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Hydrogen and electricity: Parallels, interactions, and convergence

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ABSTRACT

A future hydrogen economy would interact with and influence the electricity grid in numerous ways. This paper presents several concepts for understanding a hydrogen economy in the context of the co-evolution with the electricity sector and lays out some of the opportunities and challenges. H_2 and electricity are complementary energy carriers that have distinct characteristics, which lead to more or less utility in different applications. Despite their differences, it is possible to understand a future hydrogen economy using some of the same techniques as electricity system analysis. Hydrogen pathways will lead to additional electric demands that will influence the structure, operation and emissions in the electric sector. Examples of convergence between these sectors include a number of options for H_2 and electricity co-production and interconversion.

1. Introduction

The transport sector has traditionally had little interaction with the electricity sector because of the differences in their requirements and the historical circumstances associated with their technical development. In the early 20th century, battery electric vehicles (BEVs) and gasoline internal combustion engine vehicles (ICEVs) were emerging options for widespread personal transport [1]. Gasoline soon became the dominant energy source for vehicles, in part, because of its high energy density as compared to electricity, which cannot be easily stored at a density comparable to liquid fuels.

During the 20th century, electricity also came into wide use for almost every other conceivable application, and is now distributed to consumers throughout the industrialized world. The electricity system has taken a very different form than the transportation supply system. Unlike transportation fuels, electricity is made from a wide variety of primary sources: coal, natural gas, oil, hydropower, nuclear and renewables. And despite ongoing research and development in electricity storage, the difficulty of bulk storage of electricity has dictated the design and operation of the electricity system and battery technology still cannot match, or come close to, the energy density, refueling time or cost of liquid fuels.

Recently, concerns about air pollution, oil insecurity and especially greenhouse gas (GHG) emissions have been driving a search for new transportation fuels and vehicle technologies. In particular, the last few decades have seen a renewed interest and significant research and development on electric drive vehicles including BEVs, hybrid electric vehicles and hydrogen fuel cell vehicles (FCVs). Because of their ability to convert hydrogen into electricity, fuel cells combine the benefits of electric drive with a storable gaseous fuel with reasonable energy density that can be dispensed quickly. Using hydrogen as a transportation energy carrier has been widely, but not universally, touted as a key solution for many of the environmental and geopolitical problems associated

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with burning petroleum-based fuels such as gasoline and diesel [2,3]. Hydrogen FCVs will have zero emissions of criteria pollutants in urban areas, can be significantly more efficient than conventional vehicles, and permit the use of domestic energy and low carbon resources for fuel production. Hydrogen vehicles must, however, overcome a number of challenges, technical and economic, in order to become a feasible option for consumer light-duty vehicles LDVs [2,4,5].

This paper will present several concepts of an integrated energy future with important connections between hydrogen transportation fuels and electricity for stationary applications. One primary theme is that given these connections, the distinct transportation fuel and stationary electricity sectors will converge and co-evolve as they address the challenges of reducing GHG emissions. The future of these sectors, as envisioned, involves two energy carriers (hydrogen and electricity) that are highly integrated with numerous interconnections that need to be explored in greater detail. Another important theme is that while each of these energy carriers can be produced from a similar set of resources, each has its own set of characteristics that govern its production, transport, storage and use, so the particular requirements of the application will dictate which energy carrier is used in an integrated energy future. The first section of the paper focuses on the parallels between hydrogen and electricity and how a hydrogen infrastructure could develop along similar lines as and co-evolve with the electricity sector. Another section looks at electricity demands for a hydrogen-based transportation future. Finally, the last section analyzes issues related to convergence including feedstock competition and integrated infrastructure. While the integration between the transportation and electricity sectors appears to be one of the crucial issues for the future of a hydrogen economy, this topic has not been studied extensively. This paper will also begin to identify those interactions as well as some of the challenges and benefits of the changes that these interactions will bring about, including economic and environmental impacts.

2. Introduction to hydrogen and electricity

The potential development of a future hydrogen economy would take place in the context of an existing electricity industry that has developed over the last century and continues to evolve. Given the challenges and costs associated with large-scale bulk electricity storage, the power system has evolved in such a way to generate electricity at the time it is needed. The unique characteristics of electricity and its long history have resulted in an extensive infrastructure that converts primary energy resources such as fossil fuels, nuclear energy and renewable energy resources into electricity and distributes the electricity to consumers essentially everywhere in the developed world. Any hydrogen infrastructure development can potentially take advantage of this expansive network of energy resource extraction and transport and electricity generation and distribution systems. The new infrastructure can also utilize the advantages of hydrogen to complement the use of electricity in some applications. However, this hydrogen infrastructure development can be viewed through several different lenses depending upon how integrated a future one imagines for the co-evolution of the hydrogen and electricity systems.

2.1. *Standard view of* H_2 *and fuel cells*

Much of the interest and research in H_2 and fuel cells has been in the transportation sector, with many automotive companies developing low temperature proton exchange membrane (PEM) FCV research, development and demonstration (RD&D) programs in the last decade [6,7]. Energy companies have also been involved with RD&D projects for H_2 production and refueling. Significant research and development is also being carried out on stationary fuel cells for use in the electric sector and stationary fuel cells could become widely available before their counterparts in the transport sector. However, hydrogen infrastructure is typically viewed as a transportation fuel supply system to be used in connection with FCVs. Most stationary fuel cells do not require a ubiquitous hydrogen infrastructure since they are able to run on hydrocarbon fuels such as natural gas, which already has an extensive distribution infrastructure. Vehicles, on the other hand, require a widespread infrastructure to produce, store, transport and dispense hydrogen at a network of refueling stations [8–10].

Because of the focus on hydrogen production and refueling infrastructure in the light-duty transportation sector, the standard view of many in and out of the field is that hydrogen is a transportation fuel that will compete with and could eventually displace gasoline and diesel. Hydrogen and fuel cells are widely touted as an excellent alternative to gasoline because of its benefits with respect to efficiency, resource requirements and environmental attributes [2,6,11–14]. Perhaps the most important driver for FCVs is the challenge of addressing climate change. The logical corollary to the view of hydrogen as a replacement for gasoline is that the hydrogen infrastructure needed to convert a primary energy feedstock to H_2 and store, transport, distribute and dispense that hydrogen for use in personal vehicles will be analogous to the exploration, refining, distribution and dispensing infrastructure for gasoline and diesel fuels. Many hydrogen-related analyses and research programs focus primarily on hydrogen as a vehicle fuel [2,13–16]. This focus can be thought of as the evolutionary model of H_2 and fuel cells, because they are viewed as merely cleaner and more efficient technologies that will be used for LDVs. This framework is convenient because it does not require a fundamental change in how people will interact with or think about their vehicles and fuel, how we drive and supply fuel to our cars. In this view, hydrogen is a replacement for gasoline and fuel cells are a replacement for internal combustion engines. And the change can be thought of as merely another step in the evolution of the form of our transportation fuels, which has transitioned from solid fuels (coal and biomass) to liquid fuels (gasoline and diesel), and will transition to gaseous fuels (natural gas and hydrogen) and electricity.

2.2. *Alternative views of* H_2*, fuel cells and electricity*

In the alternative view, H_2 and fuel cells are not merely replacements for components (i.e. gasoline and internal combustion engines) in the conventional transportation paradigm. Instead, they represent a new path that will be integrated with the electricity system, forming a future energy system with two primary energy carriers (hydrogen and electricity). There are multiple reasons for this convergence of hydrogen and electricity into an integrated hydrogen electric energy system (HEES), including their complementary attributes as energy carriers, their potential production from the same primary energy resources and their ability to be co-produced and interconverted.

2.2.1. *Complementary attributes and applications*

H_2 and electricity are two decarbonized energy carriers that have several complementary attributes, which suggest specific uses and applications for each. With the emerging scientific, political, and public consensus on climate change, there will be an increasing impetus for reducing and eventually decarbonizing our energy system. Hydrogen and electricity are two energy carriers that enable conversion, transport and utilization of a wide variety of primary energy resources in a decarbonized energy system.

The specific energy carrier attributes and their alignment with the needs of particular application are the critical determinants in the choice of energy carrier. Electricity is the most useful form of energy for a wide variety of end-use applications because of its flexibility, ease of conversion to other useful forms of energy (heat, light and mechanical power) and use in powering electronic devices. The limitations of electricity are mainly a result of the difficulty of storing electrical energy. Hydrogen is an attractive fuel for a number of applications that can take advantage of its unique characteristics: It is a chemical (fluid) energy carrier that can be stored at high energy density, used with high efficiency, produces no emissions at the point-of-use, and it can be produced (at large-scale) from a multitude of energy resources at costs that are comparable to current liquid fuels. One of the main advantages that hydrogen possesses with respect to electricity relates to storage, in terms of higher energy density and lower cost. As a result, the most widely discussed application for hydrogen and fuel cells is to power LDVs, where these particular attributes are highly valued and can provide a relative advantage with respect to other available or potential technologies. This subject will be discussed in more detail in Section 2.3. Another likely application for hydrogen in a future hydrogen economy is electricity storage, for intermittent renewables (such as solar and wind) and off-peak baseload power, by means of the production of hydrogen via electrolysis. This interconversion between hydrogen and electricity could be a significant component of how a future hydrogen economy would operate since there would likely be synergies between storing electricity and producing alternative energy carriers and transportation fuels.

2.2.2. *Convergence and competition for resources*

Another basic idea supporting the concept of hydrogen and electricity convergence is that hydrogen and electricity can and will be produced from the same primary energy resources and feedstocks, such as natural gas, coal and biomass (see Fig. 1). It is important to note that there are significant benefits associated with having another energy carrier, especially one that can be used in transportation applications that can be made from a large number of primary energy resources. This would also lead to a direct competition for the fossil, nuclear and renewable energy resources that are used to produce each energy carrier. The implications of this competition are important for several reasons. The transportation and electricity sectors have traditionally been separate with very little interaction. However, with the greater reliance on the same resources, any change in the price of one energy carrier relative to the other one, would have implications for the mix of resources that are used to generate each. These dynamics would impact the trends in carbon intensity (i.e. gCO_2/MJ energy carrier) with competition for renewable and decarbonized resources to reduce GHG emissions. Also since feedstock costs play a large role in the price of energy carriers (transportation fuels and electricity), the reliance on the same resources could lead to a much tighter coupling between the price of energy in both sectors. Since a rise in price of one energy carrier leads to a higher willingness to pay for the underlying energy resources, this would lead to a higher price for the other energy carrier.

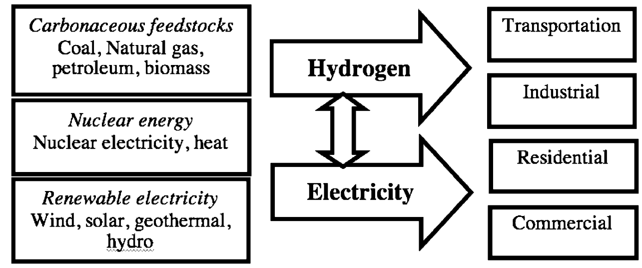

Fig. 1 – Schematic showing the parallel nature hydrogen and electricity from the perspective of the energy resources and end-use sectors.

2.2.3. *Co-production and interconversion*

A third argument for the convergence of hydrogen and electricity is related to the potential for their co-production and interconversion. A number of studies have looked at plants that can be used to produce both hydrogen and electricity [17–25]. In many of these studies, there are a number of possible benefits associated producing both energy carriers in the same plant, including improved resource utilization efficiency and lower costs. These benefits and examples of co-production options are discussed in more detail in Section 4.2. Interconversion is one of the most tangible examples of the shift towards a more integrated energy economy based upon hydrogen and electricity. With current energy carriers, there is little opportunity to convert between various forms. In addition, the widespread use and supporting infrastructure for these dual energy carriers may provide reliability benefits for consumers.

It is important to note that these interconversions are accomplished in real-world energy conversion devices (fuel cells and electrolyzers) that have non-negligible energy losses as well as significant costs. As a result, while these conversions appear to be simple and these energy carriers fungible, there are limited applications where the efficiency penalty and costs associated with interconversion make sense given current energy costs and technologies. An example of such an application is the storage of electricity to balance the intermittent generation at remote wind generation farms [26].

Fig. 2 presents two different views of the hydrogen reactions in a fuel cell and electrolyzer. The "electrochemical" view shows the fuel cell reaction (on the right) that produces electricity when hydrogen and oxygen combine to form water and the electrolysis reaction (on the left) where electricity is required as an input to split water into hydrogen and oxygen. In this view, electricity and hydrogen have different roles: hydrogen is merely an enabler, while electricity is the primary focus (i.e. either the product or the input). This view is common when focusing on the end-use of hydrogen; for example, if one thinks of a FCV as an electric vehicle, that obtains its electricity from hydrogen.

The "interconversion" view describes the exact same reactions but emphasizes the conversions between electricity and hydrogen, rather than the water to hydrogen and oxygen conversion of the electrochemical view. This alternative view shows that H_2 (plus O_2) and electricity are merely different forms of the same energy carrier that result from the addition and removal of water, where hydrogen is the hydrated form and electricity is the dehydrated form. This view emphasizes the large impacts that hydrogen production and conversion would have throughout the energy system, on the production, transmission and conversion of energy. In later sections, the paper will discuss many of the important elements that arise from the "interconversion" view, including parallels between electricity and hydrogen infrastructure systems, and co-production and interconversion schemes for the production of these two energy carriers. It is not the case that one view is better or worse than the other, but the significance of these two views is that they help to make clear, by emphasizing these different aspects of the relationship between H_2 and electricity.

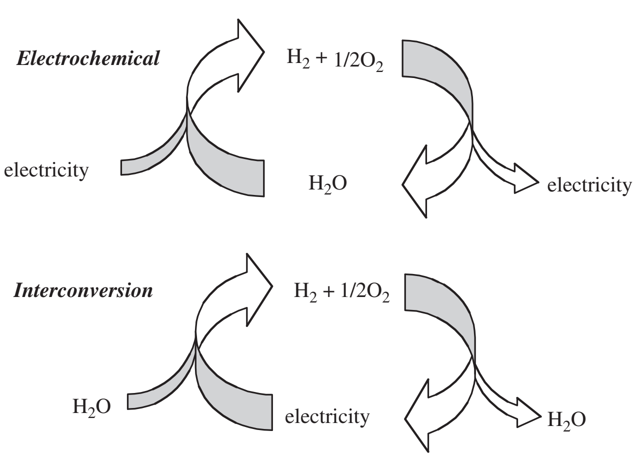

Fig. 2 – Alternative views of hydrogen and electricity reactions. The electrochemical view shows electricity as either an input or output of chemical reactions and the interconversion view shows water as an input or output of the conversion between H_2 and electricity.

2.3. *Fuel cells versus batteries for transportation*

Given the benefits associated with electric drive vehicles, hydrogen and electricity are in competition as the main energy carrier for LDVs. While a large number of automakers are actively researching and developing hydrogen FCVs, a number of them are also looking into battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) [27,28]. A third option for a future sustainable transportation fuel is the use of biofuels such as ethanol or biodiesel in ICEVs. BEVs have a long and interesting history that spans their introduction in the early 20th century and their brief resurgence and demise in the late 20th century [1]. Recently, a great deal of attention has been focused on the "plug-in hybrid electric vehicle" (PHEV), which can be called, more specifically, a grid-connected, charge-depleting hybrid electric vehicle. Users connect these vehicles to the electricity grid to recharge the vehicle. The PHEV is flexible in that if it runs on a combination of electricity and another fuel such as gasoline, so that it does not have the same charging time and range limitations of a dedicated battery powered vehicle [27–29].

Hydrogen is attractive for both vehicles and distributed generation because of its high conversion efficiency, when coupled with fuel cells. Fuel cell conversion of H_2 to electricity can be very efficient at small scale, compared to more typical internal combustion engine chemical fuel-to-electricity or fuel-to-mechanical work conversions (40–60% vs 20–40%)[1] [3]. As a result, FCVs will have a very significant fuel economy advantage over conventional ICEVs, even when considering the full life-cycle energy efficiency [27,30]. Also, unlike internal combustion engines, fuel cell efficiency is even higher at partial load, which is the typical state of a vehicle power plant, than at maximum power [3]. Improved vehicle efficiency, zero emissions, and the potential to use numerous domestic and renewable resources, makes hydrogen an attractive energy carrier for vehicles.

Electricity is, in many ways, the ideal alternative energy source for vehicles because of its numerous benefits: (i) electricity can be used very efficiently on board the vehicle, (ii) it is quiet, (iii) it has zero point-of-use emissions, (iv) since electricity generation occurs at a few central locations, it is easier to regulate and control pollutant and GHG emissions, (v) it is much less expensive per mile driven than an equivalent amount of gasoline and (vi) it can be made from numerous domestic resources. The main challenges with electric vehicles are the cost and energy density of electricity storage on the vehicle, in the form of batteries [31]. There has been significant research and development into improving batteries, but still battery-based electric vehicles are unable to compete with conventional vehicles in terms of vehicle range, refueling time and cost (related to the challenges of storing electricity). As a result of the storage challenge, electricity is generally better suited towards stationary applications, where

[1] Hybrid systems such as natural gas combined cycle (NGCC) or solid oxide fuel cell/gas turbine (SOFC-GT) can be even higher efficiency.

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electricity can be produced to match the demand, without the need for intermediate storage. In fact, FCVs are electric vehicles with an alternative electricity storage system, which consists of hydrogen fuel and a hydrogen-to-electricity conversion device (the fuel cell). FCVs produce electricity on-board the vehicle at the time and quantity that is needed to match the demands of the electric propulsion motor and vehicle auxiliaries, without the need for intermediate storage. One of the major questions for future alternative fuels and advanced vehicles is which system (batteries or hydrogen and fuel cells) will achieve the technical goals and cost reductions necessary to overcome the challenges with providing electricity for vehicle propulsion to make electric vehicles a commercial success.

However, even this competition could be turned into a complementary relationship. Given the energy storage limitations associated with batteries, some have suggested that battery vehicles can make sense for smaller low power, limited-range vehicles (e.g. electric bikes, scooters and neighborhood electric vehicles) [32]. These small BEVs would not compete directly with larger FCVs but the vehicles would occupy different niches, which respond to different consumer needs. Another view of the complementary nature of hydrogen and electricity is an exciting technology that combines both into the same vehicle. This combination was highlighted when General Motors introduced their gasoline PHEV, the Chevy Volt, and also mentioned the future possibility of a fuel cell option for the PHEV. This would enable the vehicle to obtain electricity in two separate ways, from the grid via storage batteries as well as from a hydrogen fuel cell. This hybrid system would allow for the best utilization of each of the energy carriers attributes, including low cost for grid electricity (relative to fuel cell generated electricity) and the greater energy storage and quick refueling of hydrogen relative to batteries. These systems are also complementary in the sense that beyond the energy storage component of the vehicle, the remainder of the vehicle (including electric motors, motor controllers, power electronics, and electronic drive systems) are essentially the same and advances in one class of vehicle will spill over to improve the technology for other electric drive vehicles.

Additionally, electric drive vehicles (including PHEVs and FCVs) could provide some benefits to the electricity supply system, including utilization of underutilized generation and transmission resources and potentially even feeding electricity back into the grid [33,34]. In order to appreciate the potential benefits, it is important to first understand the structure and operation of the existing electric supply infrastructure.

3. Interaction and parallels between H_2 and electricity

3.1. *Electricity infrastructure ("The Grid")*

The electric power system produces and delivers electricity to its customers in the residential, commercial and industrial sectors. The electricity is produced by power plants of different sizes and types, which can be fueled by a number of energy sources. The structure of the electric power system has evolved because of the need to balance the generation of electricity with the demand for electricity. Electricity is difficult and expensive to store and as a practical result, virtually all electricity must be generated at the time of use and distributed to the point-of-use.

3.1.1. *Electricity demand*

The typical demand for electricity varies on multiple timescales: daily and seasonal. Demand varies throughout the day because of the changing needs for lighting, heating/air conditioning, industrial demands, and other appliance and electrical equipment use throughout the day. Lighting and other appliances have specific times they are typically used. Also, seasonal effects influence the need for electricity, given that heating is needed in the winter months and air conditioning in the summer months. As a result, the demand for electricity varies throughout the year on an hourly basis. Fig. 3 shows two representative curves for electricity demand on a summer and winter day in California. The summer day shows a broad peak reflecting the need for air conditioning during the hottest part of the day while the winter day shows a late day peak attributable to lighting demands due to the shorter daylight hours.

3.1.2. *Electricity supply*

As described in the last section, electricity demand varies on an hourly basis and because little electricity is stored, power plants must generate electricity in real-time to meet the demand. This requirement affects the structure and operation of the system of electrical generation power plants. There are a number of different types of power plants that are commonly used to generate electricity, which are shown in the Fig. 4. This collection of power plants operating with various types of technology and fuels is often referred to as the "grid mix". Even without the development of a hydrogen economy, electricity supply and generation will evolve in the future as it addresses the challenges associated with increasing demand while reducing GHG emissions, with generation

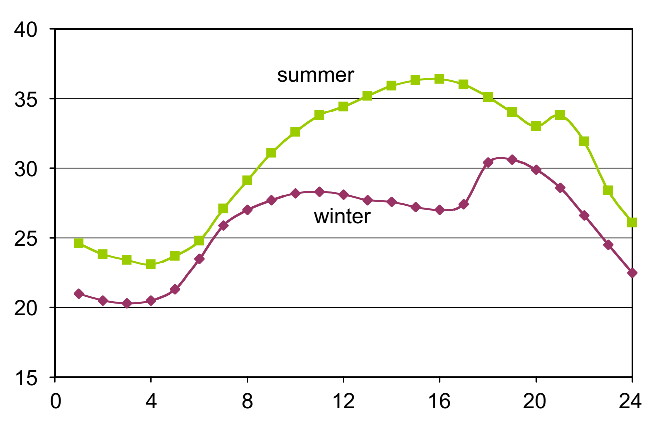

Fig. 3 – Electricity power demand (GW) in California for two representative (summer and winter) days.

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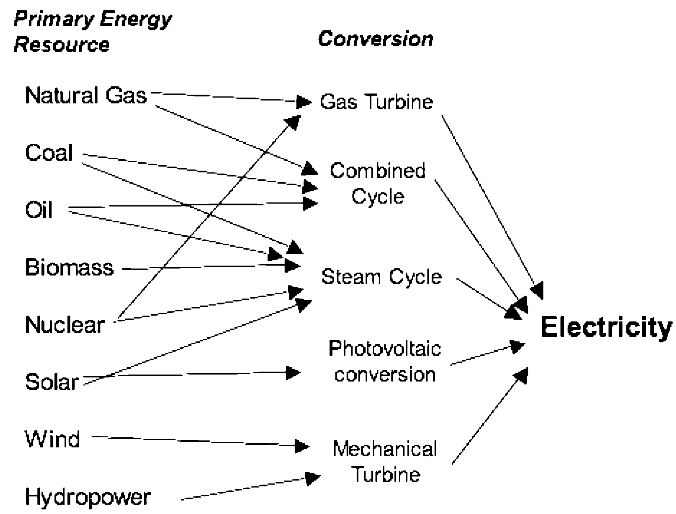

Fig. 4 – Resources and conversion technologies for electricity generation.

from renewables, nuclear and fossil with carbon capture and sequestration (CCS).

Because of the variation in the demand for electricity, not all power plants need to be operating at full capacity all the time. Excess electricity generation that is not used cannot be stored efficiently and is thus wasted, so generation is carefully managed to make sure that there is the correct amount of generation occurring. Given an expected profile of energy use for the year, it is possible to determine how many hours per year different power plants can operate. Different types of power plants have different capital and operating costs associated with them, and there is a tradeoff between high capital cost generation that has low operating costs and low capital cost generation with high operating costs. Since some plants will be operated less than others, this leads to a mix of power plant types in order to minimize costs (this topic will be discussed more in Section 3.2.2, as it is applied to hydrogen systems). Electricity storage is often touted as a key enabler of intermittent non-dispatchable renewable resources, such as wind power, because it can prevent losses of off-peak electrical generation that exceed demand or transmission capacity and must be curtailed [26]. Pumped hydro is the only major form of electrical energy storage currently used. It is used at large-scale (>1000 MW) and is efficient ($\sim 80\%$), but it only accounted for 0.5% of the total electricity generation in the US in 2005.

Electricity dispatch is the operation of the network of electricity generation plants that determines which power plants are used to generate electricity at specific times in order to match supply with the demand. Economic dispatch defines the order of power plant operation according to the plant's marginal cost of producing electricity. Thus, cheaper plants from a marginal cost perspective are run more frequently and more expensive plants are run less frequently. Without the ability to store electricity, the current increase in the use of renewables such as solar and wind that are non-dispatchable can pose a challenge to the operation of the electric grid and raise costs. Given that costs associated with power plants are generally related to the technology and fuel used, electricity is generally produced from a few technologies and fuels during periods of low demand and a larger mix of technologies and fuels during periods of high demand.

3.2. H_2 *infrastructure parallels*

Both hydrogen and electricity can be classified as energy carriers rather than energy sources, because they do not occur naturally but rather must be produced from energy resources such as fossil fuels or renewable energy resources. A key characteristic of hydrogen and electricity is that they are both zero-carbon and pollution-free energy carriers at the point-of-use, but that there are typically carbon and other pollutant emissions when the entire chain of primary energy extraction, generation/production, transmission and distribution are considered. In fact, given that there are many potential energy resources that can be used to produce these energy carriers, there is a very wide range of *life-cycle* emissions in bringing these energy carriers to the point-of-use.

Given many of the fundamental similarities between electricity and hydrogen, it is helpful to explore the various ways in which our understanding of the current electricity system can potentially help inform our understanding of how a hydrogen infrastructure system could be organized and operated.

3.2.1. *Generation resources*

As with electricity, hydrogen can be produced from range of production methods and feedstocks. A diagram analogous to Fig. 4 is shown in Fig. 5 and reveals the wide variety of resources available for hydrogen production. This is a major change, as hydrogen opens up the possibility of using these resources in the transportation sector, which is currently, and has traditionally been, reliant on and restricted to petroleum.

Hydrogen production and distribution could be organized in a system that resembles the electricity grid, with a number of production plants producing H_2 that is fed into a widespread transmission and distribution system (consisting of trucks, depots and/or pipelines) to end users. End users can include

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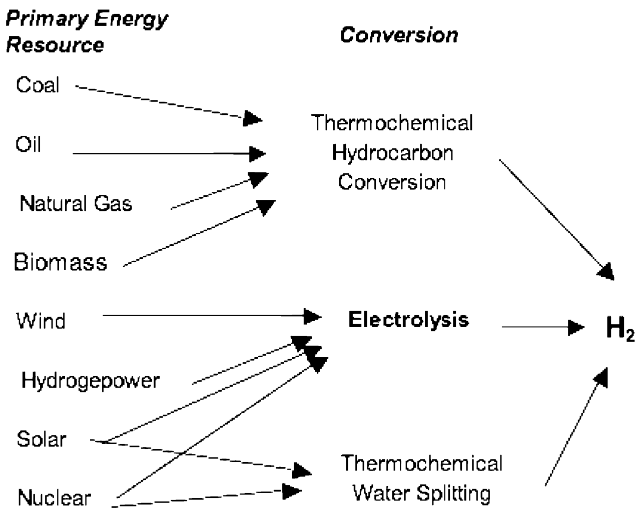

Fig. 5 – Resources and conversion technologies for hydrogen production.

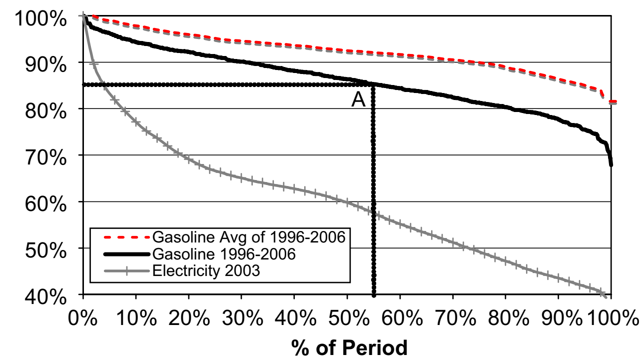

Fig. 6 – Load duration curves for gasoline demand in the US from 1996 to 2006 [36] and California electricity demand in 2003. The solid curve shows the fuel load duration curve over the entire period while the dashed curve shows the annual fuel load duration curve averaged over the entire period. Point A is the optimal demand level for coal-based hydrogen production with sequestration.

not only refueling stations, but also industrial users, such as refineries, and other residential and commercial customers.

Decarbonized, clean energy carriers that have multiple production pathways can be valuable from an environmental perspective because it allows policies and resource constraints to affect the upstream side of the supply system without any inconvenience, or even knowledge of these changes, to consumers. Currently, a number of states have enacted a renewable portfolio standard (RPS) which mandates a specified fraction of electricity generation that must come from renewable resources, such as wind, solar, geothermal and biomass. And RPS targets are expected to increase over time. The ability to produce hydrogen from a wide range of resources enables producers, over time, to alter the mix of hydrogen production, so that it can be made less polluting and with lower GHG emissions as costs for these technologies decline. Like electricity, the hydrogen that the consumer uses is the same regardless of the source so the process of shifting to lower carbon H_2 or a more diverse mix of resources would be transparent to the end user. In fact, California has enacted a law that links state funding for hydrogen refueling stations (Hydrogen Highway) to the renewable content and GHG emissions profile of the hydrogen that it dispenses (requiring a 30% reduction in GHG emissions and a goal of 33% renewable by 2010).

It is also possible to co-produce hydrogen and electricity at the same plant. In the most commonly discussed co-production methods, hydrocarbon resources such as coal, natural gas or biomass can be processed at high temperature to make a synthetic gas or "syngas", which can then be converted to hydrogen and/or electricity. Hydrogen and electricity could also be co-produced from any primary electric source via electrolysis. These options will be discussed in more detail in Section 4.2.

3.2.2. *Generation mix system analysis*

Techniques for electricity system analysis, such as integrated resource planning (e.g. [35]) and the use of screening and load duration curves can also be applied understanding a future hydrogen system. Unlike electricity, liquid transportation fuels such as gasoline can be stored fairly easily. Gaseous fuels (such as hydrogen or natural gas) can also be stored, albeit with higher capital and energy costs and at lower energy density than for liquid fuels. However, a screening curve and load duration curve analysis, which is used to investigate the timing of demand and the best mix of plants for use at different utilization rates in electricity systems, can be used to investigate the mix of resources for hydrogen production when hydrogen demand varies significantly throughout the year or grows rapidly. Because hydrogen storage can be relatively expensive, it is likely to be able to smooth out fluctuations on a daily or perhaps weekly basis, but it is thought to be too expensive to deal with variation on a monthly or seasonal basis.

A load duration curve is a useful tool for analyzing the time-varying demand for electricity and determining the infrastructure capacity needed to meet the demand (see Fig. 6). A load duration curve rearranges electricity demand so that instead of arranging hourly demands sequentially in a time series, it arranges them by demand in descending order. A load duration curve shows the amount of time in a year (typically h/yr) that the total electricity demand is above a certain value. This allows one to compare plants of specific sizes to the demand profile and determine their expected capacity factor.

The same logic can be applied to analyze transportation fuel demand (for gasoline or hydrogen). In addition to the California electricity load duration curve, Fig. 6 shows a series of load duration curves for US weekly gasoline demand, which is used to represent light-duty fuel demand. These curves show the fraction of the period in which the weekly fuel demand was higher than a given level. Fuel demand (represented by refueling) for vehicles varies over several timeframes. Refueling volume typically peaks during the afternoon, and there is variation between different days of the week. Driving (and consequently fuel demand) also

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increases relative to the annual average during the summer driving season. Finally, population and vehicle miles traveled (VMT) growth increase fuel demand on an annual basis. These load duration curves are slightly different from the typical load duration curve for electricity. The main difference is that the demands are weekly fuel demands rather than hourly averages [36]. Current design studies for hydrogen infrastructure incorporate storage at both the central production plant and at refueling stations, with total system storage typically ranging in size from about one day to one week [2,10,15,37–39]. In this analysis, hourly variations in fuel demand do not affect hydrogen production as it is assumed that hydrogen storage can accommodate fluctuations of less than one week. However, the monthly and seasonal variations in fuel demand cannot be leveled by storage cost-effectively and thus hydrogen production plants will have to operate at varying levels over the year. Hydrogen production infrastructure must match hydrogen demand on a weekly basis, just as electricity generation must match electricity demand on an hourly basis. The analyses are analogous because the load duration curves are based upon this smallest unit of variation (one hour for electricity and one week for fuel).

The figure shows two fuel load curves, one is an average annual load duration curve of the years 1996–2006 and the other is an 11-year long load duration curve. This 2nd curve is not a typical use of the load duration curve (which normally looks only at demand in one year) and the difference between these two curves reflects the year-to-year growth in demand rather than weekly or monthly variations. However, if and when a hydrogen economy becomes established, there will be a long transition period where hydrogen's share of light-duty transportation will be growing and this increasing demand will affect the capacity factor of hydrogen plants. In the context of electricity plants, the peak demand for the year (shown as the left-most point on the load duration curve) would roughly coincide with the total generation capacity in the system. In the context of a rapidly growing H_2 demand (i.e. a transition to a hydrogen economy), the total H_2 generating capacity in a given year could be much greater than the peak in a given year since the growing demand would be expected to eventually increase the utilization of equipment and facilities. Large central plants are likely to be overbuilt to take advantage of economies of scale and to meet expected demand at some point in the future. Under these circumstances, the analysis of multi-year load duration curves can be useful because it will give a better indication of the potential underutilization of large central plants than a steady-state analysis would [40–42]. Thus, the dark line in Fig. 6, while atypical for a load duration curve (because it represents several years), would represent the level of variation for a mature fuel system at steady state (with annual growth due only to population and VMT growth). A multi-year hydrogen load duration curve that would be seen during a transition to hydrogen would show much more variation (i.e. the curve will have a much lower minimum demand).

This figure gives us an indication of the range of operating levels that could be needed for hydrogen production plants. Averaging over the period from 1996–2006, the lowest demand for a week is around 80% of the annual demand peak while the average annual demand is 92% of the annual peak. When considering that gasoline demand not only varied over the year, but was generally increasing over the entire period as well, the load duration curve changes. The minimum demand week was only approximately 68% of the period demand peak while the average period demand was 86% of the period peak demand. These patterns of demand could be met by all plants operating at varying capacity levels year-round or some plants operating at full capacity while others switching on and off H_2 production in response to H_2 demand.

As with the generation of electricity, the cost of H_2 from some production plants is dominated by capital costs while the cost of H_2 from other types of plants is dominated by feedstock and operating costs. Fig. 7 shows an example of a screening curve, which helps distinguish the best operating conditions for each type of plant. The capital contribution to annual costs for the four H_2 production plants with 200 ton/day capacity is shown as the intercept on the y-axis and the slope of the line reflects the efficiency of the plant, the cost of the feedstock and other operating and maintenance costs. The crossover points indicate that below 70% capacity factor, the cost of operating a natural gas steam reformer (and as a result, the average cost of hydrogen) is less expensive than for a coal gasification plant, while below 55% capacity factor, operating a natural gas steam reformer with sequestration is less expensive than a coal gasification plant with sequestration. At capacity factors greater than these crossover points, the coal gasification technology is the cheaper method for H_2 production. This same method can be used to analyze other aspects of hydrogen infrastructure systems, including distribution, storage and refueling infrastructure.

Coupling these two figures together, the crossover points between generation types indicate at which demand levels each generation resource should be sized to best meet the system demand. The 55% crossover point of hydrogen generation with sequestration (Point B from Fig. 7) is combined with the 1996–2006 load duration curve (Point A from Fig. 6). These figures tell us that if we wanted to meet the demand over the entire period of 1996–2006, the optimum capacity level (from a cost perspective) for coal gasification with sequestration is 85% of the peak demand, with the remaining 15% met by natural gas reforming with sequestration. A higher level of coal generation would decrease the capacity factor of both generation plants and would lead to an increase in coal costs that exceeds the reduction in natural gas costs, while a lower level of coal generation would lead to an increase in natural gas costs that exceed the reduction in coal costs.

The use of a load duration curve and screening curve can be adapted from the analysis of electricity systems to hydrogen refueling infrastructure. Given the variation in demand, this analysis identifies the optimum capacity level of each production pathway to minimize total system cost. As stated earlier, a key assumption underlying this analysis is that hydrogen storage is only built to accommodate the variation in demand on the timescale of about one week or less. As a result, any variation on a longer timescale must be handled by the production plants themselves. This analysis seeks to minimize total system plant level costs and is one of the

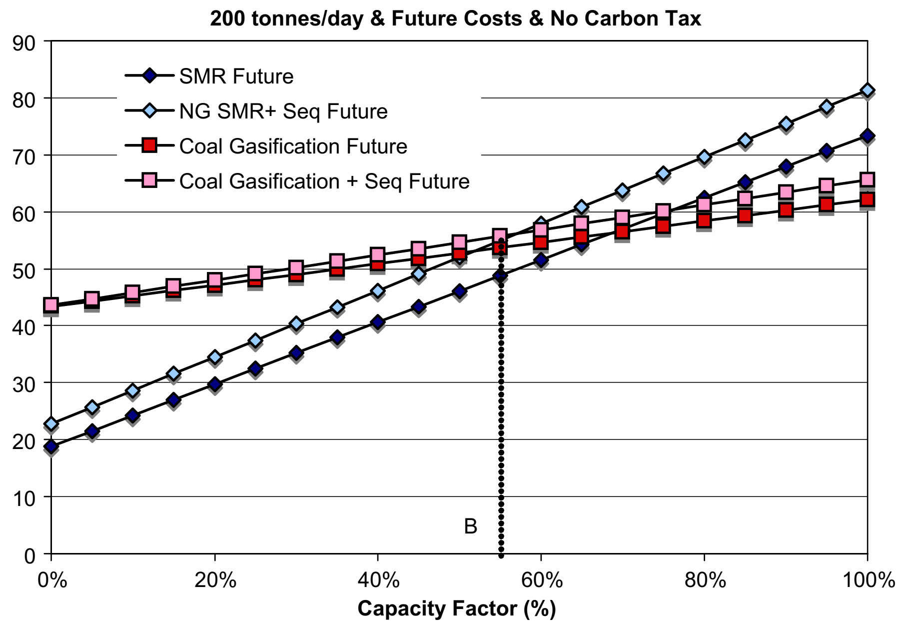

Fig. 7 – Screening curve for 200 ton/day coal and natural gas-based H_2 production plants showing annual cost as a function of capacity factor. Costs shown are from [2]. Point B shows the crossover point between coal and natural gas hydrogen production with sequestration.

important considerations that can influence what types of plants are built to meet future hydrogen demand in a region where demand is growing. Other important considerations include the variability and volatility of future prices of feedstocks, time horizon of investment decisions and other operational factors.

3.3. *Electricity demands for H_2 pathways*

As with many large and widespread systems for goods and material transport, a hydrogen infrastructure would require a significant amount of electricity. Even the gasoline infrastructure for refining, transport and refueling uses electricity (~0.2 kW h/gallon of gasoline) [43]. Hydrogen also has electricity demands, and they are typically much larger than analogous electricity demands in the current gasoline refueling infrastructure. The choice of hydrogen pathway has a very strong influence on the amount of required electricity input. The most obvious electricity demands for hydrogen pathways include hydrogen production via electrochemical water splitting (electrolysis), for hydrogen storage and transportation (for compression and liquefaction of hydrogen) as well as for operating refueling stations. Electricity can, depending upon the choice of pathway, account for a major portion of the total energy inputs that are required to produce hydrogen from a primary energy feedstock and supply it to a vehicle at a refueling station.

In Table 1, electricity input is expressed in terms of kWh per kg of H_2 and also as a fraction of the fuel energy in the delivered H_2. As can be seen from the table, the electricity inputs for some pathways can make up a large fraction of total energy in the delivered fuel while for other pathways, electricity is only a small fraction of the total. One of the more probable near-term pathways for hydrogen production (H_2 from central natural gas production with compressed truck delivery) has a moderate electricity input (accounting for about 12% of the energy in the delivered fuel). This is a significant amount of electricity, which would amount to 200,000 GW h/yr or 6% of total electricity usage in the US if all cars were running on H_2. An EPRI study has identified potential revenues for the electricity industry of up to $100 billion dollars per year if 25% of vehicles were running on H_2, mainly for H_2 production via electrolysis [33].

Table 2 shows the significant electricity input associated with some hydrogen pathways and a comparison with a BEV. The FCV running on H_2 from the electrolysis pathway would use more than twice the electricity per mile compared with a comparable electric vehicle, while the FCV using hydrogen from natural gas and delivered by liquid truck would use more than 60% of the electricity per mile compared to the electric vehicle.

3.3.1. *Timing of demand*

Besides the amount of electricity used, the timing of demand for electricity that is used in hydrogen pathways is also a very important parameter when considering the potential impacts of widespread H_2 usage on the electricity supply system. Electricity demands for H_2 pathways that coincide with the peaks in daily electricity demand shown in Fig. 3 could raise peak electric demand and require additional powerplants to be dispatched (which tend to be more expensive and often more polluting). Given the ability to store H_2, it is possible to adjust the timing of the electricity usage for production, distribution, storage and refueling to ensure that they do not contribute to larger peaks but instead fill in the demand troughs, i.e. periods of low demand. This use of 'off-peak' electricity has the benefit of reducing both the price paid for electricity by the hydrogen providers as well as the average

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Table 1 – Electricity Requirements for H_2 Infrastructure Components [15]

Component	Electricity demand (kW h/kg H_2)	Electricity fraction (% of LHV H_2)
Central H_2 production		
Central natural gas reformer	0.57	1.7
Central natural gas reformer w/CCS	1.73	5.2
Central coal gasification	−3.17	−9.5
Central coal gasification w/CCS	0.00	0.0
Central biomass gasification	1.60	4.8
Central wind electrolysis	53.40	160.4
H_2 distribution and refueling station		
Liquefaction	12.87	38.7
Liquid station	0.33	1.0
Pipeline compression	0.73	2.2
Pipeline station	2.35	7.1
Tube trailer compression	1.19	3.6
Tube trailer station	2.14	6.4
Onsite natural gas reformer station	2.92	8.8
Onsite electrolyzer station	49.18	147.7
Sample pathways		
Central natural gas with tube truck delivery	3.90	11.7
Coal w/ CCS and pipeline delivery	3.08	9.2

Table 2 – Electricity input for electric drive vehicles [15,43]

	Electric vehicle	H_2 (NG, tube trail.)	H_2 (onsite electrolysis)	H_2 (NG, liq. truck)
Vehicle fuel economy (mpgge)	86.8	57.5	57.5	57.5
Electricity in fuel (kW h/gge)	33.3	3.9	49.18	13.77
Electricity per mile (kW h/mile)	0.384	0.068	0.855	0.239

system-wide electricity price. However, the downside is that limiting hydrogen infrastructure operation to specific hours can actually increase the costs of delivered hydrogen because of underutilized equipment (i.e. to supply the same total amount of hydrogen, systems that operate fewer hours in a year, have to have larger capacity). The tradeoffs are important and the decision about capital utilization and electricity prices will depend upon the specifics of the situation, such as how much electricity is required and what the relative prices are for capital, operations and maintenance, electricity and other feedstocks.

In most parts of the US, there is coincidence between the electricity and transportation fuel demands on both a daily and seasonal timeframe. The electricity demand from H_2 infrastructure could increase the system's peak demand and the timing of H_2-related electricity demands and how it interacts with existing electricity demands has important implications for types of electricity generators needed, system load factor and electricity costs. In a hydrogen economy, H_2 storage between a day and a week's demand is likely,[2] but it is unclear whether seasonal storage will ever be feasible economically.

3.3.2. *Environmental implications*

The electricity usage of H_2 production, distribution and refueling can contribute a significant amount to the total well-to-wheel (WTW) emissions and environmental impacts associated with H_2 fuel pathways. The most important determinants of the environmental impacts associated with H_2 infrastructure, given that the FCV running on H_2 is a zero-emission vehicle (ZEV), are the energy sources and processes that are used to produce the fuel, i.e. the well-to-tank (WTT) emissions.

Because electricity can contribute a significant amount of the energy inputs for some H_2 fuel pathways, one of the most important questions associated with assessing environmental impacts is related to the emissions associated with the generation of the electricity. This is a complex question, in part, because of the fungibility of electricity once it has been generated and placed onto the grid. The inability to "track" where the electrons go, once they are in the grid, argues for looking at average emissions from a power system and assigning a set value of emissions (CO_2, NO_x, SO_x, etc.) for each unit of electricity (i.e. grams of pollutant/kW h). In turn, every user is then assigned emissions based upon

[2] The economic feasibility of hydrogen storage depends upon the method. Of near-to-medium term technologies, liquid hydrogen storage is expected to be able to accommodate a week of demand while compressed gas storage is expected to accommodate only about one to two days worth of demand at most.

their total electricity use multiplied by this average emissions rate.

However, there is another way to look at this issue, which is that there are the traditional electricity demands that the system has been built to serve and that the introduction of H_2 fuel production, distribution and refueling infrastructure will introduce an additional demand, which the power system will need to accommodate. The way the system reacts to these additional electricity demands, mainly in terms of what *additional* power plants (and fuels) are used to provide that electricity, should be attributed directly to the additional demands and may give very different emissions per kWh than the average method. The argument is that in order to accurately assess any policy or decision that would have a significant effect, such as replacing the use of gasoline vehicles with hydrogen FCVs, it is necessary to quantify the change in emissions that would occur with this change, which requires this sort of marginal analysis. This second method of using the marginal electricity generation requires a more detailed understanding of the grid operation including which plants are dispatched at certain times and what plants would be built.

Fig. 8 shows the average in-state electricity generation CO_2 emissions for each state in the US. Each state's electricity generation is composed of a number of different powerplant types with different emission characteristics, which contribute to the statewide average generation. Also shown on the graph are typical values for emissions per unit of electricity generated for different types of power plants. This figure helps to highlight the difference between average and marginal emissions. While any electricity demand could be attributed the average electricity emissions in a state (shown by the vertical bars), if the additional demand requires the operation, or if large enough, the building, of a powerplant then one could attribute the emissions of this new plant (shown by the horizontal lines) to that demand. Depending upon the timing and quantity of additional demand, marginal electricity generation can come from baseload, intermediate or peaking power plants and so the CO_2 emissions associated with these additional demands can vary quite a bit. A more detailed analysis of these questions and issues is found in McCarthy et al. [45]. This study looked specifically at the use of EVs and FCVs in California and given California's low emissions (gCO_2/kWh) and the fact that natural gas is the marginal resource that would be used to meet additional vehicle-related electricity demands, H_2 vehicles would actually increase the average emissions for the electricity grid. This would not be true of many other parts of the country, as the emissions from natural gas generation is lower than the average US emissions per unit of electricity. This same sort of analysis can also be used to characterize criteria air pollutants, in addition to GHG emissions.

4. H_2 and electricity convergence

The future of the electricity sector would be shaped significantly by the development of a hydrogen economy. Even in the absence of hydrogen, the electricity sector is evolving in response to other forces, such as the integration of renewables on the grid and the need to address climate change. Beyond the types of impacts described in Section 3.3, which show the additional generation requirements imposed by various hydrogen pathways, there are additional considerations that will influence the evolution of the electricity sector and imply a convergence towards a more integrated electricity and H_2 infrastructure. These considerations include the use of the same resources for H_2 and electricity

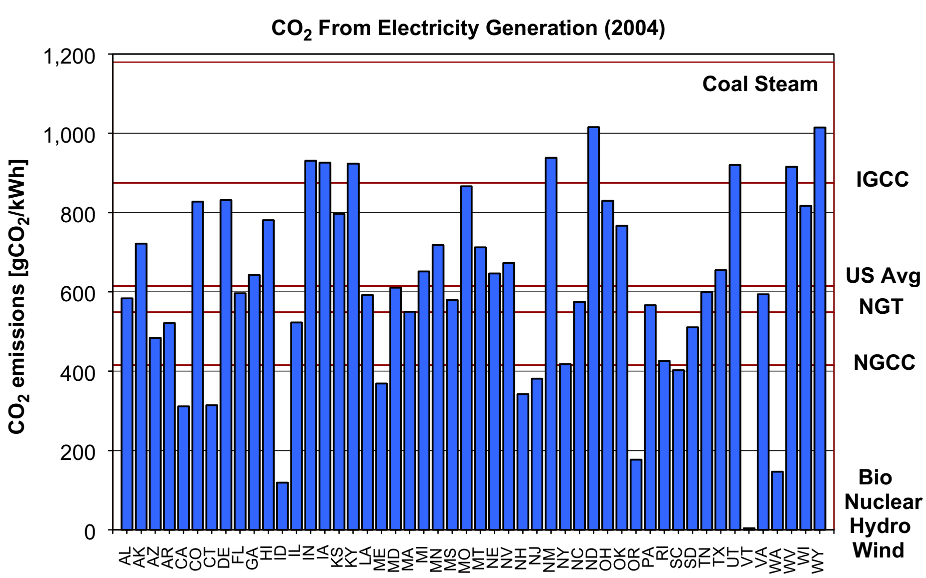

Fig. 8 – Average electricity emissions for individual US states (in-state generation) compared with the US average (616 gCO_2/kW h) and typical emissions from different power plant sources (biomass, nuclear, hydroelectric, wind, natural gas combined cycle (NGCC), natural gas turbine (NGT), coal integrated gasification combined cycle (IGCC), and coal steam). Adapted from [44].

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generation, co-production and interconversion of these energy carriers.

4.1. *Feedstock competition*

One of the key issues surrounding a shift away from petroleum-based transportation fuel to a fuel such as H_2 is the convergence in primary energy feedstocks with electricity. Of the primary energy used in the US, gasoline, which is predominantly used for LDVs, accounts for about 17.5% of the energy while the primary energy used in electricity generation is about 40%. If FCVs running on H_2 are 50–100% more efficient than gasoline and diesel LDVs on a WTWs basis, light-duty transportation would require a significant amount of the same resources (20–30%) that are used for electricity generation. Growing use of personal vehicles and VMT will likely increase required resources even more.

Looking towards the future, low carbon and renewable energy resources will become more constrained as awareness of the role of GHG emissions on climate change increases and measures and policies to reduce GHGs are enacted around the world. This will lead to a significant shift in the electric sector. Natural gas is one such feedstock that will play an important role in helping to reduce GHG emissions from a number of different sectors, including electricity and transportation. The total amount of electricity generated using natural gas has increased by 65% over the last decade [46,47]. It is also one of the most likely near-term energy feedstocks for a developing hydrogen economy because of the technical maturity and cost of the steam reforming process. One of the key concerns in looking forward towards the convergence in energy feedstocks is what the impacts will be of these additional demands from a cost, supply availability and environmental perspective.

Natural gas supplies in North America are already constrained and additional demand will be met in part by LNG imports from abroad. Additionally, the growth in demand for natural gas may contribute to continued higher prices and price volatility. This could have an impact on choice of feedstocks and cost of electricity [47]. Given these constraints, access to a wide variety of low cost and low carbon resources will be a continued challenge for the electricity sector and for a future hydrogen economy. Because of the reliance on the same primary energy feedstocks, the price of electricity and hydrogen will be more tightly coupled than electricity and petroleum energy resources are.

As mentioned in Section 3.3.1, the timing of demands for transportation fuels and electricity tend to coincide in the US on a seasonal basis. As seen in Fig. 9, electricity demand in the US peaks during the middle-to-late summer, while the gasoline demand peaks in spring and summer. This coincidence in demands amounts to an additional challenge to the use of common resources for production of both energy carriers, especially if constrained to use low carbon resources such as natural gas, nuclear, and renewables. Energy resources such as natural gas will have other demands (e.g. heating, industrial) beyond electricity and hydrogen and their timing can be important as well. The use of fossil resources with CCS would significantly increase the resource availability and reduce costs associated with utilizing low carbon energy sources.

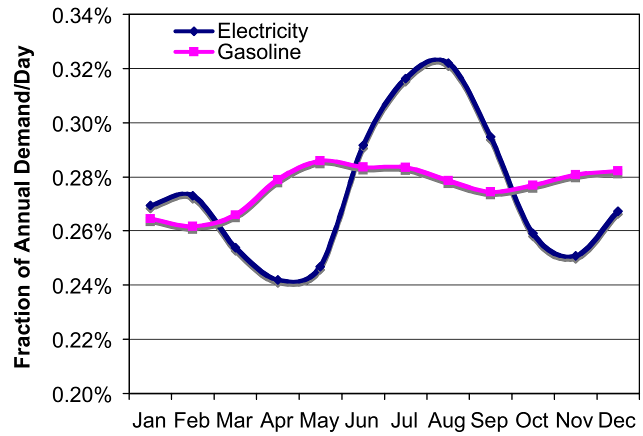

Fig. 9 – Monthly US electricity and gasoline demand profiles for 2005–2006. Adapted from [36,48].

Some have even argued that hydrogen is detrimental to efforts to lower GHG emissions because it will use constrained natural gas resources that would have otherwise gone to displacing coal in the electric sector [5]. This question about the impact of hydrogen production on overall decarbonization of our energy supply is complex, difficult to assess and depends on a host of factors including relative feedstock costs, cost reductions and technical advances for a number of renewable and low carbon technologies, the viability of CCS, and policy. It appears that near-term production of hydrogen using natural gas is an important element of a low cost transition to hydrogen, but the additional natural gas demand will be low for some time and may not lead to any significant increases in the price of natural gas. For example, if 25% of the LDV fleet were FCVs running on natural gas steam methane reformer (SMR), it would amount to a 12% increase in the current level of natural gas demand. The natural gas demand for all sectors (residential, commercial, industrial and electricity generation) is expected to rise much more than the increase from this level of hydrogen fuel production. In the long-term, powering a hydrogen economy exclusively from natural gas would not be advisable for a number of reasons (e.g. resource supply and GHG emissions) but the near-term use of natural gas-based H_2 as a transition strategy to help reduce the cost of H_2 does not appear to lead to significant problems.

Given the fact that both energy carriers can be produced from multiple feedstocks, this argument raises the important question of what resources might be used for different purposes and the resulting environmental benefits. The optimum distributions of resources for each energy carrier may actually be different if one is trying to maximize environmental benefits vs minimizing costs. While this question is too complex to answer in this paper, it would depend upon the prices of the energy carriers and energy feedstocks, which should include costs related to policies that regulate or tax them based upon their carbon content. Presumably, if carbon and other important emissions are regulated adequately and efficiently, energy markets would decide which uses are most appropriate for each of the energy feedstocks in terms of balancing costs, emissions and energy use.

4.2. Co-production

Because hydrogen and electricity can be produced from the same feedstock resources, there are also a number of opportunities for utilizing these resources simultaneously in a facility to produce both energy carriers. This co-production of hydrogen and electricity can potentially offer significant benefits for overall energy efficiency and economics, akin to the benefits associated with combined cycle power plants or co-generation of heat and power (CHP). Co-production facilities may gain these benefits for multiple reasons[3]:

1. Better heat and energy integration—multiple products and processes can allow for waste streams from one process to be utilized for the other, improving overall system efficiency.
2. Better scale economies—distinct demand for two separate products allows for redundant equipment to be eliminated and common equipment to benefit from scale economies.
3. Better equipment utilization—divergence in the timing of the demand for each of the products can allow for common equipment to be utilized at a higher rate.
4. Decarbonization benefits—technologies for reducing carbon can be applied to multiple products simultaneously.

This section will review a number of co-production strategies and studies that can be found in the literature [17–25].

4.2.1. Large-scale thermochemical co-production

Hydrocarbon fuels can be converted into hydrogen by high temperature thermochemical processing such as partial oxidation (including gasification) and steam reforming. Other thermochemical methods of hydrogen production are also possible using high quality, high temperature heat. These primary resources (fossil fuels, nuclear and solar energy) are already commonly used for electricity production and these processes could be coupled to take advantage of synergies in co-production of electricity and hydrogen.

4.2.1.1. Syngas-based co-production options. The production of a synthesis gas ("syngas"), which is a mixture of H_2, CO and CO_2, is a common industrial process that has been adapted for both hydrogen and electricity production. A number of studies have investigated the co-production of electricity and hydrogen in a single fossil fuel plant [15,17,18,20,22,23]. Hydrogen production from any hydrocarbon fuel such as coal, natural gas, or biomass would occur through the primary step of producing a syngas. After syngas production, the concentration of hydrogen gas is increased by reacting the CO in the mixture with steam in a water gas shift (WGS) reactor to form CO_2 and H_2. Final steps include H_2 purification, typically by removal of CO, CO_2 and other trace contaminants. Similarly, electricity production can be accomplished via syngas production. In the case of the integrated gasification combined cycle (IGCC) power plant, coal is gasified to produce the syngas, which is fed into a GT generator and additional electricity is generated using a bottoming steam cycle. In a co-production facility, these two production processes can be combined. Gasification of coal or biomass, or steam reforming of natural gas can be used to produce syngas. Depending upon the desired production ratio of hydrogen to electricity, the syngas may be shifted to enrich the hydrogen content. In either case, hydrogen is separated from the syngas, and the remaining gas can still contain significant energy content in the form of CO and residual H_2. These remaining gases can be passed to a GT or SOFC generator to generate electricity. These systems are compatible with CCS because the electric generator exhaust is predominantly CO_2 and water, which is easily removed. This CO_2-rich stream can be further purified, transported and injected for storage into geologic formations.

In the early years of a transition to hydrogen, the demand for hydrogen may not be large enough to warrant building large central plants dedicated solely to hydrogen production. An important benefit of co-production can be the utilization of "slipstream" hydrogen, which diverts a small stream of H_2 from an existing IGCC coal plant with CCS. In order to capture hydrogen from this plant, additional hydrogen purification (PSA) and compression equipment is required, but the IGCC plant already contains all of the equipment to produce hydrogen. Some initial analyses of slipstream hydrogen has found that delivered hydrogen costs as low as $2/kg could be achieved at refueling stations that are near an existing IGCC with CCS [49]. This system could be cost-competitive with distributed natural gas steam reformers but have lower WTW emissions. These systems are useful because the existing electricity demand can help lower the cost of H_2 production and they are inherently flexible because of redundancy in electricity generation plants. The diversion of hydrogen from a large coal power plant to meet a relatively low initial demand for fuel would decrease the electricity production of that particular plant but would not have a significant impact on the overall electricity generation of a given region. As demand for H_2 increased, the hydrogen output could be increased by increasing the capacity of the PSA and compression equipment.

Additionally, the incremental cost of adding CCS to hydrogen production is relatively small. Kreutz et al. show a smaller increase in price associated with the addition of carbon capture equipment on a hydrogen production plant (+14–19%) compared to the addition of carbon capture to electricity production (+32–36%) [23]. This is due to the fact that hydrogen production and separation produces a CO_2-rich stream regardless of whether CO_2 is vented or captured. As a result, the co-production of hydrogen and electricity can help enable the cost-effective addition of carbon capture to electricity production, which could have an important impact on decarbonization efforts in the electric sector.

4.2.1.2. High temperature nuclear/solar cycles. Thermal power plants that use nuclear heat energy to generate steam for use in traditional rankine (steam) cycles are quite common, generating approximately 20% of US electricity [48]. Power plants that rely on solar heat input are less common, but a number of demonstration plants exist. The use of these heat sources directly for H_2 production is currently only a detailed concept in the laboratory research phase. The temperatures

[3] Not every co-production plant will realize all of these benefits at all times and for all designs.

required for water splitting are significantly higher than for conventional pressurized and boiling water reactors that make up the majority of nuclear power plants. Instead of electrolysis, splitting water to produce H_2 and O_2 can also be accomplished through a complex series of coupled chemical reactions driven by heat at temperatures between 400 and 1000 °C from nuclear reactors or solar concentrators. A number of these thermochemical water splitting cycles have been investigated for use with nuclear or solar heat and a recent assessment of these methods has identified the sulfur–iodine process as one of the most promising cycles [50].

General Atomics proposed a system based upon an advanced helium gas cooled reactor, modular helium reactor MHR [50]. The new class of reactors is designed to reduce the issues surrounding earlier nuclear reactors in terms of safety and efficiency. The system (H_2-MHR) is modular such that the helium reactor is physically separated from the hydrogen production plant via an intermediate heat loop. The intermediate heat loop can also be coupled with a GT to produce electricity (GT-MHR). Co-production, while not explicitly discussed in any of the studies, could be an excellent application for this technology, involving coupling of the intermediate heat loop with both a H_2 production facility and GT or bottoming steam cycle. Given the modular nature of the system, co-production using this technology could be quite flexible to vary H_2 to electricity output ratio depending upon the time of day or product revenue. The potential benefits for this type of system (based on nuclear or solar concentrated heat) are improved waste heat utilization, helium reactor utilization and system flexibility.

Thermochemical water splitting cycles are still undergoing research, and are not as technically mature as fossil-based hydrogen production pathways such as steam reforming, coal gasification or water electrolysis, and should be considered a longer term possibility.

4.2.2. *Small to medium-scale energy stations*

An energy station is a system that converts the energy in a feedstock such as natural gas into hydrogen for vehicle refueling, electricity and possibly heat for use by the station or associated buildings. The three main parts of an energy station are: (1) the hydrogen production unit, (2) the electricity generator and (3) the H_2 compression, storage and dispensing system. For some designs, systems 1 and 2 can be integrated into one unit. Energy stations can also have an integrated co-generation system that uses the waste heat from the electricity generator to help meet a building's heat and/or cooling loads. By providing three value streams (vehicle fuel, building electricity, and building heating/cooling) they potentially offer a faster return on the initial capital investment cost and the potential to lower H_2 costs relative to stand-alone distributed hydrogen stations.

Two fundamentally different energy station configurations have been proposed. The first is based upon a natural gas steam methane reformer (SMR) and a PEM fuel cell. The SMR is used for hydrogen production which can be compressed and stored for dispensing to H_2 FCVs or diverted to a PEM fuel cell (or internal combustion engine generator) for the production of electricity and heat for use in stationary building applications [24,25,51]. The other configuration is based upon a high temperature fuel cell for both hydrogen generation and electricity production. The high temperature fuel cell (either SOFC or MCFC) can be fed natural gas and an internal reforming reaction occurs that creates a syngas that can be used for electricity production in the fuel cell. The system can be operated to vary the amount of energy in the anode syngas. Extracting more of the anode exhaust will allow for more hydrogen production, because it is a mixture of H_2, CO and CO_2 that can be purified, compressed and stored for distribution to FCVs [19,24].

The benefits of these energy stations really come about when considering near-to-medium term hydrogen refueling stations. One of the major issues with these early stations is the low level of vehicle hydrogen fuel demand, which reduces utilization of the station and its components and raises the cost of hydrogen produced by these systems. For the first energy station configuration, one of the major capital costs is the reformer and by coupling H_2 production with electricity generation, the energy station can increase the size and utilization of the reformer, which due to economies of scale and higher capacity factor, can help lower the per unit hydrogen production costs. The system can also offer product flexibility so that, as hydrogen demand from vehicles grows over time, the system can shift the ratio of products to favor hydrogen production. Any reduction in the electricity generation by the energy station for building or station electricity demands can be made up from the grid. By offering a means of lowering near-term costs of hydrogen stations with low utilization, energy stations can help reduce some of the infrastructure hurdles associated with the challenging transition to a hydrogen economy. However, the economics of energy stations and the resulting price of H_2 will depend upon the prevailing costs of electricity and natural gas. Lipman et al.'s analysis found that hydrogen energy stations could be the means to lower the cost of H_2 in locations where electricity rates are high. Energy stations are especially useful when there is only a limited demand for H_2 as with an early market where few vehicles are running on H_2 and stations (and the production equipment) are not likely to have high utilization [25]. High natural gas prices could be a hindrance to the economics of energy station.

4.3. *Convergence in H_2 and electricity delivery*

Along with co-production, another interesting and innovative idea for the future evolution of these two sectors is co-delivery, the simultaneous transmission of chemical and electrical energy in a supergrid proposed by Starr and others [52]. As envisioned, the continental supergrid would evolve alongside the current transmission grid improving electrical current capacity and reliability while simultaneously transporting hydrogen. Liquid hydrogen (at 20 K) in pipes surrounding the lines would cool the conductors to enable superconductivity and minimize transmission losses. The supergrid would allow electricity to be transmitted far from the generation source, which would enhance electricity reliability and enable higher levels of intermittent renewable generation because of divergence in peak demand timing and intermittent generation across the US.

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Even without such radical new ideas for hydrogen and electricity co-delivery, hydrogen delivery via pipelines appears to be an important distribution mode at high levels of demand [10]. There are opportunities to co-locate transmission and distribution infrastructure, i.e. to place hydrogen pipelines where there are already existing rights-of-way, such as electricity or natural gas transmission lines. This can help reduce the cost of obtaining additional rights of way. However, co-locating delivery infrastructure for multiple energy carriers can also exacerbate problems associated with localized outages due to natural disasters or terrorist attacks. However, having multiple widespread and complementary (not necessarily co-located) modes of energy carrier distribution can greatly improve energy system reliability. FCVs are essentially large distributed electric generators (capable of producing around 50 times the average household power demand). While this electricity would not be economically competitive with grid power, FCVs could be capable of supplying about 100 kW h (i.e. several days) of electricity that would be very useful for mobile backup and emergency power.

4.4. Interconversion

Interconversion is a broad term that encompasses a wide range of potential interactions between hydrogen and electricity production. Interconversion describes the production of one energy carrier and subsequent transformation to the other energy carrier, including those that occur at different locations and scales. Interconversion is useful because it can allow for the production and transport of one energy carrier, but the use of another energy carrier when its attributes are of particular value. Examples of these important attributes are the storage energy density for H_2 or the low cost, existing infrastructure, and abundance of off-peak electricity.

These systems can be classified into five different broad categories determined by the locations and order of production for each energy carrier:

(1) Central electricity production, central H_2 production (intermittent renewables).
(2) Central electricity production, distributed H_2 production (onsite electrolysis).
(3) Central H_2 production and central electricity production (fossil w/CCS).
(4) Central H_2 production and distributed electricity production (V2G).
(5) Distributed H_2 and electricity production (E-station).

As described in Section 2.2, the main mechanisms for interconversion between H_2 and electricity are fuel cells that convert H_2 (and air) to electricity and electrolyzers that convert electricity into H_2 (and O_2). Examples of interconversion include the generation of electricity in a wind farm and subsequent production of H_2 via water electrolysis at a refueling station for use in a FCV (category 2) or the production of H_2 via natural gas steam reforming and use for electricity production in a stationary fuel cell (category 4). While a thorough review of all possible applications and options for interconversion is beyond the scope of this paper, this section presents applications that may become common in the categories listed above.

4.4.1. *Renewable intermittent electricity storage*

Hydrogen can be used to complement the production of renewable electricity, mainly in cases where the electricity is generated intermittently and transmission is constrained. For example, large remote wind farms that generate electricity at low capacity factors (~30%) also underutilize transmission lines. The production and storage of hydrogen, coupled with a fuel cell, can generate electricity when the wind turbines are not, leveling the system electricity output and potentially sending more electrical energy over the same transmission lines [26]. Despite these options, there are challenges with this approach including the low utilization of the electrolyzer, which would be lower even than the capacity factor of the wind turbines.

Hydrogen is just one option for large-scale electrical energy storage that can help to better integrate a growing amount of intermittent renewables into the rest of the electricity grid. While the hydrogen generation could also provide the additional benefit of providing H_2 for refueling vehicles, many large-scale wind farms that could utilize these sorts of energy storage technologies are far from major population centers where significant numbers of H_2 vehicles would be located. There are also other technology options that should be considered when determining whether H_2-based electricity storage is appropriate, including compressed air energy storage, pumped hydro, and batteries. Lipman et al. [53] provides a useful overview and evaluation of these technologies.

Others [54] have suggested that hydrogen should be produced and transported as a means of energy transmission for large-scale renewables that are located far from large electricity demands. However, it is not clear that hydrogen conversion and delivery is competitive with other methods of long-distance electricity transmission such as high voltage DC (HVDC) systems [55]. Compared to electricity transmission for large quantities of renewable energy, hydrogen production and transmission would not only act as a transport mechanism, but would also serve to firm and level the intermittent renewable resources. Additionally, such as system would have a ready supply of hydrogen to fuel vehicles. Proponents of this strategy suggest that hydrogen will be an important enabler for utilizing renewables in both the stationary and transportation sectors.

4.4.2. *Off-peak electrolysis*

One of the most often cited examples of interconversion is the electrolytic generation of H_2 at off-peak hours. This hydrogen can be utilized in H_2 vehicles or reconverted back to electricity and fed onto the grid when electricity prices are higher (during peak demand periods). Off-peak electricity can often be very inexpensive (and occasionally negative) due to the need to run some power plants continuously even during periods of low electricity demand. In order for electrolysis to compete economically with fossil-based hydrogen production, low cost electricity is essential. Electrolysis of water to produce H_2 makes the most sense when coupled with the low cost of electricity from off-peak coal or nuclear or excess renewable electricity, which can be around 1–2 cents/kW h. At these low electricity costs, this translates to approximately $\$0.50-1.00\,kg^{-1}\,H_2$ simply for the electricity, without even considering the cost of electrolyzers and other capital equipment, including transport, storage and refueling. Average industrial electricity prices are approximately 6 cents/kW h, which amounts to approximately $\$3\,kg^{-1}H_2$ for the electricity alone. Studies have put the remaining (non-electricity) costs between \$0.70 and $\$4.00\,kg^{-1}$ for a refueling station that produces hydrogen onsite [2,15]. Along with the price of electricity, these equipment costs and their utilization is a major driver in the cost of hydrogen via electrolysis. Operation of electrolyzers during only off-peak hours (less than $\frac{1}{3}$ of the day) leads to a tradeoff between operating costs (in the form of lower average electricity costs) vs capital costs (which would increase due to lower equipment utilization). Even with the low electricity costs, the low equipment utilization (for both electrolyzers, compressors and storage tanks) can lead to H_2 prices that may not be competitive with other H_2 sources.

4.4.3. *Central H_2 production and electricity generation (powerplant w/CCS)*

The production of hydrogen-rich syngas is an intermediate step in a number of industrial processes, including hydrogen production from coal, biomass and natural gas, co-production of hydrogen and electricity that was described in Section 4.2.1, and the generation of electricity in an integrated gasifier combined cycle plant (IGCC). The purification of hydrogen is generally only accomplished if H_2 is a desired end product or if decarbonization is required. One example of the production of H_2 as a decarbonized intermediate for power production has been announced by BP at their refinery in Carson, California, which is expected to be opened in 2011. This power project will gasify petroleum coke, a refinery byproduct, producing H_2 and CO_2. The H_2 will be fed into a turbine to generate electricity (500 MW) while the CO_2 will be captured and injected underground to enhance oil recovery and for permanent storage. Like the co-production systems described in Section 4.2, the production of H_2 (here as an intermediary rather than as a transportation fuel), enables pre-combustion carbon separation, which is generally regarded as an easier and less expensive means of carbon capture for storage purposes. Having multiple products, in this case electricity and high value products such as CO_2 for EOR (and potentially H_2) can add to the value proposition of the production plant.

4.4.4. *Central H_2 production and distributed electricity production (MobileE and V2G)*

One of the innovative ideas surrounding the evolution in how consumers will interact with advanced electric drive vehicles is “Mobile Energy”. FCVs that refuel at H_2 stations have the ability to produce clean electricity for use in a range of applications almost anywhere. The propulsive power requirements for these vehicles is on the order of 50–100 kW, which is on the order of 50 times the average household power usage and several orders of magnitude more than any one appliance or device. Thus, these vehicles have significant capabilities to not only provide propulsion energy, but to bring a host of other activities to the vehicle setting that will help to provide additional value to electric drive vehicles relative to conventional vehicles [34].

If FCVs were a substantial part of the fleet, their capacity could be sufficient to displace a significant portion of electricity use from the grid, and also provide the grid with significant amounts of peaking power or ancillary services. The application of the hydrogen fuel cell power plant could be economical and provide significant benefits to the electricity grid because the vehicle and fuel cell engine capital cost is already sunk and electricity from stationary power plants providing ancillary grid services including spinning and regulation services can be quite expensive. However, significant obstacles to V2G implementation exist, including issues relating to the utility permission, building the necessary grid-connection infrastructure and adding the capability to the FCVs [56].

4.4.5. *Distributed H_2 and electricity production (E-station and building systems)*

A distributed model for H_2 and electricity production, the low temperature energy station, is described in Section 4.2.2. In that system, a distributed natural gas reformer produces hydrogen for FCVs and also electricity generation. The electricity production from the fuel cell would help serve the electrical needs of a building or location and would be complementary to the existing electricity grid and could enhance the reliability of its electricity supply. Another example of this model, without the H_2 vehicle refueling, is seen in the first commercial applications of fuel cells, for building stationary power. United Technologies Corporation (UTC) installed several hundred 200 kW phosphoric acid fuel cells (PAFC) in building applications. In these systems, natural gas is reformed to H_2 and then fed to the PAFC for electricity and heat co-generation (combined heat and power), which can be very efficient (40% for electricity and 80% for heat and electricity) and very reliable. This is another non-transportation application of hydrogen that can lead to convergence and have important impacts on the stationary power sector.

5. Conclusions

Petroleum currently provides the primary energy for nearly all of the world’s transportation fuels and a switch to H_2-based transportation could help in diversifying energy resource use for transportation as well as improve the environmental and climate footprint of this sector. The widespread use of H_2 for transportation would open up new opportunities and challenges for integration with the rest of the energy system, especially the electricity sector. This paper discusses some of the major ways that a future hydrogen economy would interact with the electricity sector and how the transportation fuels and electricity sectors might converge. H_2 and electricity are both zero-carbon, flexible, useful and complementary energy carriers that could provide power for a wide range of applications. The use of each energy carrier will depend upon the attributes of hydrogen and electricity and their suitability for specific applications. Hydrogen is touted as an important

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future transportation fuel in the light-duty sector because of its storage characteristics, efficiency, and emissions.

A hydrogen infrastructure could develop that mirrors the existing electricity infrastructure in a number of ways, with a variety of feedstocks converted to an energy carrier and fed into a widespread distribution system. Based upon a screening and load duration curve analysis, it is proposed that several different hydrogen production technologies would be operated at different times and with different capacity factors to handle the time-varying demands for hydrogen. While hydrogen infrastructure can incorporate storage, storage cannot smooth the demand variations longer than a week. As a result, hydrogen production will have to follow hydrogen demand, much like electricity, albeit on a weekly rather than hourly basis. This H_2 infrastructure (production, delivery and refueling) would also have significant electricity demands, which need to be characterized to accurately assess the life-cycle emissions and energy impacts that accompany its use. An understanding of how the electricity sector operates and utilizes capacity is necessary to adequately determine the impacts of these additional electricity demands. Liquefaction and electrolysis are two elements of some hydrogen pathways that require large amounts of electricity and, as a result, would have the largest impact on the electricity grid.

Another important interaction is the competition and synergies for the use of energy resources for producing H_2 and electricity. An increase in H_2 production that would displace a significant amount of petroleum usage would also have a large impact on the usage of primary energy resources that are used for electricity generation. Because of supply constraints for these resources, especially those that can help reduce greenhouse gas emissions, large additional demands could increase prices and affect the mix of resources used for electricity production. On the other hand, the option for co-production and interconversion promote energy system efficiency, flexibility and reliability because of the ability to couple the production processes and modify the outputs of each of the energy carriers. The complementarity between H_2 and electricity comes about because of their distinct characteristics that will be matched to the specific requirements of the application. Their convergence can also help promote sustainability because this hydrogen and electricity future enables zero pollution to the end user as well as a seamless and transparent transition from current production via fossil fuels to lower carbon and renewable resources such as biomass, solar and wind. A future hydrogen economy will not only be defined by the impact on the kinds of cars we drive and the way that we fuel those cars. It will likely be determined by the wide ranging impacts (both in terms of opportunities and challenges) that this future hydrogen economy has on the other energy sectors, especially electricity, and how these two systems will interact and co-evolve.

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