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Multi-Energy Hub for Zero-Emission Fleet and Energy Transition

Delivering the Lowest-Cost Energy for Your Operation

Randal Kaufman[1], Jagmeet Khangura[2], Leslie Ponder[3], Kumaresh Ramesh[4]

[1]*Randal Kaufman, Black & Veatch, KaufmanR@bv.com*

[2]*Jagmeet Khangura, KhanguraJK@bv.com*

[3]*Leslie Ponder, PonderLB@bv.com*

[4]*Kumaresh Ramesh, RameshK@bv.com*

Summary

For established fleets, the transition to zero-emission vehicles often requires a phased approach. As existing vehicles age, new zero-emission vehicles are purchased and integrated. The charging and fueling infrastructure for zero-emission fleets can follow a phased approach, as well. The multi-energy hub concept allows fleets to use existing energy pathways as part of the transition to a decarbonized energy-efficient fleet. Utilizing a modular approach over time where multiple energy sources combined with energy storage results in a future state of monetized low-cost energy, balanced supply and demand, predictable performance, built-in resilience, and diversity of resources.

Keywords: energy source, energy storage, hydrogen, infrastructure, ZEV

1 Decarbonizing Transportation and Energy Systems

Many companies and organizations are setting goals to be zero-emission in the next decade or two. Fleets offer a first step toward reducing emission as well as re-shaping energy systems for operation. Decarbonization requires a fundamental shift in fleet operations. This shift is an opportunity to benefit from a holistic view of mobility – one that includes energy generation and sourcing. Site planning needs to embody this principle because today's zero-emission fleet design decisions impact tomorrow's longevity, scalability for future growth, and bottom-line cost-efficiency. Transportation and energy technologies keep evolving, so site planning can occur in stages, with incremental deployment of technologies as budgets align. The shift to a zero-emission fleet may start with a feasibility study and site evaluation, followed by deployment of baseline charging and hydrogen filling infrastructure for a small fleet; adding capabilities as demand increases and technologies mature.

Black & Veatch's proprietary Zero-Emission Vehicle (ZEV) Multi-Energy Hub concept illustrates a scaled future state with monetized low-cost energy, balanced supply and demand, predictable performance, and built-in resilience scaled for fleet autonomy. The ZEV Multi-Energy Hub (Hub) uses existing energy pathways as part of the transition to a decarbonized, energy-efficient fleet. The ZEV Multi-Energy Hub diversifies energy sources to match route conditions, weather, and range, and allows for a variety of vehicle technologies. Within the Hub, battery energy storage and hydrogen storage balance energy fluctuations, mitigate intermittency from renewables, and provide continuous energy. The power distribution scheme also ensures high power availability for critical loads by utilizing design fundamentals that reduce single points of failure and allow for concurrent maintenance. The Hub provides both versatility and energy autonomy for organizations to respond to supply and demand for charging and filling needs.

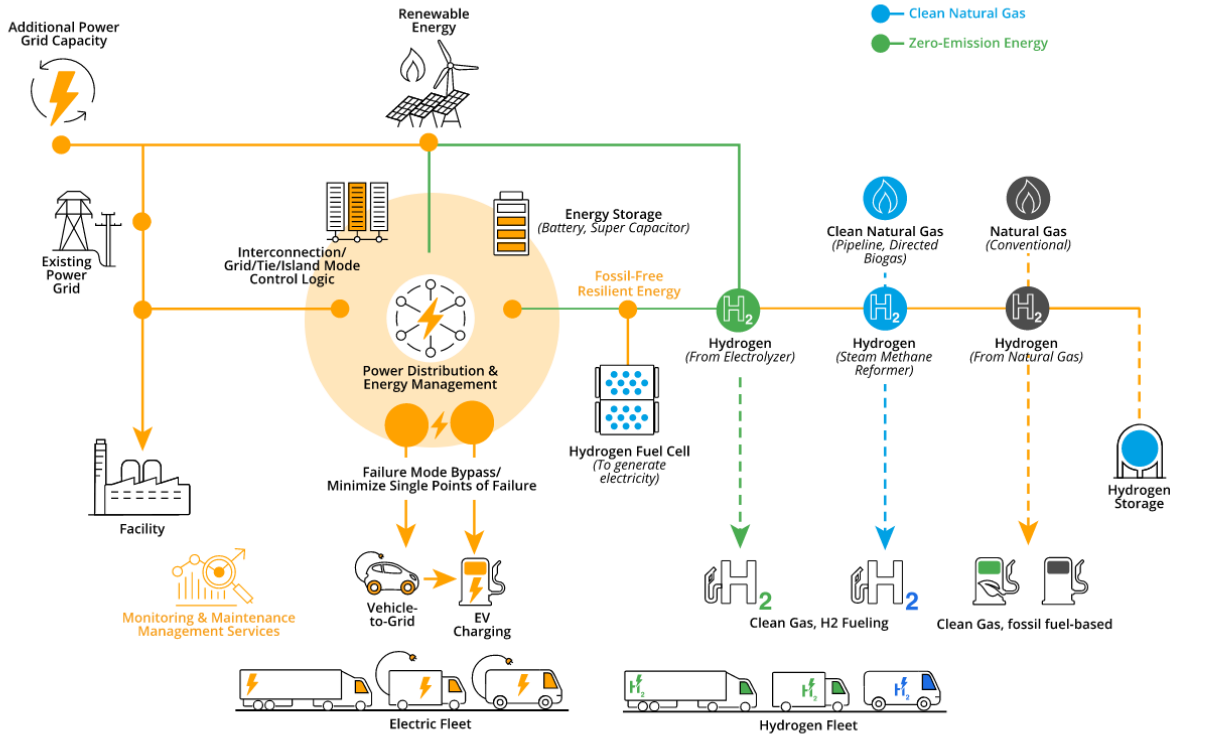

Figure 1: Zero-Emission Vehicle Multi-Energy Hub
Lowest-Cost Clean Energy

1.1 Energy Planning

As more organizations begin to decarbonize, competition for electrons from utilities and energy companies will increase. Large electrical load demands could also require utility grid or feeder upgrades, which could delay power availability. Furthermore, organizations also need to consider more than just energy quality and costs. Good energy planning includes consideration of cost savings and rate stability, reduced environmental footprint, changes to critical load based on fuel type changes, reliability, and resilience, as well as technology improvements and future proofing of Hub design. Beginning with the end in mind by implementing a phased plan to meet long term objectives will contribute to a no-regrets strategy for energy transition.

Transportation and electricity are becoming increasingly intertwined, which allows fleet operators to decarbonize their fleets, build in energy resilience, and economize the cost of energy. Peak energy requirements, along with site specifics like the availability of existing infrastructure, corporate and governmental environmental mandates, and the need for flexibility to support cost stability, reliability and resiliency should all be considered as a part of your Hub planning and design process. This Hub enables operators to deploy ZEV networks incrementally, scaled over time as energy and transportation technologies mature, as capabilities are needed, and as budgets allow. Conversion of internal combustion engine (ICE) fleets to ZEV will require a significant amount of energy and, in the case of electric vehicles, a significant level of charging power. To accurately understand fleet electrification opportunities and challenges, it is important to determine both energy needs and charging requirements over the lifecycle of the fleet conversion roadmap. Vehicle specifications, travel patterns and charging options are all components of determining peak energy requirements for each phase of the plan. In addition, if the plan is to optimize energy across a full operation, similar characteristics for the operation should also be added to the plan.

The benefit of a ZEV Multi-Energy Hub is that the option for multiple sources of energy coordinated to meet the needs of a fleet can help shield an organization from spiking energy costs and capacity constraints by providing a flexible framework for the delivery of sustainable energy to the operation at the lowest cost and at the time it is needed. Energy storage can provide insurance for system reliability by storing energy that can be used when supply is inadequate or unavailable. Storage can also be utilized to reduce peak demand for utility sources, as well as smoothing for intermittent resources which will allow for better control of energy costs and power quality. In addition, the ability to store energy can provide the opportunity for additional revenue streams by allowing for support of ancillary services (i.e., balance supply or demand to maintain a stable voltage and the frequency of the grid) to the utility in markets where this option is available. The increased flexibility and reduced emissions for energy storage, when compared to more traditional backup generators that typically rely on diesel, should be considered when comparing the total cost for these assets.

1.1.1 Technology Considerations

Any major technology investment requires diligence in selection. As organizations transition to ZEVs and energy options, they may wish to evaluate as-a-service and make-ready options. In regions with power constraints, a microgrid may provide the best power supply and resilience. If connecting to utility service, planning for the extended schedule and cost of distribution infrastructure upgrades is crucial. When evaluating impact of new loads to the grid, gaps and bottlenecks, and solutions to solve them, are an important aspect of planning. Organizations that plan for future energy needs will see the greatest returns. The phased approach to build the infrastructure will allow for new technologies to be added as they become more affordable and advanced, and as older technologies age. An example of technology considerations is the future transition from natural gas to hydrogen as a transportation fuel source. Tracking the cost-effectiveness of these types of transitions and building signposts into the Hub technology plan will allow an organization to evaluate potential fueling options for each phase of fleet transition.

Another consideration for technology selection is the modularization of common infrastructure components. Modularization allows for a cost-effective path to planning for and adding capacity as energy requirements increase. Understanding capacity requirements over time allows planning for the space and infrastructure required to support future upgrades. Digital technologies offer another critical set of opportunities to support achievement of decarbonization objectives. In the era of Big Data, it is possible to collect and analyze vast amounts of information, creating a 360-degree view of Hub infrastructure [1]. This capability enables owners to drive efficiency and lower carbon emissions. An energy optimization platform can analyze current and forecasted conditions of both load and energy sources and respond to market signals like demand respond to lower the cost of energy and ensure system reliability. An Energy Management System (EMS) is required to regulate generation and load balancing for the Hub. While branch circuits to each charger will be sized for full load ampacity, the EMS monitors control and protection against overcurrent loading across the entire electrical system at the main metering circuits. This allows correct sizing for the various Hub energy supplies and associated infrastructure to fit the power required to support complete fleet operation. The resulting EMS design can unburden the project from excessive utility fees, eliminate or reduce utility upgrade waiting periods, and reduce unnecessary capital costs resulting from limitations in evolving technologies by mitigating these risks with other technology options.

Redundant EV supply equipment can increase resiliency and charger uptimes, but this redundancy does not have to increase the peak energy requirements for the Hub. Irrespective of apparent load excess brought by the nameplate capacity of additional chargers in aggregate, the design load supplied by the Hub can be governed by a fixed maximum demand allowed across the system.

1.1.2 Reduced Environmental Footprint

As companies and nations navigate the tangled web of sustainability drivers — government incentives, regulation, technology advancements, shareholder and commercial pressures, and workforce demands — many struggle to identify and analyze the multitude of uncertainties and create a coherent strategy. A joint survey by GreenBiz and Black & Veatch, detailed in the 2021 Corporate Sustainability Goal Setting and Measurement report, found that more than 80 percent of companies surveyed with revenues greater than $250 million have set greenhouse gas reduction goals, yet 25 percent are unsure about how to meet these goals [2].

Within the energy sector, transportation is the second-largest source of emissions (6.9 GtCO2e in 2018, or 14.2% of total emissions) [3]. Road transportation alone contributed 12.5 percent of total global emissions in

2018. Since 1990, transportation GHG emissions grew by 79 percent. Increased travel by automobiles is the predominant reason transportation emissions are on the rise. A good starting point for any company is to define their current and future state and then develop a phased approach by identifying the gaps and prioritizing flexibility. Beginning with easy-lift projects that can immediately shrink the carbon footprint gets the ball rolling for weightier efforts. Once an entity has its priorities in order, it can begin to evaluate solutions, matching each challenge with the right technologies to overcome it.

Drivers for change include regulatory mandates like the European Union "Fit for 55" program. This program is designed to leverage climate, energy, land use, transport, and taxation policies to reduce net greenhouse gas emissions by at least 55 percent by 2030 [4]. Another example is the United States' target of electric vehicles representing half of the new vehicles sold in 2030 [5]. In addition, local areas and corporations have their own sustainability targets to consider.

As a part of the Hub planning process, analysis of environmental and social impacts should be considered. Initial analysis should include:

- Environmental and social regulations and standards, including those of potential financiers
- Site land cover/land use evaluation
- Greenhouse gas emission reduction model

This analysis should be used to identify potential negative impacts and risks, determine existing gaps and where mitigation strategies should be employed, and develop a process for future evaluation as new technologies are available.

1.2 Energy Economics

Fluctuating energy costs make it difficult for organizations to plan for expenditures. In addition, ZEVs and infrastructure have higher upfront costs. The ZEV Multi-Energy Hub shares infrastructure and energy across systems, which can reduce the Total Cost of Ownership (TCO). With multiple energy options in the Hub, operators can select site-specific options from the available, lowest-cost sources at the appropriate times. By generating and storing energy onsite, organizations can begin to monetize their energy sources to control fleet expenditures and establish a predictable cost of energy.

Generation, import, and storage of electricity and hydrogen make up the six broad classes of technologies that could be co-located along with supporting infrastructure at the Hub. One or more technologies from each of these families would be chosen based on the techno-economic characteristics of the technologies, the ownership model, the requirements of the fleet it supports, the policy regime, and other factors. The TCO assessment must be undertaken in an integrated manner for the entire Hub, as the presence of multiple technologies may induce additional integration costs as well as reduce costs due to shared infrastructure. The most common technologies or alternatives in each family along with their costs are discussed below.

1.2.1 Electricity Generation

Electricity generation technologies situated at the Hub would be examples of distributed energy resources (DER), an umbrella term used to refer to energy generating assets located onsite to serve the local load. Electricity generation technologies well-suited to be deployed as DER include solar photovoltaic systems, combined heat and power (CHP) using bioenergy or natural gas, small wind turbines, and geothermal power generation. To determine the appropriate technology or technologies, the resource availability and siting requirements corresponding to each technology must be assessed. For renewables, the quality and variability of the resources, viz., solar radiation, wind, and geothermal energy, are considered in the assessment. For dispatchable sources, viz. bioenergy and natural gas, fuel availability and storage requirements are taken into consideration. The cost of electricity generation is composed of one-time upfront costs and running costs that are typically calculated annually. The upfront costs consist of the capital cost for the power plant and the land, infrastructure, and development costs. The capital cost is generally calculated as a product of the installed capacity (constant, expressed in kW) and the capital cost rate (expressed in US$/kW). However, the capital cost rate for most technologies also depends on the installed capacity; it typically decreases with an increase in capacity. Thus, using the same cost assumptions as utility-scale power plants would usually result in an underestimate of the capital cost.

Annual running costs include the cost of fuel, the fixed operations and maintenance (O&M) cost, and the variable O&M cost. However, not all generation technologies would have all three running cost components. Typically, renewables have a near-zero cost of fuel as their input resources such as solar radiation or wind are free. For others, the cost of fuel is calculated as the product of the fuel cost rate (expressed in US$/MMBtu or other unit depending on the fuel), the specific fuel use (expressed in MMBtu/MWh or other unit depending on fuel), and the annual generation (expressed in MWh/year). The term 'fixed O&M cost' refers to the fact that the cost incurred is independent of the quantum of generation; rather, it is calculated as the product of the installed capacity (constant, expressed in kW) and the fixed O&M cost rate (expressed in US$/kW per year). On the other hand, the variable O&M cost is calculated as the product of the annual generation (variable, expressed in MWh/year) and the variable O&M cost rate (expressed in US$/MWh). Over a long period, the total running costs would be influenced by the variations in the corresponding fuel rate, the fixed O&M cost rate, and the variable O&M cost rate. Further, technical characteristics such as annual capacity degradation, outage factors, and resource availability (as discussed above) also need to be considered. The structure of annual running costs is summarized in Equation 1.

$$\boldsymbol{Annual\ running\ costs} = [\boldsymbol{Fuel\ cost\ rate} \times \boldsymbol{Specific\ fuel\ use} \times \boldsymbol{Annual\ generation}] + [\boldsymbol{Fixed\ O\&M\ cost\ rate} \times \boldsymbol{Installed\ capacity}] + [\boldsymbol{Variable\ O\&M\ cost\ rate} \times \boldsymbol{Annual\ generation}] \quad (1)$$

The capital cost rate, fixed O&M cost rate, and variable O&M cost rate for some DER electricity generation technologies are provided in Table 1.

Table 1: Capital cost rate, fixed O&M cost rate, and variable O&M cost rate for distributed generation technologies

Technology	Capital cost rate	Fixed O&M cost rate	Variable O&M cost rate
Solar photovoltaic	1,910 US$/kW	20.4 US$/kW-year	-
Wind power (0-20 kW)	5,675 US$/kW	35 US$/kW-year	-
Wind power (21-100 kW)	4,300 US$/kW	35 US$/kW-year	-
Wind power (101-999 kW)	2,766 US$/kW	35 US$/kW-year	-
Wind power (≥1,000 kW)	2,239 US$/kW	35 US$/kW-year	-
CHP Class 5 engine (3,300 kW)	1,800 US$/kW	-	12.5 US$/MWh
CHP Class 5 engine (9,300 kW)	1,430 US$/kW	-	12.5 US$/MWh
Geothermal power (<1,000 kW)	4,000 US$/kW	-	20 US$/MWh

Sources: [6], [7], [8]

1.2.2 Electricity Import

The available land area may not be sufficient to completely meet the electricity demand at the Hub in an economic manner. Thus, the owner of the Hub may choose to import electricity. This power purchase agreement (PPA) can be signed between the Hub and the utility, where the Hub is like a commercial and industrial consumer, or between the Hub and an independent power generator or aggregator. The former model, also known as a Utility PPA, mitigates the risk of failure on the generation side by diversifying among the available sources. However, it is difficult to calculate the effective CO_2 emissions of the electricity imported due to a dynamic supply mix. The second model, also known as a Corporate PPA, helps in more rigorous quantification of the emissions and reduces the number of participants in the value chain, potentially reducing the cost. However, the impact of any failure, intermittency, or variability would be felt more acutely by the Hub in this model. Further, variations within these two broad models can be developed for a specific business case which are in line with regulatory structure, suit the risk appetite of the parties involved, and minimize the transaction costs. Examples of such variations include:

- *Green Utility PPA*: This is similar to a Corporate PPA except that the aggregator is the distribution utility itself, with typically a higher-than-average tariff due to the 'green premium'. The utility must be able to demonstrate that the total power supplied to all customers with green utility PPAs at any instant is not more than the total power produced from zero-carbon sources at that instant or stored earlier and drawn from energy storage systems.

- *Physical Delivery PPAs*: This is a form of Corporate PPA where the independent power generator or aggregator delivers electricity and the associated renewable energy certificates (RECs) to the purchaser (offtaker). The delivery of power can happen through either the existing grid infrastructure or on a separate network. If the existing grid infrastructure is used, there would either be a provision for wheeling charges or back-to-back agreements signed by the utility with both the offtaker and the independent power generator or aggregator.

- *Virtual or Synthetic PPAs*: In a virtual PPA, the offtaker buys power from and the independent power generator sells power to the utility at the spot price. The agreement itself is usually a contract-for-difference, where the parties are compensated for the difference between the spot price and the PPA price. If the spot price was higher than the PPA price, the offtaker is paid the difference by the independent power generator and vice-versa if the spot price was lower than the PPA price.

Broadly, any import of electricity to the Hub would result in two types of costs. First, there would be a requirement for the installation or upgrade of distribution-side infrastructure in accordance with the amount of power being imported. Depending on the structure of the PPA and the regulations governing the upgrade of infrastructure, the burden of this cost on the owner of the Hub may vary from zero to the full cost of the upgrade. The second is the power purchase cost itself. Time-of-use tariffs and other variabilities in the power purchase cost structure can be exploited to structure the profile of the import such that the cost is minimized.

1.2.3 Energy Storage

There are four broad categories of energy storage technologies, viz., mechanical, chemical, electrochemical, and thermal. Further, applications of energy storage technologies can be classified as energy applications measured in MWh, i.e., uses which require energy discharge over an hour or more and for which capacity equals the total amount of energy the system can store, and power applications measured in MW, i.e., applications that require discharge in under an hour and for which capacity equals the maximum amount of power that can be discharged at a given moment. Typically, however, applications in the power category require discharge over seconds and minutes. Table 2 lists the common energy storage technologies under each category and matches them to the suitable type of application.

Table 2: Energy Storage Technologies

Category	Type	Technology	Application suitability
Mechanical	Gravity Battery	Pumped Hydro	Energy
	Rotating Mass	Mechanical Flywheel	Power
Chemical	Hydrocarbon Fuel	Storage Tanks	Energy and Power
Electrochemical	Electrochemical Reaction	Super/Ultracapacitors	Power
		Secondary Battery – Cell-based	Energy and Power
		Secondary Battery – Flow-based	Energy
Thermal	Sensible Heat: Molten Salt	Solar Power Tower	Energy
	Latent Heat: Liquefied Air		Energy

As discussed, there are multiple energy storage technologies. This section focuses on electrochemical storage technologies as they can achieve high energy density, can store energy for a fairly long period (~8 hours), and are not constrained by geography. While there are multiple secondary (i.e., rechargeable) electrochemical storage technologies, battery development has been focused on increasing the energy density (kWh) both gravimetrically (per unit mass) and volumetrically (per unit volume). Lithium-ion batteries have accomplished both lighter weight and smaller volume since their invention in the laboratory in the 1970s, their commercialization in mobile devices in the 1990s, and their scaling to power-grid applications in the

2010s. Note that the generic name "lithium-ion" does not mean that the battery is made of lithium. Rather the "charge carrier" in the electrochemical reaction is a positively charged lithium-ion that physically moves from one electrode to the other within the battery carrying the charge, the electricity.

With lithium-ion batteries being used for a variety of applications and at different scales, the underlying lithium-ion chemistry is chosen by matching the requirements of the application with the characteristics of the chemistry. Some are better for power, some for energy, some for a balance between power and energy, some for cycling, and yet others are better for safety. Since less than 5 percent of a lithium-ion battery is lithium, the other constituents of the battery chemistries determine the performance characteristics of the battery. The different elements typically used in the battery electrodes include nickel, manganese, cobalt, iron, aluminum, titanium, oxygen, and combinations thereof. A subset of the constituents has evolved to show up in the common name as a form of identification in terms of a three-letter acronym. The various battery chemistries are listed in Table 3.

Table 3: Lithium-ion Battery Chemistries and Characteristics

Chemistry	Abbreviation	Characteristics
Lithium–Nickel–Manganese–Cobalt–Oxide	NMC	Good power, high energy, low cost
Lithium–Iron–Phosphate	LFP	More power than energy, safest, low cost
Lithium–Cobalt–Oxide	LCO	Low power, high energy, less safe
Lithium–Manganese–Oxide	LMO	Balanced power and energy
Lithium– Nickel–Cobalt–Aluminum–Oxide	NCA	Good power, high energy, less safe
Lithium–Titanite–Oxide	LTO	Good power, low energy, long cycle life, high cost

Currently, NMC is the most used battery in both electric vehicles and stationary energy storage. However, price spikes for cobalt due to geopolitical unrest in world regions where it is mined have caused battery suppliers to reduce (if not eliminate) the amount of cobalt in their cells. LFP is emerging as the challenger to NMC for electric buses and stationary grid-energy applications due to its relatively greater stability and safety and lower cost. An integrated Battery Energy Storage System (BESS) consists of many components in addition to the battery cells and modules. While the battery modules are the most expensive component of the system, significant layers of protection and design are necessary to ensure a safe and reliable battery project. Integrated BESS products typically include:

- Power conversion equipment, to convert AC to DC (charging) and DC to AC (discharging)
- Battery racks, to support the modules
- Battery Management System to provide monitoring and control of multiple racks
- DC collection and recombiner panel, to provide short-circuit protection and isolation
- Enclosures or buildings to maintain a temperature-controlled environment, including associated heating and cooling equipment
- Fire and gas detection and suppression equipment, in case of a thermal or off-gas events; and
- Energy Management System to provide site-level control and a SCADA interface

Standalone battery storage sized for Commercial and Industrial use costs \$442-\$643 per MWh (1 MW/2MWh). Commercial & Industrial storage integrated with solar (0.5 MW/2MWh) costs \$235-\$335 per MWh. Battery warranty is typically provided by the vendor. Warranty for lithium-ion grid-scale batteries typically requires that the environment around the battery modules be maintained within a specified temperature range. One Tier 1 supplier requires 23 ± 5 °C while another Tier 1 supplier requires 20 ± 5 °C.

1.2.4 Hydrogen Production

Multiple techniques can be used to produce hydrogen. The hydrogen obtained from each technique is given a corresponding label as shown in Table 4. While there are additional labels and corresponding techniques, the ones given below are commonly used across the industry. It is important to consider sustainability goals and GHG emission regulations when selecting the hydrogen production technique.

Table 4: Techniques of Hydrogen Production

Color/Label	**Production Technique**
Gray	Steam methane reforming (SMR) using natural gas
Brown	Gasification using fossil fuels such as coal or petroleum coke
Blue	Grey or brown hydrogen combined with carbon capture
Green	Water electrolysis using renewable energy resources

Gray hydrogen or steam methane reforming involves heating methane (from natural gas) and steam in the presence of a catalyst to produce hydrogen and carbon monoxide. 60 percent of the world's total hydrogen production, i.e., around 54 million tons, in 2020 was undertaken using this technique, which required 240 bcm of natural gas [9], resulting in an average requirement of 4.4 m^3-CH_4/kg-H_2. Brown hydrogen contributed to 19.6 percent of the global hydrogen production in 2020, while blue hydrogen made up only 0.7 percent of the production share. Owing to the dominance of gray hydrogen and brown hydrogen, hydrogen production was a significant contributor to direct global CO_2 emissions, emitting 900 million tons of CO_2, i.e., nearly 2.5 percent of global CO_2 emissions in energy and industry. Hydrogen production from electrolysis, including non-renewable electricity, accounted for less than 0.05 percent of the total production in 2020. The rest of the hydrogen produced in 2020 was obtained as a byproduct of other industrial processes.

***Steam Methane Reforming**:* The chemical reaction governing steam methane reforming is as given below:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2$$

The product mixture (carbon monoxide and hydrogen) is also known as syngas. The obtained carbon monoxide is further oxidized to carbon dioxide by reducing water to hydrogen via the water gas shift reaction.

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

As the overall reaction is endothermic, methane is used as both feedstock and fuel. The cost of hydrogen production using this technique can be split into three components – capital expenditure (Capex), non-fuel operational expenditure (Opex), and the cost of natural gas. In a study in 2018, IEA estimated the costs for multiple geographies for both cases – without CCS (gray hydrogen) and with CCS (blue hydrogen) [10]. These costs are presented in Figure 2, with the data labels indicating the share of each component.

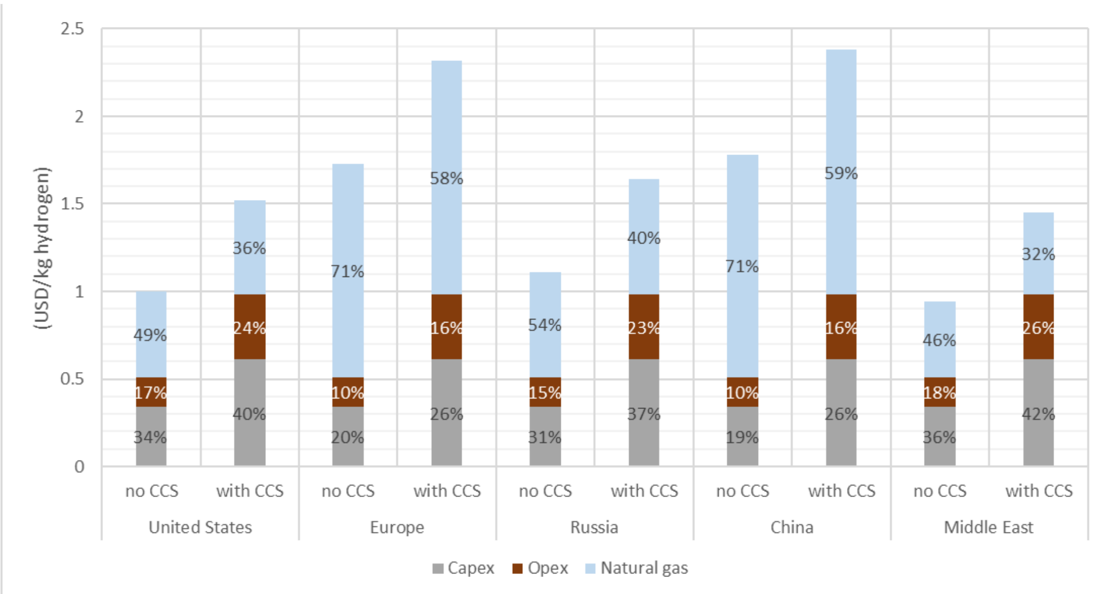

Figure 2: Levelized cost of hydrogen production from SMR (2018)

Natural gas is responsible for the major share of the cost, contributing between 32 and 71 percent to the total cost of production. Thus, any change in the cost of natural gas would have a significant impact on the total cost of hydrogen production. Further, these costs are utility-scale costs, and distributed production of hydrogen using SMR could cost over twice the estimate for utility-scale hydrogen [11].

Electrolysis: Electrolysis is the process of splitting water into hydrogen and oxygen using electricity in an electrochemical cell. Electrolyzers come in a variety of capacities and chemistries, but the fundamental concept remains the same. Electrolyzers, like fuel cells, have electrodes (i.e., anodes and cathodes) separated by an electrolyte. The combination of electrodes and electrolyte vary by the type of chemical reactions taking place. Three types of electrolysis, viz. proton exchange membrane (PEM) electrolysis, alkaline water electrolysis (AWE), and solid oxide electrolysis (SOE) are briefly discussed below.

PEM Electrolysis: As the name suggests, PEM electrolyzers exchange a proton through the electrolyte between the electrodes. In a PEM electrolyzer, water is split into oxygen and hydrogen, with the hydrogen ions traveling from the anode to the cathode and exiting out the cathode side of the stack. Oxygen, in turn, exits out of the anode side of the stack. Catalysts help lower the activation energy required for splitting water**.**

Alkaline Water Electrolysis: An alkaline water electrolyzer fundamentally functions similarly to PEM electrolyzers; however, the ion transported in the electrolyte is OH^- and travels from the cathode to the anode. The hydrogen then exits out the cathode side of the stack and the oxygen exits out of the anode side of the stack. Since AWEs have a lower current density, they also require a larger footprint compared to PEMs. However, the technology is considered more mature for large-scale hydrogen production [12].

Solid Oxide Electrolysis: A solid oxide electrolyzer consist of two porous electrodes surrounding a dense ceramic electrolyte capable of conducting oxide ions (O^{2-}). Typically, between 30 to 100 SOE cells are combined in series and assembled into stacks to achieve the desired hydrogen production rate. SOE stacks have high conversion efficiencies relative to PEM/AWE, primarily because they operate at higher temperatures (i.e., 600°C to 850°C) where thermodynamics and reaction kinetics are favored. Additionally, SOE can be used for the direct electrochemical conversion of steam, CO_2, or both into hydrogen, carbon monoxide (CO), and/or synthesis gas. SOEs can further convert captured CO_2 and water into synthetic natural gas (i.e., CH_4), gasoline, methanol, or ammonia. However, SOE is still in the early stages of commercial development.

For a typical hydrogen production facility, additional electrical equipment is required to step down the grid voltage for medium- and low-voltage consumers. The electrolyzers require low-voltage and high-amperage power, while the rotational equipment (e.g., compressors) requires medium-voltage power. The electrolyzer is the largest power consumer in a typical project; however, ancillary systems such as the fin-fan cooler, compressors, pumps, and/or liquefaction equipment also require power.

Similar to SMR, the cost of hydrogen production from electrolysis can be divided into Capex, Opex, and cost of electricity. However, at a high plant utilization factor, the total cost is determined almost completely by the cost of electricity [10]. If the electricity used to produce hydrogen is being generated on-site using a dedicated renewable resource, then it would be economical to run the electrolyzer at the maximum possible load subject to the availability of electricity. However, if electricity is being sourced from the grid, then the optimum operation point would depend upon the electricity tariff structure.

1.2.5 Hydrogen Import and Storage

Pipelines are currently the most cost-efficient way to transport large quantities of hydrogen over long distances. There are currently approximately 1,600 miles of hydrogen pipelines installed in the US, primarily in the Gulf Coast region, which are predominantly owned/operated by major industrial gas companies. Hydrogen pipelines are considered mature technologies and typically cost up to 10 percent more than a traditional natural gas transmission pipeline. For dry hydrogen service, the use of carbon steel is perfectly acceptable for the typical temperatures/pressures associated with most electrolysis projects. In instances where corrosive contaminants or condensate are present, a stainless-steel pipeline material would be selected instead, which can drive costs even higher [13]. Import of hydrogen to the Hub would result in two types of costs. First, there would be a requirement for the installation of pipelines from the source to the Hub. Depending on the pressure of hydrogen being transported, the costs for carbon-steel and stainless-steel piping are expected to range between $2.4-8.7/ft and $2.4-26.4/ft respectively.

As hydrogen is the lightest element, it can be challenging to store in large quantities. Hydrogen storage techniques can broadly be categorized into physical-based storage techniques and material-based storage techniques. While the former has matured commercially, the latter is still in research and development. The two main physical storage techniques are compressed hydrogen storage and liquefied hydrogen storage.

Compressed hydrogen storage is the most common method of storage for today's industrial hydrogen consumers. Depending on the amount of hydrogen being stored, pressures can range from 140 to 690 bar, with the high end of this range being more suitable for small cylinders used in the transportation sector rather than large bulk tanks for industrial users. Depending on the pressure and storage volume, many smaller vessels may be more economical than one large bulk tank. Hydrogen also presents an issue with leakage. Some compressed storage applications may require special lining inside of the vessel to prevent leakage.

Hydrogen liquefaction is more energy-intensive than compressed storage. However, depending on the amount of hydrogen storage needed, it can be an attractive option. The larger the quantity of stored hydrogen, the more economical liquefaction becomes relative to compressed storage on a mass basis. The storage volumes for liquefied hydrogen are much smaller than that of compressed hydrogen for the same mass. However, liquefied hydrogen requires far more complicated auxiliary equipment.

1.2.6 Carbon Capture

Carbon capture is the process by which carbon emissions from carbon-emitting sources, such as natural gas reformation to produce hydrogen, natural gas fuel cells, and engines, are captured and utilized for commercial and industrial processes. The carbon emission being captured, in this case, CO_2, are processed through carbon capture technology and can be utilized as chemicals, materials, fuels, and several other applications which could serve as a revenue stream for the Hub. The use and the value of the carbon captured will be based on the process used and the quality of carbon dioxide. Up to 98 percent carbon capture rates are possible at a relatively low marginal cost [14].

2 ZEV Multi-Energy Hub Business Models and Benefits

The feasibility of the ZEV Multi-Energy Hub depends on the costs that would be incurred and the benefits that would be realized from the Hub, both calculated from the perspective of the owner of the Hub. While the costs would be influenced by the portfolio of technologies at the Hub, as discussed above, and their integration, they would be ultimately determined by the level and profile of usage of these technologies. The level of usage, in turn, depends upon the users of the Hub and their demand for hydrogen and electricity. Similarly, to calculate the nature and value of the benefits, it is important to understand the ownership of the Hub, the primary users, and the full range of value streams available to the owner. Thus, the business model of the ZEV Multi-Energy Hub is crucial to understanding its feasibility. Further, this would also help in determining the optimum combination of technologies from the perspective of the owner. While there are multiple Hub business models possible, two key models, user-owned and as-a-service are discussed below.

2.1 ZEV Multi-Energy Hub Business Model 1: User-Owned

For this business model, the primary benefits to the owner would be in the form of avoided cost of refueling its fleet. Further, the use of electricity storage also allows the fleet owner to partially decouple its electricity cost from intra-day variations in the tariff by charging the storage when the tariff is the lowest. Electricity storage also provides the opportunity to deliver ancillary services to the grid which could be monetized. Finally, depending on the regulatory regime, the fleet owner can also sell carbon credits.

Ownership of the Hub provides the fleet owner an opportunity to plan their fleet and energy use in an integrated manner. Firstly, the fleet owner must forecast their transportation requirements. Having done so, they must choose the fleet composition and technology portfolio such that these requirements are met, considering the technical characteristics (e.g., efficiency, availability, degradation, start-up time) and the difference between the total benefits and the total costs of ownership of the Hub and the fleet is maximized. These costs also include the cost of the land, manpower, and any other regulatory costs that may be applicable. In the short term, the optimization may be constrained by the existing fleet mix and lead times for acquiring new technologies. Furthermore, the owner of the Hub may also consider using the Hub for powering their operations outside of refueling their fleet, allowing for energy optimization of their full operation.

2.2 ZEV Multi-Energy Hub Business Model 2: As-a-Service

For this business model, the primary benefits to the owner would be in the form of revenue collected from the licensed users of the Hub. This revenue can be based on actual usage by the user, predefined contracts, or a mixture of both. Similar to the previous business model, the owner of the Hub can charge their electricity storage when the cost of electricity (as produced or procured) is the lowest. Further, the owner can offer ancillary grid services and carbon credits as a possible value stream.

The owner of the Hub should obtain the profile of the hydrogen and electricity requirements from the users. Then, the technology portfolio must be chosen such that the requirements of the users are met considering the technical characteristics and the difference between the total revenue and the total costs of ownership of the Hub is maximized. It is vital to ensure that the structure of the agreement between the owner and the user of the Hub is well-defined and proportionally allocates the impacts of any deviation from the demand profile.

3 Conclusion

Driving to zero emissions is a global imperative, and time is of the essence. By using the Hub, organizations can make the transition to zero-emission operations in a coordinated and cost-effective manner. The modular ZEV Multi-Energy Hub allows for cost-control, energy sustainability, and flexibility to implement the newest technology as it becomes available. In addition, organizations that plan for future transportation and clean energy needs can ensure evidence-based investments, see a faster return on those investments, lower total cost of operation, and perhaps even monetize energy assets. Beginning with the end in mind by implementing a phased plan to meet long term objectives will contribute to a no-regrets strategy for fleet energy transition.

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Authors

Randal Kaufman is a sales manager at Black & Veatch where he advises clients on cost-efficient, sustainable, and resilient transportation and energy systems. He has over 15 years of expertise in electric vehicle charging infrastructure, data centers, distributed generation, energy management, power quality, power backup systems, hydrogen generation, and hydrogen fueling. Randal holds a bachelor's degree in International Relations from California State University-Chico, and an MBA from the University of California-Irvine.

Leslie Ponder leads the evaluation and delivery of technical solutions for distribution, distributed generation, and asset management for Power business clients at Black & Veatch. She has over 30 years of technology and management consulting experience with Fortune 500 clients across the U.S. She holds bachelor's degrees in biology and computer science from Tarkio College and an MBA from Queens University of Charlotte.

Jagmeet Khangura is a leader in Innovation Solutions in the Black & Veatch Growth Accelerator. She has over 15 years of experience in resiliency planning, utility planning, microgrids, transportation electrification, energy storage, and renewable energy. She has worked on projects of varying size including rural microgrids, commercial buildings, industrial buildings, military installations, and utility distribution systems.

Kumaresh Ramesh is an analyst for the Global Advisory practice at Black & Veatch where he supports clients with technical due diligence for transactions and developing sustainability strategies. He is experienced in modeling transitions in power systems and transport fleets to support decarbonization goals. He holds a bachelor's and a master's degree in Energy Engineering from the Indian Institute of Technology Bombay (India).