Continued research on HTHP shows that conversion efficiencies of more than 90% are achievable in applications around 700-900^{0}C. This will substantially impact the operational conversion cost due to lower electricity cost per unit of hydrogen production (Boardman and Ding, 2019; Vostakola et al., 2023). Of course, the cost of generating the heat supply for efficiency gains must also be taken into account, as must the question of whether the heat supply results from a residual process or is dedicated for hydrogen production.

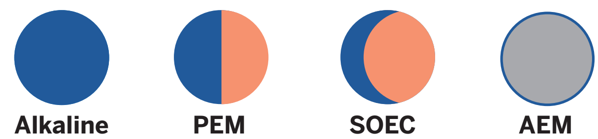
For power system investment decisions and forecasts, the use of average heat rates or less detail may be satisfactory. But in cases where greater accuracy is valued, Baumhof et al. (2023) found that for operational problems, simplifications caused sub-optimal scheduling of hydrogen production in response to grid needs and reduced profit, essentially under-estimating the value of flexibility from hydrogen. This under-estimation is sensitive to assumptions about electricity prices, hydrogen prices, standby power consumption, and start-up costs. Further research is required to understand the trade-offs between operational detail and computational burden for assessing intra-hour flexibility.

Degradation

An important and ongoing research question is the impact of operating profiles on electrolyzer stack degradation, measured as reduction in hydrogen production. Efficiencies and response time will be impacted by the degradation of the stack over time; however, we do not have sufficient data to assess how variable operating conditions, as required especially for operational flexibility, will impact degradation. Stack degradation can likely affect cost estimates and operator willingness to provide grid flexibility services, as stack replacement costs are the

FIGURE 7

Stack Lifetime for Electrolysis Systems



Alkaline electrolysis has the longest stack lifetime, and it may be possible to refurbish rather than replace the stack. SOECs' ceramic materials cause shorter stack lifetimes. Blue shading indicates a longer stack lifetime, and orange shading indicates a shorter stack lifetime. Gray shading indicates that information was not available.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

Source: Adapted from EPRI (2023).

largest non-electricity operations and maintenance costs. Among electrolysis technologies, alkaline stacks have the longest life, due to the technology's maturity and mild operating conditions. Recent surveys of manufacturers suggest that the degradation rate for alkaline electrolysis is approximately 1% to 1.5% per year and approximately 1.5% per year for PEM. SOECs have the shortest life: since these operate at a much higher temperature, the ceramic materials used in their design cause much shorter stack lifetimes. See Figure 7.

Incorporating Results of Site-Specific Models into Electric Power System Models

Site-specific models are in use today to support electrolyzer design and evaluate multiple site designs, sizes, and operational profiles for economic analysis. Common outputs are system capital and operating costs. In many cases, these models are used to determine the levelized cost of hydrogen (LCOH), a metric that indicates the cost of producing hydrogen, often without consideration of additional conversion, storage, or transportation costs. Like the related metrics of levelized cost of energy (LCOE) and levelized cost of storage (LCOS), LCOH does not evaluate the market value, potential revenues from the provision of ancillary services, or total system costs. Today, site-specific models are typically used alone to inform plant design decisions (likely considering only how to minimize LCOH). However, if co-optimized or integrated into power system models, modelers can develop insights on designs that facilitate operation of

a hydrogen plant when providing flexibility to the power system.

Site-specific models consider various site details and performance optimization options including:

- Optimizing electrolyzer design and its coupling with battery storage or other on-site generation
- Electrolyzer technology
- Size of electrolyzer relative to the supply of renewables (considering both renewable generation and transmission network capacity) to maximize efficiency
- Size and design of hydrogen storage to meet minimum and maximum pressure and mass requirements
- Design of blending controls for specific systems
- Generation turbine sizing to meet efficiency and output needs

Site details can be used as inputs of power system models; conversely, power system models that describe the supply of renewables or other grid-connected generation can be input into site-specific models.

One beneficial outcome of site-specific models for power system planning and operational studies is an understanding of which components may be the slowest-responding component of the hydrogen production facility. While the discussion above focuses on electrolyzers, if there are slower-responding components at the hydrogen production facility, power system models should capture these limitations, perhaps by reducing the resolution on the electrolyzer and emphasizing a different component. For example, components that can potentially be as important as the electrolyzer in determining response time include the rate of compression of hydrogen into storage (and whether it is stored in gaseous or liquid form in pressure vessels), the type of storage (e.g., salt cavern or aquifer), transportation lags and pressure considerations of hydrogen pipelines, and other operational considerations relating to hydrogen storage. Although site-specific modeling and power system modeling are typically conducted separately, better integration between the two can provide more insights on plant designs that provide both flexibility and reduce the cost of hydrogen.

Components that can potentially be as important as the electrolyzer in determining response time include the rate of compression of hydrogen into storage, the type of storage, and transportation lags and pressure considerations of hydrogen pipelines.

Data Needed to Evaluate Emerging Flexibility Resources

To model multiple energy systems, a range of system-level data will be needed across the systems. Below, we describe what is currently used and where gaps will need to be filled.

Power System Data

To model how hydrogen technology interacts with the electricity sector, a range of data types will be needed including the following:

- Generation resources, current and expected transmission, and other data typical to power system production cost modeling studies (e.g., heat rates, minimum/maximum output, start costs for generators, and transmission flow constraints for the network)
- Renewable resource information and hourly (or sub-hourly) output in locations both close to the electrolyzer and system-wide, ideally over multiple years
- System services needed in future electric power systems, including the amount needed and capabilities that generation resources will need to have to provide such services
- Load profile and demand data for both the electrical load and the electrolytic hydrogen production at a suitable spatial granularity
- Information about the feasibility of hydrogen storage for shifting electrical load across time for different end uses
- Likely location of the new renewable resources that can be used to supply green hydrogen in relation to the transmission network (i.e., are they located in industrial hubs and may already have good transmission, or are they likely to need network upgrades)

Modelers and planners typically gather these data from various sources, and there is a need for high-resolution country- and region-level datasets with all the key parameters reviewed and updated regularly.

In addition to power system data covering renewable electricity generation and electricity transmission, the green hydrogen supply chain requires detailed information on water acquisition, green hydrogen production processes, additional feedstock sources, hydrogen molecule conversion technologies, conversion efficiencies, transport infrastructure, seasonal storage solutions, and reconversion processes for direct use (Figure 8, p. 23).

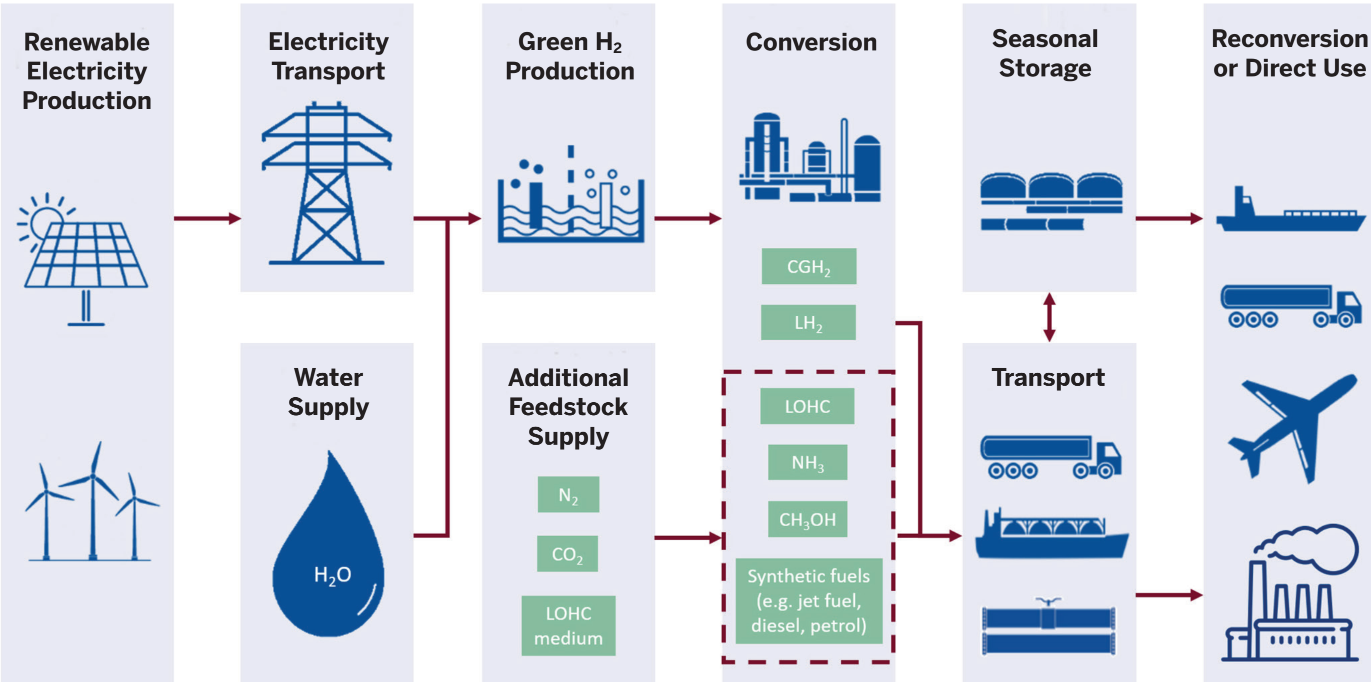
Renewable Electricity Generation Data

Renewable resource datasets provide information on the available renewable resources, such as wind and solar, that can be used for electrolysis-based hydrogen production. These datasets are typically sourced from historical generation data, created using numerical weather prediction and statistical methods, or, more recently, processed using artificial intelligence and machine learning models. While historical generation data can provide insights into past generation, they tend to overlook energy that was not produced due to grid constraints (curtailed energy) when data on actual generation are used instead of data on available generation (i.e., the sum of the nameplate capacity of installed resources). Including curtailed energy can provide a more transparent and accurate representation of the available energy resources. In contrast, forecasts using numerical weather prediction and statistical methods, as well as artificial intelligence and machine learning models, can provide estimates of the available generation, but the results require validation.[9]

9 See Energy Systems Integration Group (2023) for an extensive discussion of weather data needed for power system modeling for high-renewables systems.

FIGURE 8

Green Hydrogen Supply Chain



The hydrogen supply chain has multiple stages, beginning with renewable electricity production and transmission (or electricity transport) and continuing through the production of hydrogen, conversion and transport of hydrogen molecules, and reconversion processes for direct use.

Source: https://www.hoou.de/projects/green-hydrogen/pages/3-4-hydrogen-supply-chains.

Generally, renewable resource datasets have at least one hour of granularity with locations closest to the existing and candidate power plants. The system or market operators typically publish actual generation data of the existing power plants, but data completeness is not always guaranteed. Some operators publish actual generation of renewable resources on a plant basis, while others aggregate actual generation system-wide and regionally. Weather datasets can be used to derive renewable resource datasets to address the data completeness issue, but validation is required (see ESIG (2023)). Both datasets can be obtained either publicly or commercially.

Uncertainty in the data can be addressed by using multiple years. For example, the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 Reanalysis has solar data with one hour of granularity and 31 km spatial resolution from 1979 to the present;[10] however, renewable resource datasets are needed that can achieve high temporal (e.g., 15 minutes or less) and spatial (e.g., less than 5 km) resolution to capture as much resource variability as possible, and obtain at least 30 weather years to reflect climate trends as recommended by the World Meteorological Organization (WMO, 2021).

Electricity Transmission and Water Supply Data

Data on the amount and location of existing and future electricity infrastructure and freshwater supply are essential to estimate the practical sites for hydrogen technology for use in power system modeling. Green hydrogen facilities will locate near renewable resources and will require robust transmission infrastructure; however, renewable resources are often in regions

10 See https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form.

with weak transmission infrastructure. While data on transmission lines are generally available, and there is widespread interest in and efforts around expanding large-scale transmission, uncertainty about future projects remains. The relative timing of new generation projects and new transmission projects also remains challenging: how to justify building transmission to regions that do not yet have high generation, or how to incentivize renewables developers to build in regions that do not yet have adequate transmission infrastructure in place. Green hydrogen facilities will also need freshwater supply. Like renewable resource datasets, data on freshwater supply can be gathered from various water agencies, but there is no assurance the data are complete. One example is the National Water Information System developed by the U.S. Geological Survey to map and provide data access to water sites in the United States.[11] The level of information varies by water site in the system, with some water sites having time series data as far back as October 1, 1950, and others having only the most recent 120 days of provisional data available.[12]

In addition to needing the actual data on transmission and water supply, modeling green hydrogen production's potential contribution to power system flexibility requires capturing the interaction between these two data types and the hydrogen technology in space and time. Additional information is needed on the dynamics between the operation of the hydrogen technology and the power system while utilizing the water supply spatially and temporally. In certain instances, the choice of location for hydrogen production will be dictated by the end user's location, particularly large industrial facilities with high hydrogen demand, and not influenced solely by its proximity to renewable energy sources.

To be able to model optimized locations for hydrogen technology, it is ideal to have a country- or region-level dataset of electricity transmission, both existing and future, and water supply. However, confidentiality concerns, especially for transmission data, can be a roadblock. Data aggregation, supported by appropriate policy frameworks, presents a practical way to balance privacy and usability. This simplifies complex datasets, facilitating efficient analysis and optimized hydrogen siting, ultimately paving the way for a role for hydrogen in providing flexibility to future power systems.

Data for Hydrogen Production

Green Hydrogen Production Data

Because green hydrogen technology is not yet proven at scale, the estimated capacity and location of green hydrogen production is driven by the scenarios considered and the assumptions made in a given model. For example, the National Renewable Energy Laboratory has estimated green hydrogen's economic potential in the U.S. by the mid-21st century as approximately 35 megatonnes per year, assuming low-temperature electrolysis using a low-cost, dispatch-constrained electricity scenario (see Ruth et al. (2020)). Other projections suggest the green hydrogen production potential in European Union countries in 2050 to be 106 megatonnes per year (Nuñez-Jimenez and De Blasio, 2022).

Electrolyzers, as the key component of hydrogen technology, are typically simplified in power system models and limited to a few input parameters: investment cost, operation and maintenance cost, efficiency, lifetime, and water consumption (Nuñez-Jimenez and De Blasio, 2022). Assumed values for these parameters are typically constant and do not consider learning curves: costs and efficiency values are likely to change as hydrogen technology matures and reaches economies of scale. The increased efficiency may impact the level of operation of hydrogen technology, which in turn could affect water consumption. It may also impact electrolyzers' lifetime as well as degradation, a parameter not listed in the simplified electrolyzer models. Patenting trends are already pointing to increased technological efficiency and production capacity, which will likely reduce electrolyzers' costs (IRENA, 2022).

A set of firmly established hydrogen production data for existing and new parameters of electrolysis-based hydrogen technology is needed to better characterize the potential role of green hydrogen technology as a flexible resource on the grid (see the section "Modeling Grid Services from Hydrogen Production via Electrolyzers" above).

11 See Water Resources of the United States—National Water Information System Mapper at https://maps.waterdata.usgs.gov/mapper/index.html.

12 See the U.S. Geological Survey's Water Data for the Nation at https://waterdata.usgs.gov/nwis/?IV_data_availability.html.

> **To better simulate electrolyzer operations, electrolyzer models must expand beyond typical parameters to include auxiliary loads, start times, ramp rates, operating ranges, and capacity factors.**

Operational Data

To better simulate electrolyzer operations, electrolyzer models must expand beyond typical parameters to include (but not be limited to) auxiliary loads, start times, ramp rates, operating ranges, and capacity factors. In addition, incorporating constraints arising from water scarcity is essential for realistic assessments, especially in regions with limited water supply.

Data on Hydrogen as a Fuel and Feedstock

Conversion, Transport, and Storage of Hydrogen

Hydrogen can be stored using physical methods or material-based methods. Physical storage includes compressed gaseous hydrogen and liquefied hydrogen, while material-based storage includes the use of liquid organic hydrogen carriers, ammonia (NH_3), methanol (CH_3OH), and metal hydrides. Material-based storage methods, unlike physical storage methods, require additional feedstock to be supplied to function as hydrogen carriers. Hydrogen is then transported in special tanks or stored further before being used or transported through dedicated pipelines for electricity generation or other industries.

Since hydrogen technology is not yet commercially deployed at scale, existing power system models tend to neglect data related to hydrogen conversion, transportation, and storage processes that may be crucial in the analysis. However, the performance of conversion, transport, and storage processes will vary depending on assumptions (e.g., efficiency and operational constraints). Similar to operational data, a set of firmly established data supporting modeling assumptions on conversion, transport, and storage processes is needed for existing and new parameters that significantly impact the performance of hydrogen technology as a provider of system flexibility.

Direct Use and Export

Green hydrogen can be used both in power generation and in industrial processes as feedstock. In power generation, the input parameters for hydrogen combustion turbines are typically benchmarked with natural gas

turbines (see Table C-1 of Ruth et al. (2020) for assumed values). NO_6 emissions should be represented for hydrogen combustion turbines, which will need either (a) better emission mitigation using selective catalytic reduction (SCR), (b) improved combustion physics to reduce NO_x production, or (c) utilization of pure oxygen rather than air for combustion, which could make a lot of sense for dual hydrogen production/power generation systems in which pure oxygen is an output of the electrolyzer. Also, it is worth noting the trade-off between capital expenditure and efficiency for hydrogen turbines and fuel cells, where turbines are likely to have lower capital expenditure, while fuel cells have higher thermodynamic efficiency.

Where green hydrogen is used in the manufacture of industrial products such as green steel and ammonia, the input parameters in power system models will be focused on the additional hydrogen demand and potential hydrogen export, which are driven by scenario assumptions. To cite an example, 1 megatonne of annual green steel production would require 50,000 tonnes of green hydrogen, 0.56 GW electrolyzer capacity, and 0.7 GW of renewables capacity (Wallach, 2022). Excess hydrogen in the process can be utilized as a potential export to other countries or regions.

The data assumptions about hydrogen conversion processes used, projected hydrogen demand in the industry, and potential hydrogen exports can significantly impact the amount of system flexibility hydrogen technology can provide. It is essential to establish the values of the parameters specific to the hydrogen combustion turbine. Gathering more data, including demand profiles, will improve forecasts of future hydrogen needs and potential exports, facilitating better planning.

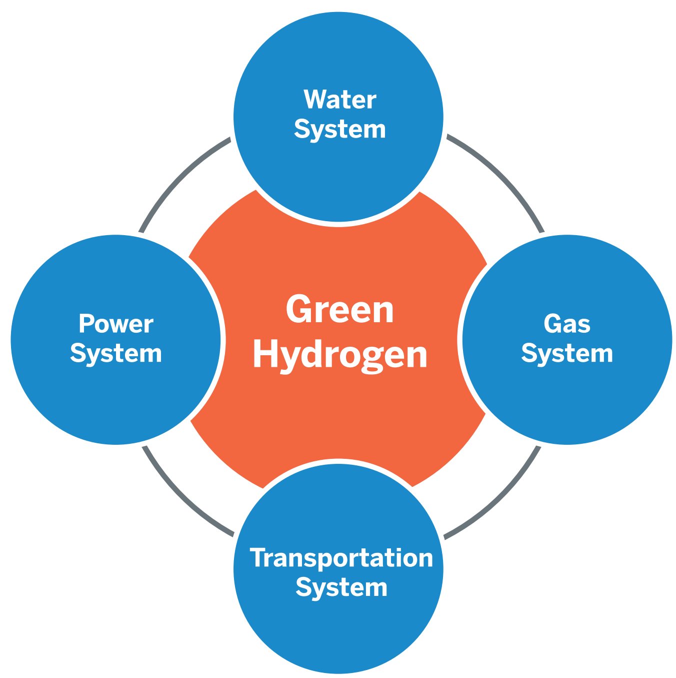
Synergies with Other Sectors

Hydrogen technology, while a potential player in the clean energy revolution, is not a solo act. Its true potential as a provider of system flexibility can be realized when it synergizes with other sectors. It will be fundamentally important to model how hydrogen technology interacts with sectors other than the electricity sector and assess how the whole system will likely interact to build a green hydrogen economy (see Figure 9) in order to understand the data needs in the future. While cost-sharing and benefits from system-coupling are not the focus of this report, it is worth discussing these synergies, as the operation of one system may directly or indirectly impact other systems in the future, particularly with more hydrogen technology.

Ideally, modeling a fully integrated system, where green hydrogen is coupled with all other systems, is the preferred approach to capture the cost-sharing and benefits from system coupling (or sector coupling). However, the complexity of this approach makes modeling costly and time-consuming.

One alternative approach is to couple green hydrogen with each system in a staged manner. For example, begin with stage 1 analysis using a green hydrogen/water system–coupled model to assess the estimated hydrogen potential. Feedback loops will or should exist between systems and need to be considered to capture aspects not seen in a stand-alone model. Note that industrial electrification

FIGURE 9
Green Hydrogen's Synergy with Other Sectors



Assessing green hydrogen's potential to provide flexibility can also factor in other interdependent systems, including water, gas, and hydrogen demand in the transportation system.

Source: Energy Systems Integration Group.

needs to be taken into account in each element of the system coupling.

To be able to model these system couplings, data for the water system, natural gas system, and transportation system are necessary.

Water System Data

As mentioned earlier, water supply data, including water infrastructure, are usually in various water agencies. Missing information entails additional research and surveys. To effectively model the effects of water availability on hydrogen production will require a national dataset of water supply data, including the water network.

Natural Gas System Data

Data on the natural gas system, consisting of gas demand, supply, and infrastructure, are considered sensitive data and kept confidential. There is a need for a national dataset of gas system data suitable for modeling the green hydrogen/gas system coupling. Such a dataset could be made available only to national planners, who would provide analytical insights to all stakeholders regularly.

Transportation System Data

Transportation system data comprise the transportation sector's demand, supply, infrastructure, and electrification data. Historical and forecasted data are typically available from state and federal transportation, and missing information will require additional research and surveys. While a country- or region-level dataset on the transportation system is ideal, an aggregated version suitable for the green hydrogen/transportation system coupling is practical considering the confidentiality of information. Again, not all of the above information will be available, but the idea is to develop the concepts and identify potentially essential gaps in understanding while laying out what we currently know.

Next Steps

Modeling the flexibility of hydrogen introduces new considerations beyond what power system models have typically incorporated. Modeling hydrogen's potential to provide grid flexibility is a complex effort, involving many options and permutations of potential electrolysis systems, operating regimes, and grid services to target.

Potential grid services include:

- **Regulation:** To manage, on a second-to-second basis, uncertainty from forecast errors and generator responsiveness
- **Balancing (also known as ramping or load-following):** To manage variability and uncertainty within an hour and across hours
- **Operating reserve:** To manage contingencies or operational events—such as any combination of forced outages and periods of low wind or solar
- **Seasonal energy arbitrage:** To manage the mismatch of resource availability and load across seasons

Modelers may consider the following questions to narrow their scope of study and select appropriate data inputs to incorporate:

- What grid services are needed in a given geographical area?
- What models are best suited for assessing these grid services?
- What is the time horizon being studied?
- How might other end uses impact the flexibility that a hydrogen facility provides?
- What electrolysis system is best suited for providing the grid service(s) needed?
- What model inputs (degradation rates, response times, etc.) are most critical for the grid service(s) being studied?
- How can the availability and uncertainties of supporting infrastructure be considered (such as cost of pipelines or hydrogen storage)?
- Is it important to consider the interactions between hydrogen production and use and electric power markets, especially as they relate to real-time pricing or availability?
- What data sources are available to develop model inputs?

This report aims to assist modelers in assessing how green hydrogen production could contribute to grid flexibility as levels of renewable generation rise. As an emerging resource for power system applications, there is limited consensus today on best practices for modeling hydrogen production. However, organizations can still begin to study the role of hydrogen in providing grid flexibility. They can develop initial models, monitor improvements in the cost and performance of hydrogen, and use this information to continually update their models. In parallel, research and software improvements will enhance modeling techniques for future studies. As the industry matures, knowledge and experience from academia, research institutions, software developers, hydrogen technology developers, and system modelers can be shared and used to move the industry toward effective techniques and best practices.

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PHOTOS

Assessing the Flexibility of Green Hydrogen in Power System Models

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

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The report is available at https://www.esig.energy/green-hydrogen-in-power-system-models.

To learn more about ESIG's work on this topic, 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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