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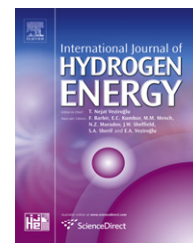
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Efficiency comparison of tri-generating HTFC to conventional hydrogen production technologies

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ABSTRACT

This study compares the production of hydrogen with high temperature fuel cells (HTFCs) that tri-generate power, heat and hydrogen to distributed and centralized steam methane reformation (SMR) supply chains. The defined supply chain steps of hydrogen production include: production, treatment, distribution, storage, dispensing and use. Different technologies for each step in the supply chain have been analyzed from an energy standpoint, resulting in ten different supply chain scenarios.

Results show that liquefaction of hydrogen is the most energy intensive of all the treatment processes and that it is only effective for long delivery distances. When the energy required for the hydrogen treatment (i.e., liquefaction, compression) is included, it is shown that compressed gas hydrogen at 200 bar is the least energy intensive for delivery distances shorter than 84 km if transported by diesel truck. For distances longer than 84 km, 500 bar compressed hydrogen is more efficiently transported than at 200 bar compressed hydrogen. For distances larger than 550 km, liquefied hydrogen is more efficiently distributed than compressed hydrogen at 500 bar.

Results show that the highest supply chain efficiency corresponds to distributed hydrogen production via tri-generating HTFC (~76%) followed by centralized SMR with 500 bar compressed hydrogen distribution (~71%). The lowest supply chain efficiency values correspond to distributed SMR plants (~60%) and centralized SMR with transportation of hydrogen in liquid form (<60%).

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1. Introduction

Hydrogen is foreseen by many as the petroleum product's replacement for fueling automobiles to reduce criteria pollutant emissions and greenhouse gases, especially if hydrogen is produced from renewable sources. Hydrogen is widely used in the chemical industry for making nitrogen fertilizers and upgrading crude oils into transportation fuels [1]. Hydrogen world demand in refineries and chemical plants is equivalent to roughly 200 GW of thermal energy [2]. Fuel cell

technology can solve many challenges in the transportation sector due to its higher efficiency than internal combustion engines, zero criteria pollutant emissions, reduced greenhouse gas well-to-wheel footprint, and the ability to achieve range and refueling times similar to today's gasoline vehicles [3]. As an example, a recent study from NREL shows that the total mileage range for the Toyota FCHV-adv fuel cell vehicle under open road driving conditions is around 430 miles [4].

Unfortunately, hydrogen gas is not naturally occurring and it has to be produced from primary energy sources. There are

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numerous primary energy sources that can be used to produce hydrogen, including nuclear power, renewable power or fuels, and fossil fuels. Hydrogen production methods can be classified into thermochemical, electrochemical, photolytic and biological processes [7]. The current work focuses on the thermochemical processes that involve thermally assisted chemical reactions to produce hydrogen from hydrocarbon fuels and/or water. The most common thermochemical process for hydrogen production is steam methane reforming (SMR) [7]. This technology is quite mature and efficient but involves a fossil hydrocarbon feedstock that has potential energy security, sustainability and climate change implications.

Hydrogen can be produced through steam methane reforming on a distributed scale or in a centralized fashion. Previous studies [8] have concluded that distributed hydrogen production via small scale reforming is less costly than centralized production until a large geographically concentrated hydrogen demand has built up. However, this conclusion is based on the assumption that hydrogen demand relies merely on the fuel cell vehicle fleet deployment. In most developed countries, hydrogen demand in refineries and chemical plants is already significant [2]. Therefore, it makes sense that even in the early stages of fuel cell vehicle deployment, a small portion of the hydrogen produced in centralized SMR plants could be diverted to meet the transportation demand while taking advantage of large scale production.

According to Ogden [8], hydrogen production efficiency in a centralized plant may be between 75% and 80%, whereas distributed SMR efficiencies with current technologies are about 66%. Energy penalties associated with distribution and storage of hydrogen are important to accurately assess to determine whether overall hydrogen production and delivery efficiencies are greater with local or with centralized hydrogen production.

Steam–methane reforming reactors are currently designed to operate under steady state conditions [1]. Therefore, in the early stages of fuel cell vehicle deployment, significant hydrogen storage infrastructure or dynamic dispatch of local SMR plants might be required if hydrogen is produced locally and exclusively to meet transportation needs. This presents a second challenge to the economic viability of distributed production of hydrogen via SMR.

A novel and revolutionary method to produce hydrogen in a distributed fashion is by tri-generation using the reformation capabilities of stationary high temperature fuel cells [5]. Solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) have the capability of converting methane into hydrogen by external reforming and/or within the anode compartment through steam methane reformation and water–gas shift reactions [6]. Heat and water produced by the fuel cell electrochemical reactions are used directly in the endothermic fuel processing reactions. In a conventional high temperature fuel cell, hydrogen that is not electrochemically consumed in the fuel cell is oxidized in catalytic thermal oxidizer to produce thermal energy to preheat the fuel cell input streams (water, air and fuel). However, due to the magnitude of exothermic heat released during the fuel cell reactions, there is an opportunity to efficiently produce

additional hydrogen that could be separated and purified for other uses such as fuel cell vehicles [6]. This novel method is known as tri-generation of hydrogen, heat and power with HTFC technology. HTFC tri-generation can potentially produce three valuable products, electricity, hydrogen, and high-quality waste heat, in various quantities at high efficiency to address the major challenges of distributed hydrogen production.

The literature presents analyses of various hydrogen supply chains as accomplished by a large number of groups [7–10]. Although much research has been performed to analyze the efficiency of traditional hydrogen production methods, there is little work that compares the novel tri-generating HTFC method with conventional hydrogen production methods. The current work estimates the total energy required to produce, transport and dispense hydrogen with tri-generating HTFC and compares it with conventional hydrogen production methods such as centralized and distributed SMR. In addition, state-of-the-art and widely used hydrogen preparation, transportation and delivery methods are also included in the analysis resulting in ten different hydrogen supply chains. Comparisons amongst the various hydrogen production and delivery methods allow objective understanding of the energy and environmental benefits and challenges of distributed hydrogen production, especially by tri-generation.

2. Hydrogen fuel supply chain

Today, most hydrogen is produced from natural gas in large steam methane reformation (SMR) plants in a centralized fashion. To produce hydrogen at large scale in a centralized plant is more efficient than producing hydrogen at small scale [8]. Stephens-Romero et al. [9] define production, treatment, distribution, storage and dispensing as the main steps of a well-to-tank hydrogen supply chain. Each step can be accomplished with a variety of different technologies. Fig. 1 shows the main steps of a generic hydrogen supply chain with the most widely used technologies.

One of the main benefits of producing hydrogen in a distributed manner versus centralized manner is the elimination of the fuel transport step which may be energy intensive. Furthermore, if hydrogen is produced on-demand as in a tri-generating HTFC, hydrogen storage capacity may be considerably reduced compared with the distributed reformer case which must operate, in terms of production rates, within a narrower band of operation regardless of consumption patterns. In the present study, overall efficiencies for various means of producing, distributing and delivering hydrogen to the end-user vehicle are calculated.

2.1. Hydrogen production

2.1.1. Distributed hydrogen production via tri-generating HTFC

High temperature fuel cells generate electricity and heat through exothermic electrochemical reactions. Generated heat is utilized by the endothermic internal reformation reactions which usually require much less heat than there is

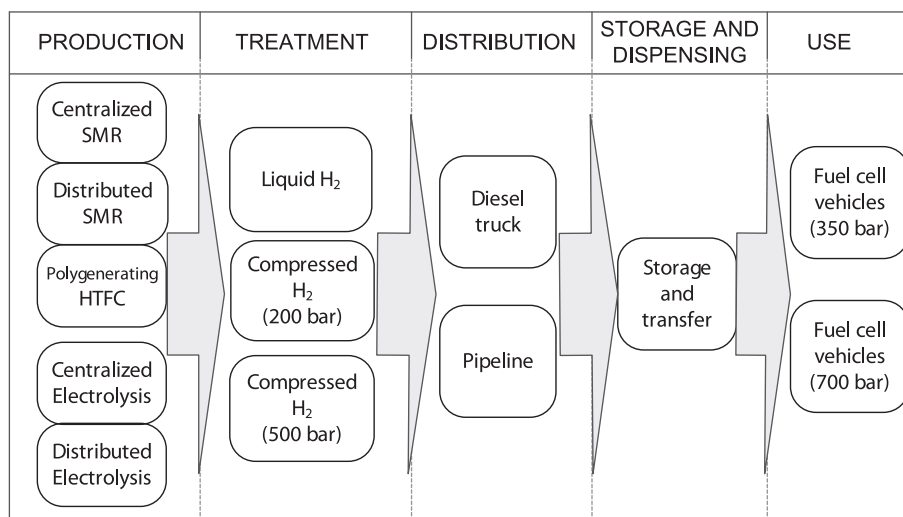


Fig. 1 – Steps in well-to-tank efficiency analysis of H₂.

available [11]. Surplus heat is used to preheat the fuel and oxidant streams before they enter the fuel cell and to produce the steam required for system operations. In addition, the remaining thermal energy contained in the exhaust gases can be used downstream of the fuel cell for cogeneration applications [12]. One possibility is to use this downstream heat to produce hydrogen via steam methane reforming in an external reformer. Another possibility relies upon the internal reforming capabilities of HTFC and on the fact that the amount of high-quality heat produced by the exothermic reactions within the stack is typically much greater than that heat required for fuel processing. Therefore, more hydrocarbon fuel than that required for the electricity generation could be processed in a HTFC, creating a hydrogen-rich stream that could be subsequently purified and delivered to the point of use without the need of an external reformer [13].

Margalef et al. [13] analyzed six different configurations of tri-generating solid oxide fuel cells (SOFCs). Four of them are based on external reformation whereas the rest are based on internal reformation. In the referred study, it is demonstrated that the energy required to separate and purify one kilogram of hydrogen from the reformat gas is greater when the hydrogen is produced via internal reformation. However, hydrogen production efficiencies are still higher in the internal reformation cases than in the external reformation case due to higher hydrogen product yields. In addition, it is confirmed that electrical and overall efficiencies are higher when the internal reformation capabilities of the HTFC are used to produce hydrogen rather than producing it in an external reformer. Higher electrical efficiencies of tri-generating HTFC are associated with the synergistic effects of operating the fuel cell at lower fuel utilizations which result in higher cell voltages and lower cooling air requirements [13].

The first tri-generating fuel cell system was developed by FuelCell Energy and Air Products and Chemicals (APCI) under the sponsorship of the California Air Resources Board with the support of the South Coast Air Quality Management District and the U.S. Department of Energy [15]. The developed system takes advantage of the internal reformation capabilities of the

commercial molten carbonate fuel cell (MCFC) system DFC300 and relies upon pressure swing adsorption (PSA) to separate and purify the hydrogen from the anode-off-gas. Fig. 2 shows a schematic of the developed system.

As shown in Fig. 2, the anode-off-gas is directed through a water–gas shift reactor (WGSR) to shift carbon monoxide and water into additional hydrogen and carbon dioxide. A set of heat exchangers (HEXs) are placed strategically in order assure the thermal balance within the fuel cell balance of plant. Hydrogen is then separated from the anode-off-gas at the hydrogen separation unit (HSU). The remaining exhaust gas is combusted in an anode gas oxidizer (AGO) before entering the fuel cell cathode [14].

The first commercial tri-generating HTFC was installed at the Orange County Sanitation District (OCS)D wastewater treatment plant in Fountain Valley, CA. The system is operated with anaerobic digester gas (ADG) produced in-situ from wastewater operations and produces 240 kW of net AC electrical power and maximum of 165 kg of hydrogen per day to supply a hydrogen fueling station installed by APCI at the OCS)D facility [16].

Because the tri-generating HTFC simultaneously produces electricity, hydrogen and useful thermal energy, efficiencies can be measured and expressed in a number of different ways. Standardized methods to calculate the efficiency of multi-output systems for comparative analyses were developed by Margalef et al. [17].

$$\eta_{\text{H}_2\text{ES,overall}}(\text{LHV}) = \frac{P_{\text{net}} + H_2}{E_{\text{tot}}} \quad (1)$$

$$\eta_{\text{H}_2\text{ES,e}^-}(\text{LHV}) = \frac{P_{\text{net}}}{E_{\text{e}^-}} \quad (2)$$

$$\eta_{\text{H}_2\text{ES,H}_2}(\text{LHV}) = \frac{H_2}{E_{\text{H}_2}} \quad (3)$$

where P_{net} is the net electrical power produced [kW] and H_2 is the hydrogen power produced [kW]. E_{tot} is the total energy flow input [kW], E_{e^-} is the portion of energy flow input allocated to co-produce electricity and E_{H_2} is the portion of energy

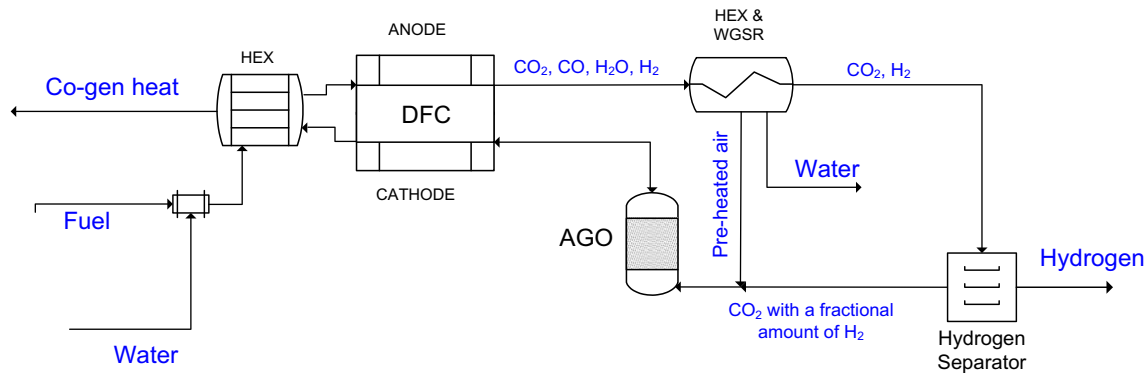


Fig. 2 – Configuration of the first tri-generating MCFC [16].

flow input allocated to co-produce hydrogen. Margalef et al. developed three different methodologies to calculate E_e and E_{H_2} [17]. For the present study, the methodology labeled as *Supplemental Input Method* has been used [17].

Table 1 shows the efficiency results obtained by using the Supplemental Input Method in conjunction with actual performance data obtained from the OCS installation [16].

Another attractive feature of tri-generating HTFC is the capability of producing hydrogen on-demand. Contrary to Distributed SMR, which must continually generate hydrogen to maintain the consistent operating temperature necessary for long equipment lifetime, a tri-generating HTFC has the potential to generate hydrogen only when there is hydrogen demand, and maintain temperature at other times by simply continuing to generate electricity. When hydrogen demand does not exist, more electricity can be generated and exported to the existing electric grid.

2.1.2. Centralized hydrogen production via SMR plants

Steam reformers for large scale chemical processes generate between 2500 and 20,000 kg/h of hydrogen. These systems consist on long catalyst filled tubes that operate at high pressures (15–25 atm) and high temperatures (850 °C) [8]. This technology can be scaled down to produce distributed hydrogen. However, it is important to note that economies of scale are significantly important for these type of plants due to costly materials requirements for high temperature, high pressure operation, and to engineering/installation costs. Fig. 3 shows the estimated costs of a hydrogen production plant including the reformer, shift reactors and pressure swing adsorbers (PSA) as a function of the hydrogen production capacity.

As shown in Fig. 3, for low hydrogen production rates, the capital cost of the production plant is much higher per unit of

hydrogen produced than for high production volumes. Therefore, from an economic perspective, if there is enough hydrogen demand, it makes sense to produce large volumes of hydrogen in centralized reformation plants than in small scale generators.

Fig. 4 shows the schematic of a steam methane reformation hydrogen production plant. As shown, it consists of a catalytic steam reformer, two shift reactors and a pressure swing adsorber.

Spath and Mann [10] performed a life cycle analysis (LCA) of hydrogen production in a centralized SMR plant. In their analysis, they define two types of efficiencies: (1) hydrogen plant efficiency and (2) external energy efficiency. The latter accounts for the upstream energy used in producing and distributing the natural gas and in producing the electricity required to operate the hydrogen plant. The values obtained were 79.2% and 60.4% (on an LHV basis), respectively. For this analysis, the centralized SMR hydrogen plant efficiency value 79.2% is used because the external energy required to produce and distribute natural gas is assumed to be equivalent amongst all the analyzed technologies.

2.1.3. Distributed hydrogen production via small SMR plants

Significant efforts to develop small scale steam reformers have led to commercialization and relatively affordable stages for these types of systems. Ogden reviews the development and commercialization status of various types of small scale reformers [8].

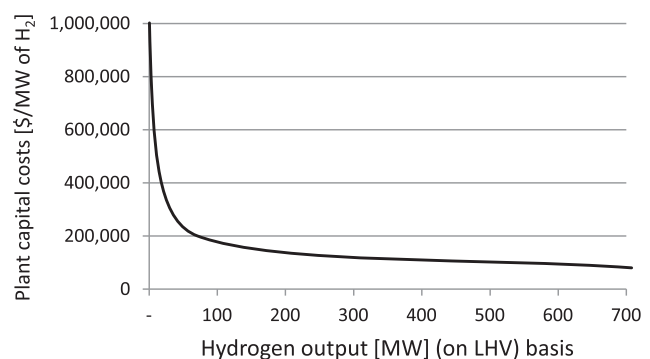


Fig. 3 – Capital costs of centralized SMR plant [8].

Table 1 – H₂ generation comparative efficiency with tri-generating HTFCs (based upon LHV).

	Efficiency, %
Hydrogen production (η_{H_2})	84.1
Electrical (η_{elec})	54.8
Overall ($\eta_{overall}$)	75.2

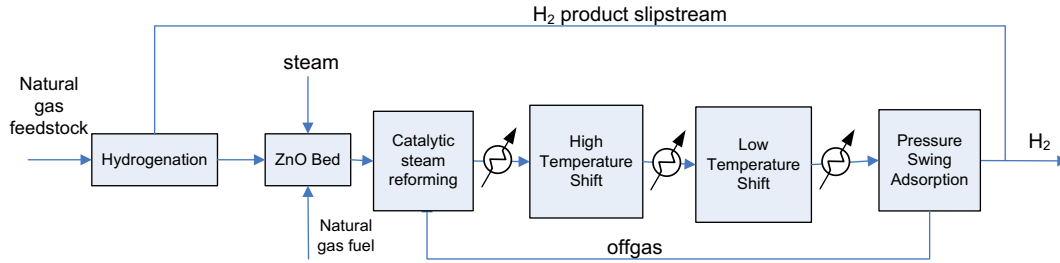


Fig. 4 – SMR hydrogen production plant schematic.

Conventional steam reformers consisting on long catalyst filled tubes that operate at high pressures (15–25 atm) and high temperatures (850 °C) have been successfully scaled down to as small as 10–100 kg/h. However, at such low size, costs are too high to compete with large scale hydrogen production, as shown in Fig. 3. For this reason, more compact and inexpensive designs have been, and are being, developed by many manufacturers. In all cases, average hydrogen production efficiency ranges between 60% and 77% (on an LHV basis) [8]. The efficiency value used in this work for the small scale SMR will be 68.5%, which represents the average value between the minimum and the maximum values found in literature.

2.2. Hydrogen Treatment

The step between hydrogen production and distribution may be referred as hydrogen Treatment, required to store hydrogen in one of four different types of packaging media: compressed H₂, liquid H₂, hydrides (physical) and hydrides (chemical) [18]. In this work, only hydrogen liquefaction and compression are considered and evaluated as treatment processes since these are the most commonly used in both commercial facilities and the nascent hydrogen vehicle fuel industry.

2.2.1. Hydrogen liquefaction

At atmospheric pressure, hydrogen gas becomes liquid at temperatures below 20 K. Theoretically, only 14.2 MJ/kg (or 11.7% of the LHV energy content of hydrogen) has to be removed to drop from ambient to cryogenic temperatures and to condense the hydrogen. However, cryogenic refrigeration processes involve Carnot cycles and physical effects (e.g.

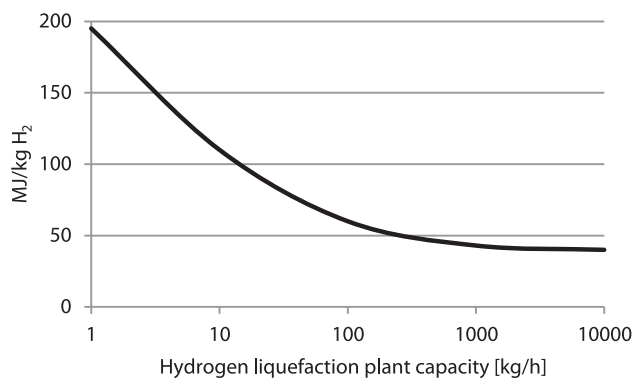


Fig. 5 – Energy required to liquefy 1 kg of H₂ as a function of the production capacity.

Joule–Thomson effect) that may increase the necessary energy to 54 MJ/kg (or 44.6% of the LHV energy content of hydrogen) when hydrogen is produced in small liquefaction plants [18]. As shown in Fig. 5, economies of scale play a significant role and the required energy to liquefy one kilogram of hydrogen can be reduced substantially if hydrogen is produced in large production plants [18].

Nevertheless, even the lowest values achieved represent 35.8% of the energy content of hydrogen (or 40 MJ/kg of H₂) which represents a significant portion of the total energy content of the fuel [18].

Main components required to liquefy hydrogen include electric motors, compressors, gas coolers and turbo-expanders. These apparatus are more efficient at large scale operation [10]. As a result, liquefaction of hydrogen is currently performed only at large scale.

2.2.2. Hydrogen compression

The amount of work required to compress the hydrogen gas depends on the thermodynamic process. Ideal isothermal compression, which is physically impossible, follows the following equation:

$$W_{\text{isothermal,comp}} = p_0 v_0 \ln \left(\frac{p_1}{p_0} \right) \quad (4)$$

For ideal gases, and real gases far above their boiling temperature, the thermodynamic process is more closely described by the adiabatic compression process which follows the equation

$$W_{\text{adiabatic,comp}} = \left[\frac{\gamma}{\gamma - 1} \right] p_0 v_0 \left[\left(\frac{p_1}{p_2} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (5)$$

where W [J/kg] is the specific compression work, v_0 [m³/kg] is the initial specific volume, p_0 [Pa] is the initial pressure, p_1 [Pa] is the final pressure and γ [–] is the ratio of specific heats (adiabatic coefficient) [18].

Hydrogen compression is energy intensive due to its high specific volume when compared with other fuel gases such as methane or propane. In order to minimize the compression work, the gas-specific volume must be minimized (or volumetric density maximized) during the compression process. A practical way of keeping v low is by cooling the gas as it is compressed. A largely used technique to compress hydrogen is multistage compression with intercooling where the gas is compressed in stages and cooled between each compressor stage [19]. Such technique reduces the compression work input to the compressor and operates somewhere between the

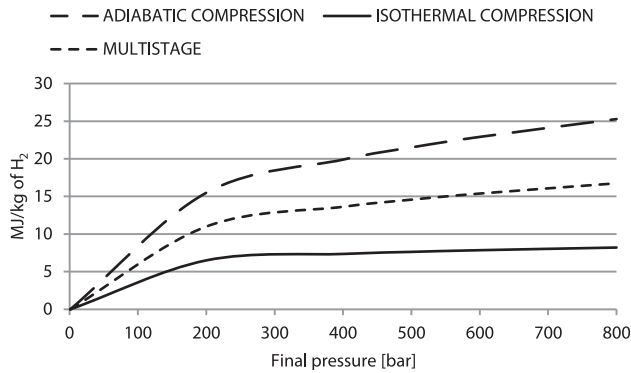


Fig. 6 – H₂ compression work as a function of the final pressure.

isothermal and adiabatic processes. Fig. 6 shows the specific compressor work as a function of the final pressure [18]. In all cases, hydrogen gas is initially at atmospheric conditions.

As shown in Fig. 6, ideal isothermal compression requires the minimum compression work whereas adiabatic compression requires the maximum work. For the herein presented analysis, multistage compression with intercooling has been used since it represents the most realistic compression process [19].

2.3. Hydrogen distribution

Delivery of hydrogen can be done by truck, rail, ship, or pipeline. Generally, most of the merchant hydrogen is transported by truck rather than rail or ship since centralized hydrogen production plants are built relatively close to hydrogen consuming industries. If distances between facilities are reasonable, hydrogen pipelines are frequently used to directly inject the hydrogen into the process line. To justify the construction and use of pipelines, a high demand of hydrogen should be expected [20].

For this study, one delivery method, by diesel truck, is analyzed. It is assumed that compressed hydrogen at two different pressures (i.e., 200 bar and 500 bar) and liquefied hydrogen is transported by diesel truck from the hydrogen production plant to the end user.

2.3.1. Hydrogen delivery by truck

Table 2 summarizes the main assumptions used to evaluate the energy required to transport hydrogen by diesel truck.

Traditionally, hydrogen has been transported at 200 bar due to material limitations; steel pressure vessels must be robust enough to contain the pressure, yet light enough to be pulled by truck. However, utilization of carbon fiber composite storage tubes by Air Products & Chemicals [21] allows higher transportation pressures (500 bar) increasing each truck load capacity from 320 kg to 920 kg of hydrogen. Liquefied hydrogen trucks can transport up to 4000 kg per truck due to its high volumetric density [21].

To estimate the energy required to transport one kilogram of hydrogen by diesel truck, it has been assumed that it varies linearly with the delivery distance. In all the analyzed cases (i.e. liquid H₂, 200 and 500 bar compressed H₂) the hydrogen payload is relatively small compared with the truck curb weight (40,000 kg). Consequently, the diesel fuel consumed per kilogram of hydrogen and per distance traveled (c_{truck}) can be considered as constant in all the cases.

The energy used to transport one kilogram of hydrogen can be calculated as follows:

$$W_{\text{transport, truck}} = \frac{c_{\text{truck}} \times \text{GW} \times \text{LHV}_{\text{diesel}}}{l_{\text{H}_2}} \times d \quad (6)$$

where $W_{\text{transport, truck}}$ is the energy used to transport one kilogram of hydrogen [MJ/(kg H₂)], d is the delivery distance [km], GW is the truck Gross Weight (truck curb weight plus the hydrogen load) [tons], $\text{LHV}_{\text{diesel}}$ is the energy content of the diesel fuel [MJ/(kg diesel)], c_{truck} is the diesel truck consumption [kg of diesel/(ton of H₂ × km)], and l_{H_2} is the hydrogen payload [kg]. Fig. 7 shows the energy required for road delivery by truck of one kilogram of hydrogen.

As shown in Fig. 7, to transport liquefied hydrogen requires less energy than compressed hydrogen due to the higher volumetric density of liquid hydrogen. Similarly, compressed hydrogen at 500 bar requires less energy than transporting hydrogen at 200 bar. However, as shown in Fig. 8, if the energy required for the hydrogen treatment (e.g. liquefaction and compression) is considered, transportation of liquid hydrogen requires more energy than compressed hydrogen. The total energy required for the preparation and the transport of hydrogen has been obtain as follows

$$W = W_{\text{prep}} + W_{\text{transport, truck}} \quad (7)$$

where W_{prep} is the liquefaction work shown in Fig. 5, or the compression work shown in Fig. 6, depending on the method selected to transport the hydrogen.

According to this analysis, when delivery distances are shorter than 84 km, compressed hydrogen at 200 bar is the least energy intensive strategy. However, for distances larger

Table 2 – Main assumptions for truck delivery analysis.

	Compressed H ₂ @ 200 bar	Compressed H ₂ @ 500 bar	Liquefied H ₂
Truck curb weight ($(w)_{\text{truck}}$)	40,000 kg	40,000 kg	40,000 kg
Hydrogen load ($(l)_{\text{H}_2}$)	320 kg	920 kg	4000 kg
Hydrogen delivered	288 kg	720 kg	4000 kg
Truck Gross Weight (GW)	40,320 kg	40,920 kg	44,000 kg
Diesel truck consumption ($(c)_{\text{truck}}$)	0.01 kg diesel per ton per km [18]		
Source	[18]	[18]	[22]

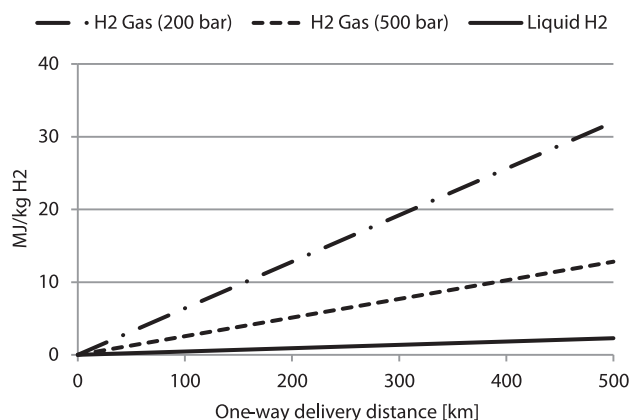


Fig. 7 – Delivery energy required by diesel truck.

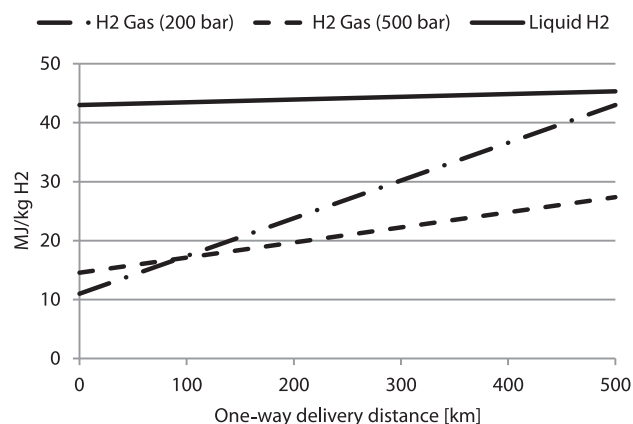


Fig. 8 – Treatment and delivery energy by diesel truck.

than 84 km, hydrogen gas is more efficiently transported at 500 bar. This establishes a breakpoint distance that determines the most efficient pressure to transport compressed hydrogen by truck as a function of the delivery distance. However, other factors may ultimately determine the preferred delivery method such as the availability of forecourt electrical power required for onsite compression up to dispensation pressure, site footprint, or desire to limit the number of deliveries per day or week.

2.4. Hydrogen storage

Once hydrogen has been delivered to the end user, it has to be stored onsite until its final use. Recent developments in materials and manufacturing technology allow the use of portable composite tanks from the production plant to the end-user site [21]. Full tanks replace depleted tanks that will

be taken back and refilled at the production plant for the next use.

2.5. Hydrogen dispensing

To use the hydrogen as a transportation fuel in a fuel cell or internal combustion vehicle it has to be transferred from the storage medium to the vehicle tank. Toyota, Mercedes-Benz, General Motors, and Hyundai/Kia fuel cell vehicles are all equipped with 700 bar onboard storage tanks. Honda is the only active FCV manufacturer with 350 bar onboard storage.

State-of-the-art hydrogen refueling stations incorporate fast fill option which requires pre-cooling of the hydrogen before it enters the vehicle tank. An energy use of 0.54 MJ/kg has been added to the compression energy in all the selected supply chains to pre-cool the hydrogen during fast filling [24].

Table 3 – Definition of the analyzed hydrogen supply chains.

Supply chain	Generation	Treatment	Distribution	Storage	Dispensing
1	Centralized SMR	Liquid H ₂	Diesel truck (Delivery distance 100 km)	Liquid H ₂	Vehicle tank pressure = 350 bar
2	Centralized SMR	Liquid H ₂	Diesel truck (Delivery distance 100 km)	Liquid H ₂	Vehicle tank pressure = 700 bar
3	Centralized SMR	Compressed H ₂ (200 bar)	Diesel truck (Delivery distance 100 km)	Compressed H ₂ (200 bar)	Vehicle tank pressure = 350 bar
4	Centralized SMR	Compressed H ₂ (200 bar)	Diesel truck (Delivery distance 100 km)	Compressed H ₂ (200 bar)	Vehicle tank pressure = 700 bar
5	Centralized SMR	Compressed H ₂ (500 bar)	Diesel truck (Delivery distance 100 km)	Compressed H ₂ (500 bar)	Vehicle tank pressure = 350 bar
6	Centralized SMR	Compressed H ₂ (500 bar)	Diesel truck (Delivery distance 100 km)	Compressed H ₂ (500 bar)	Vehicle tank pressure = 700 bar
7	Distributed SMR	Compressed H ₂ (500 bar)	N/A (Delivery distance 0 km)	Compressed H ₂ (500 bar)	Vehicle tank pressure = 350 bar
8	Distributed SMR	Compressed H ₂ (500 bar)	N/A (Delivery distance 0 km)	Compressed H ₂ (500 bar)	Vehicle tank pressure = 700 bar
9	Tri-generating HTFC	Compressed H ₂ (500 bar)	N/A (Delivery distance 0 km)	Compressed H ₂ (500 bar)	Vehicle tank pressure = 350 bar
10	Tri-generating HTFC	Compressed H ₂ (500 bar)	N/A (Delivery distance 0 km)	Compressed H ₂ (500 bar)	Vehicle tank pressure = 700 bar

Table 4 – Energy required on a per-kg basis for each step for each of the ten hydrogen supply chains.

Supply chain	Generation [MJ/kg]	Treatment [MJ/kg]	Distribution [MJ/kg]	Storage [MJ/kg]	Dispensing [MJ/kg]	Total [MJ/kg]
1	179.6	40.0	0.46	0.00	7.76	200.12
2	179.6	40.0	0.46	0.00	9.18	201.54
3	179.6	11.0	6.4	0.00	1.75	171.05
4	179.6	11.0	6.4	0.00	2.44	171.75
5	179.6	14.6	2.6	0.00	0.54	169.58
6	179.6	14.6	2.6	0.00	1.14	170.18
7	218.3	14.6	0.0	0.00	0.54	199.74
8	218.3	14.6	0.0	0.00	1.14	200.33
9	168.6	14.6	0.0	0.00	1.08	158.24
10	168.6	14.6	0.0	0.00	1.14	158.30

Table 5 – Overall efficiencies (on an LHV basis).

Supply chain	Overall efficiency, %
1	59.96
2	59.54
3	70.15
4	69.87
5	70.76
6	70.51
7	60.08
8	59.90
9	75.83
10	75.80

2.5.1. Liquid to compressed hydrogen

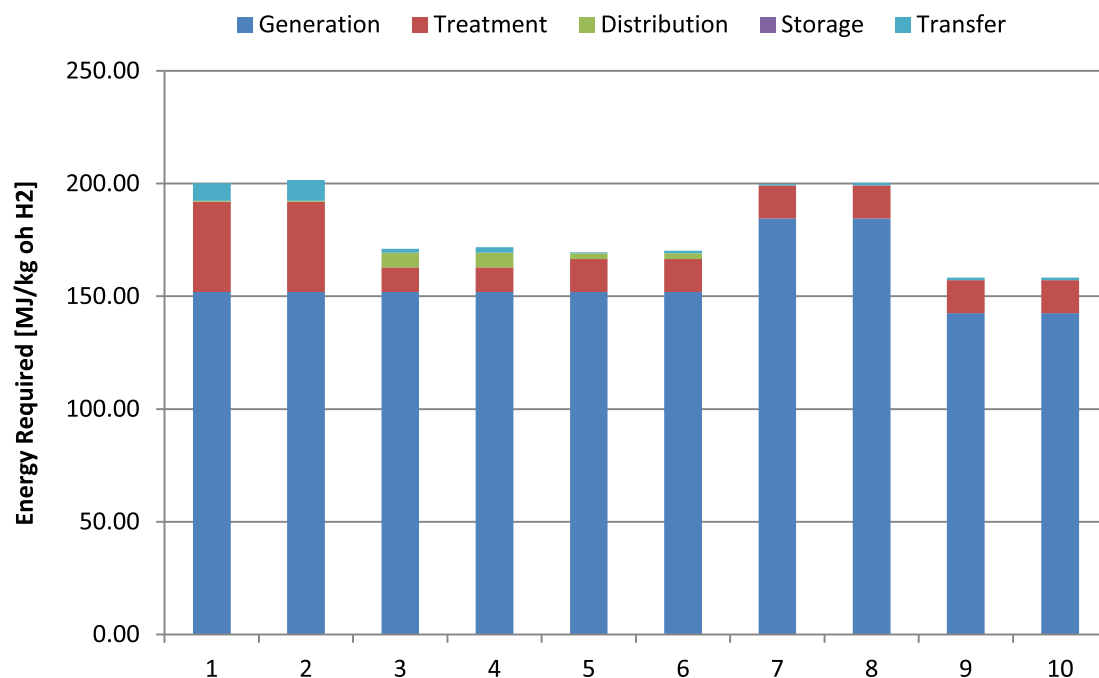
For onsite liquid storage, the hydrogen can either be compressed using a liquid compressor, or first vaporized and

then compressed in gaseous form. Although the latter method is more used today, it is expected that the vaporization and compression technology will be eclipsed by higher efficiency liquid compression in the near future.

For this analysis, it is assumed that hydrogen is compressed in its liquid form. Recent studies related to cryogenic hydrogen refueling technologies [23] have predicted the following energy usages: 8.64 MJ/(kg LH₂) for compression up to 700 bar and subsequent heating up to –40 °C; and 7.2 MJ/(kg LH₂) for compression up to 350 bar and subsequent heating up of –20 °C.

2.5.2. Compressed gas to compressed gas

When stored as a compressed gas, the hydrogen may have sufficient pressure to fill a vehicle, depending upon the storage pressure required. If the onsite pressure is below the required vehicle pressure, a booster compressor is needed which draws hydrogen from the onsite storage tubes at elevated pressure, compresses the gas to raise the pressure

**Fig. 9 – Energy used for each hydrogen supply chain.**

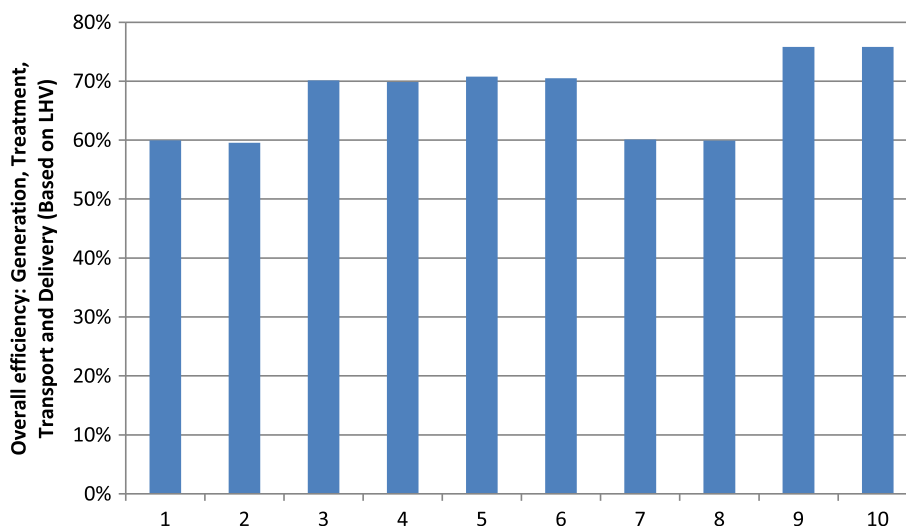


Fig. 10 – Supply chain efficiencies.

beyond that of the vehicle, and then outputs to either onsite high pressure storage tubes, or directly into the vehicle tank.

3. Analysis and results

After evaluating the energy required for each step from the production to the use of hydrogen, the overall efficiency of different hydrogen supply chains have been evaluated. Table 3 summarizes in detail each of the selected hydrogen supply chains. As shown, each supply chain includes two different final uses corresponding to the two available fuel cell vehicle tank pressures (i.e. 350 bar and 700 bar) [21]. In addition, when hydrogen is produced in a centralized SMR plant, the three available treatment methodologies have been investigated. As a result, ten different supply chains have been evaluated.

The results obtained for each supply chain are shown in Tables 4 and 5 and in Figs. 9 and 10.

As shown, the lowest efficiency values are observed for the distributed SMR cases whereas the highest values correspond to tri-generating HTFC. As expected, due to the significant energy penalties associated with liquefaction processes, WTT efficiencies of centralized SMR with liquid hydrogen transportation are almost as low as the distributed SMR cases. Central SMR with liquid delivery and small scale onsite SMR may both play vital roles in future hydrogen refueling infrastructure for a variety of reasons including existing hydrogen manufacturing equipment, distribution distances, and station throughput, but they are not the best options from a pure efficiency standpoint.

It is important to mention that the energy required for the production step includes the energy content of the fuel feedstock. The efficiency values have been obtained by dividing the energy content of one kilogram of hydrogen (on an LHV basis, 120 MJ/kg) by the total energy required for each path.

4. Summary and conclusions

The current analyses show that local HTFC tri-generation is the most efficient means to produce and deliver hydrogen amongst those means considered herein. In addition, HTFC tri-generation has the potential to continuously operate regardless of the immediate hydrogen demand. As such, tri-generation technology may play an important future role by introducing an efficient combination of distributed power and vehicle fuel production. Hurdles to the widespread adoption of this technology include system cost, complexity, and footprint. As FCV technology enters commercialization in the near future, the expanding market for hydrogen fuel will provide economic motivation to improve all hydrogen supply chains, which may include significant use of HTFC tri-generation.

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Nomenclature

- AC: alternating current
 ADG: anaerobic digester gas
 AGO: anodic gas oxidizer
 APCI: Air Products and Chemicals Inc.
 CA: California
 DFC: direct fuel cell
 GW: Gigawatt
 HSU: hydrogen separation unit
 HTFC: high temperature fuel cell
 kW: kilowatts
 LCA: life cycle analysis
 LHV: lower heating value
 MCFC: molten carbonate fuel cell
 OCSA: Orange County Sanitation District
 PSA: pressure swing adsorption
 SMR: steam methane reformation
 SOFC: solid oxide fuel cell
 WGSR: water–gas shift reaction
 WTT: well-to-tank
 E_{tot} : total energy flow, kW
 E_{H_2} : energy flow portion to produce hydrogen, kW
 E_{e^-} : energy flow portion to produce electricity, kW
 H_2 : hydrogen fuel produced, kW
 P_{net} : net electric power, kW
 W_{comp} : compression work, kW
 v : hydrogen-specific volume
 $\eta_{overall}$: overall efficiency of a tri-generating HTFC
 η_{elec} : electrical efficiency of a tri-generating HTFC
 η_{H_2} : hydrogen production efficiency of a tri-generating HTFC