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Economic prospects and policy framework for hydrogen as fuel in the transport sector

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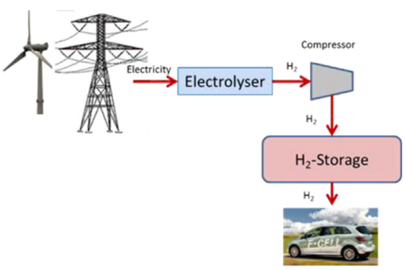
GRAPHICAL ABSTRACT



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ABSTRACT

For a long time hydrogen has been considered a clean energy carrier to be applied universally and contribute to a sustainable energy system. However, in the real energy world hydrogen has not yet delivered. The major reason is that it has still to become economically feasible. With increasing electricity generation from variable renewables and its temporarily cheap surplus production, new prospects for hydrogen are on the horizon especially due to the rising need for a solution to the problem of the long-term storage of excess electricity.

The core objective of this paper is to analyze the economic prospects of hydrogen use in the energy system keeping in mind two challenges: (i) integration of variable renewables in power systems, and (ii) substitution of fossil fuels in the transport sector. The future economics of hydrogen in passenger car transport is investigated regarding hydrogen production costs and possible learning effects of the fuel cell vehicles.

The major conclusion is that the future perspective of hydrogen use depends on the policy framework, the full exploitation of economies-of-scale and technological learning for electrolysis as well as possible full-load hours per year. However, cost reduction of fuel cells for mobility through technological learning is essential for the economic competitiveness of hydrogen use in transport.

1. Introduction

The global energy system currently faces two major challenges. On the one hand it is important to ensure a sufficient and secure energy supply. On the other hand, it is important to reduce energy-related greenhouse gas (GHG) emissions and to move towards a sustainable energy system. In this context two issues are of highest priority: (i) the increasing use of renewable energy sources (RES), and (ii) the provision of clean energy carriers.

For a long time, hydrogen has been discussed as the energy carrier of the future. Already in 1874, in his novel “The Mysterious Island” the French science-fiction writer, Verne saw hydrogen and oxygen as the energy sources of the future (Verne, 1874). In his vision, hydrogen was produced by the breaking down of water (via electrolysis) and would

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replace coal, which at the time was the primary energy source (Shell, 2017).

Due to increasing fossil fuel prices in the 1970s and more and more visible environmental problems, the interest in alternative fuels and technologies intensified. At that time the concept of a solar economy was developed, with hydrogen as the central energy carrier (Shell, 2017; Ajanovic, 2015).

With technological progress achieved in the 1990s, the discussion on hydrogen has intensified at the beginning of the 21st century. Hydrogen is considered to be a clean energy carrier to be applied virtually universally leading the world towards a sustainable energy future, see Rifkin (2003). In his seminal contribution, "The Hydrogen Economy", Rifkin envisions the dawn of a new economy powered by hydrogen that will fundamentally change the nature of our market, political and social institutions, just as the change to coal and steam power did at the beginning of the industrial age. Rifkin observes that we are fast approaching a critical watershed in the fossil-fuel era with potentially dire consequences for industrial civilization. He claims that policy makers have to anticipate the consequences and make significant interventions to turn the energy system towards a CO_2-emission free future.

The possible benefits of hydrogen in the energy transition were recognized by European policy makers and stakeholders in the early 2000s, see (EC, 2003). The strategies for the transformation of the current energy system towards a more sustainable one include, among others, further technological developments in the concepts of converting renewable power into easily-storable energy carriers such as hydrogen, as well as the implementation of corresponding policies.

In 2003 the European Commission presented a roadmap showing how an integrated energy system based on hydrogen and fuel cells might appear up to 2050. A skeleton proposal with the main elements and time lines of the European hydrogen and fuel cell roadmap is presented in Fig. 1 (EC, 2003).

More recently, the IEA (International Energy Agency) has published a technology roadmap discussing the role of hydrogen, and providing recommendations for actions for different stakeholders when heading towards hydrogen-based energy systems (IEA, 2015a, 2017). However, in the real energy world hydrogen has not yet delivered. The major reason is that it has yet to become economically feasible.

However, rapidly growing electricity generation from variable RES, such as wind and solar energy could lead to new chances for hydrogen due to an increasing imbalance between energy supply and demand. As an example, in Fig. 2a hypothetical scenario is depicted with a high level of electricity generation from wind, solar and run-of-river hydro plants using synthetic hourly data for an average year in Austria over a week in summer. Imbalance between electricity supply and demand can be observed, as well as the corresponding volatility in electricity market prices. With the increasing use of photovoltaics (PV) and wind for electricity generation, increasing amounts of temporarily cheap or even free surplus electricity could also become available (Haas et al., 2013). Already in recent years, for example in Germany, prices on the electricity market have fluctuated greatly mainly due to the increasing quantities of the new variable RES.

One of the means of coping with this challenge is to convert electricity to hydrogen and create a back-up capacity for electricity generation or to use hydrogen for other energy services.

Over the last few years, different aspects of hydrogen have been analyzed in literature. Bartels et al. (2010) analyzed the economic attractiveness of different hydrogen production technologies, concluding that coal and natural gas are the most attractive processes from an economic perspective, however, without considering technological improvements and environmental concerns. Environmental aspects of mobility with hydrogen are evaluated by Ajanovic (2013), Burkhardt et al. (2016), and Sweeting and Winfield (2012). A comprehensive literature review on economics of fuel cell vehicles, as well as other electric vehicles, is provided by Veziroglu and Macario (2011), Hervey (2018). Economic assessment of hydrogen as a renewable fuel for a transport is analyzed by Specht et al. (1998), Ajanovic (2008) and Singh et al. (2015). Detailed cost analyses of fuel cell systems have been conducted by Sinha et al. (2008) and James et al. (2010). They have reported that economies-of-scale have a major influence on fuel cell component costs. Based on work of these authors, Miotti et al. (2017) conducted an integrated environmental and economic assessment of current and future fuel cell vehicles. They find out that economies-of-scale effects alone are not sufficient to make fuel cell vehicles competitive with conventional cars. Marchenko and Solomin (2015) have compared hydrogen and electricity in terms of energy and economic expenditure for each stage of these technologies, concluding that in case of short-term energy storage it is more preferable to use the electric system, whereas in the long-term energy storage the hydrogen system is more efficient. Ball and Weeda (2015) provide a comprehensive coverage of the most relevant aspects related to the wider use of hydrogen in the energy system. They state the relevance of a higher number of full-load hours and low electricity prices for economic viability of hydrogen production. Several authors address the role of hydrogen in different countries or regions (e.g. Sgobbi et al., 2016; Usher and Strachan, 2012; Ball et al., 2007; Sigal et al., 2014; Sacramento et al., 2013; Rahmouni et al., 2017; Ogden et al., 2014; Liu et al., 2018). Regardless of different focusses and approaches, most common conclusion of all these studies is that investment costs of hydrogen

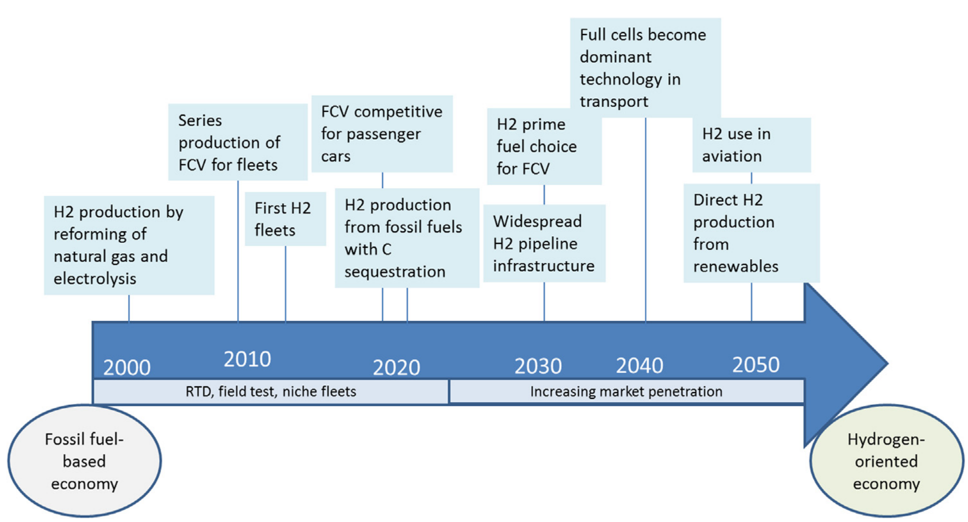

Fig. 1. Major milestones in the European hydrogen vision.

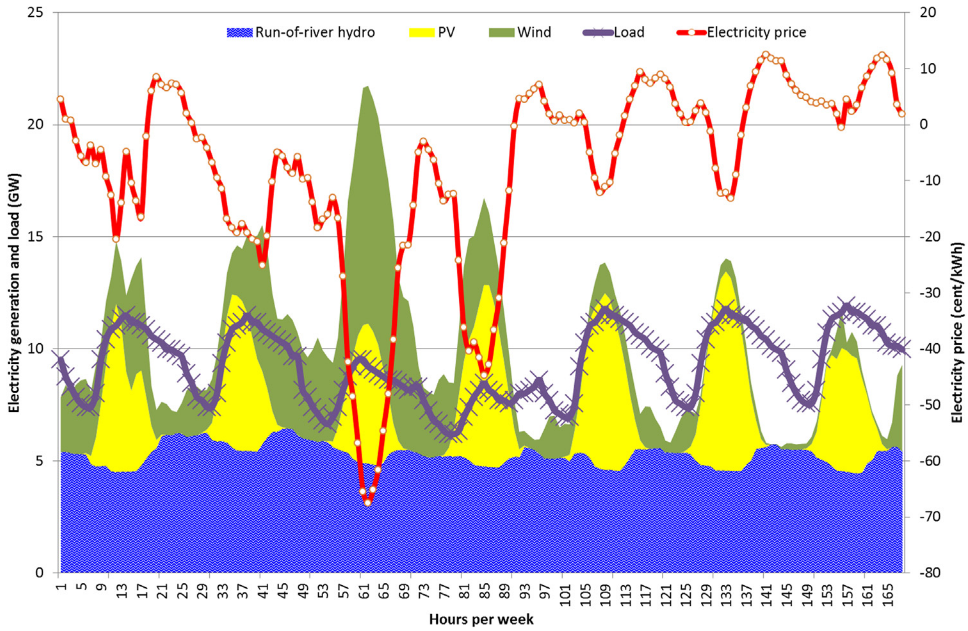

Fig. 2. Example: Supply of variable renewables from wind, PV and run-of-river hydro plants on an hourly basis over a week in summer in comparison to demand and resulting electricity market prices
(adapted from Haas et al, 2013).

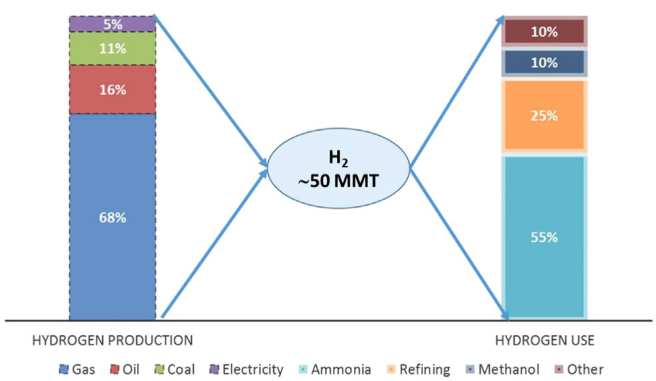

Fig. 3. Share of energy carriers in hydrogen production and share of hydrogen use for different purposes, (Shell, 2017; USDE, 2013; Bakenne et al., 2016).

production and consumption technologies are a key barriers for the broader use of hydrogen. Most of them have emphasized the importance of hydrogen production from RES.

Starting from existing literature, in this paper we provide a comprehensive dynamic assessment of hydrogen production by electrolysis using surplus electricity from RES depending on the full-load hours and plant size, as well as hydrogen use in fuel cell passenger cars.

The core objective of this paper is to analyze and discuss the economic prospects of hydrogen use in the energy system keeping in mind two challenges: (i) the integration of variable renewables in power systems, and (ii) the substitution of fossil fuels in the transport sector. It is of specific interest to analyze the potential impacts of technological learning and possible economies-of-scale of hydrogen production via electrolysis. Finally, the future economics of hydrogen in passenger car transport is investigated regarding hydrogen production costs and the possible learning effects of fuel cell vehicles.

This paper is organized as follows: Section 2 provides background information about current hydrogen production and use. In Section 3 costs of electrolytic hydrogen production are analyzed depending on size of the electrolysis system and the number of the full-load hours. Different hydrogen chains based on renewable electricity are presented in Section 4. Section 5 provides an assessment of current economics of hydrogen in transport as well as long-term perspective. Section 6 focus on policy issues related to hydrogen use. Finally, Section 7 highlights the key findings and draws conclusions.

2. Background: Hydrogen production and use

Hydrogen is a very flexible secondary energy carrier that can be produced from different types of locally and regionally available primary energy sources. More than 50 million metric tons (MMT) are produced annually worldwide (USDE, 2013; Bakenne et al., 2016) using different hydrogen production methods. Some of them are well developed and mature technology but there are also some methods (e.g. photochemical and biological methods), which are under fundamental research. Although, hydrogen is seen as means to integrate variable RES into electricity systems, currently, the largest amount of hydrogen, about 68%, is produced by steam reforming of natural gas, as this is the cheapest way of hydrogen production. The share of primary energy carriers in global hydrogen production as well as the share of hydrogen use for different purposes is depicted in Fig. 3. As can be noticed, only a small proportion of hydrogen, about 5%, is produced by electrolysis. However, for the future it can be expected that hydrogen production from electrolysis will rise significantly if surplus electricity from renewable energy sources becomes increasingly available (Shell, 2017).

Currently, the largest amount of hydrogen is used for different industrial and chemical processes. About 55% of the global hydrogen production is used for ammonia synthesis, 25% in refineries, 10% for methanol production and just about 10% is used for another applications, see Fig. 3. Hydrogen use for mobility is currently negligible. Currently, there are about 600 fuel cell vehicles worldwide (IEA, 2015a).

3. Costs of electrolitic hydrogen production

As discussed above, hydrogen can be produced using different primary energy carriers in different production processes and can be used for different purposes. It is a very flexible energy carrier with which different energy supply chains could be created.

However, for the future of special interest are energy supply chains based on hydrogen produced from RES by electrolysis. In the course of the energy transition, the proportion of variable RES in electricity generation will rise significantly. A great expansion of wind power and photovoltaics is already visible. Due to their fluctuation over time balancing of supply and demand is becoming more challenging.

Since hydrogen production from surplus electricity could be an option to increase flexibility of the energy system given the increasing use of variable renewable energy sources, hydrogen generation using electrolysers is becoming an important option. An electrolyser is a device which splits water into hydrogen and oxygen using electrical energy. In this process electricity is converted in chemical energy. This technology is essential to link the transport and power sector.

However, the success of this sector coupling is dependent on the development of the cost of hydrogen. Costs of hydrogen are very dependent on the investment costs of electrolyser and the cost of electricity used. In future, investment costs could be reduced by technological learning and economies-of-scale. To minimize the cost of electricity we can use cheap surplus electricity from RES for hydrogen production. Yet, this leads to lower number of full-load hours per year, increasing the impact of the investment cost. Considering all relevant impact parameters, hydrogen costs are calculated as:

$$C_{H_2} = \frac{IC \cdot \alpha + C_{o\&m}}{T} + \frac{P_{Ele}}{\eta} (\text{EUR/kWh}) \tag{1}$$

where IC is specific investment cost of electrolysis system (EUR/kW), α is a capital recovery factor, $C_{o\&m}$ are operating and maintenance costs (EUR/kW), T is the number of full-load hours per year (h), P_{Ele} is the price of electricity (EUR/kWh), and η is conversion efficiency.

Including energy losses in hydrogen storage, Eq. (1) can be adapted as:

$$C_{STO} = \frac{C_{H_2}}{\eta_{STO}} (\text{EUR/kWh}) \tag{2}$$

where C_{STO} are total costs of hydrogen (EUR/kWh), and η_{STO} is efficiency of storage.

Another important aspect, relevant to the cost of hydrogen production, is the size of the production system. Fig. 4 shows relation between the specific investment costs of electrolysers and the power of the plant. It is obvious that small-size electrolysers are rather expensive, leading to higher hydrogen costs.

Corresponding total costs of hydrogen production are depicted in Fig. 5. Using small-size electrolysers (ca. 100–500 kW), hydrogen costs are above 0.23 EUR per kWh. In the case of the large-size electrolysers (above 4000 kW) total hydrogen costs are below 0.15 EUR/kWh.

Current efficiencies and investment costs of electrolysers and the total plant costs for different production capacities are given in Table 1. The investment costs refer to the corresponding numbers in Fig. 4. Note that there is a difference between kW_{Ele} and kW_{H2} due to the efficiency of the conversion process. Hence, cost figures related to kW_{H2} are always higher. This is often a problem in literature since the distinction is not always clear.

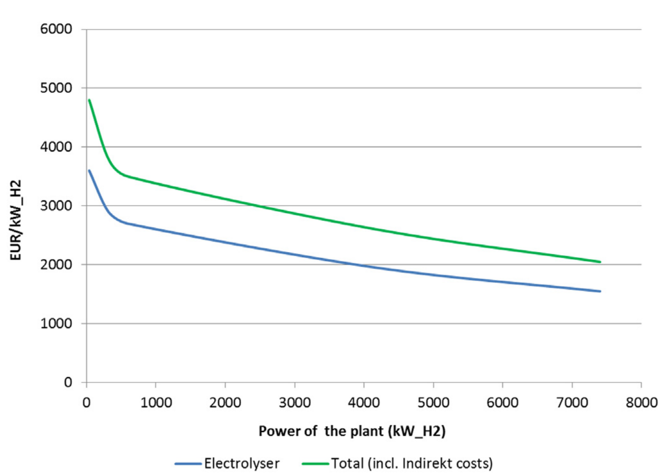

Fig. 4. The specific investment costs of electrolysers for hydrogen production depending on the power of the plant (as of 2016)
(data source: Platts, 2018; Steinmüller et al., 2014).

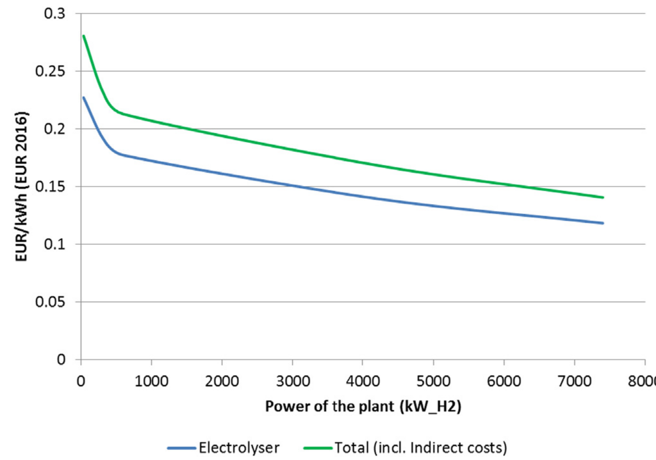

Fig. 5. The costs of hydrogen depending on the power of the electrolyser.

Table 1
Total investment costs of hydrogen production depending on the power of the plant (EUR/kW_{Ele} and EUR/kW_{H2} as of 2016), (data source: Platts, 2018; Steinmüller et al., 2014).

Investment costs of the electrolysis:			
	Efficiency η	EUR/kW_{Ele}	EUR/kW_{H2}
500 kW_{Ele}	0.63	1800	2900
10 MW_{Ele}	0.74	1150	1550
Total system costs (incl. conversion of electricity, compression and storage of hydrogen):			
500 kW_{Ele}	0.63	2400	3800
10 MW_{Ele}	0.74	1550	2050

Remark on the efficiency η: it encompasses the conversion efficiency of the electrolysis and the efficiency of compression of hydrogen.

Today mainly small systems with capacities below 500 kW are in operation. However, there are already plans for constructing plants with 10 MW or beyond (Platts, 2018). This would reduce the specific hydrogen generation costs remarkably, see Fig. 5.

As seen from Eq. (1) the costs of electricity are an important parameter for calculating the total hydrogen costs. In this context, Fig. 6 shows the classified frequency of hourly marginal prices and average prices of electricity in Austria and Germany in 2016 over a year. The marginal prices are the actual prices on the day-ahead market, and the average prices show the average of the prices below a certain number of full-load hours (FLH). It can be seen that, for example, the average electricity price is about 2 cents/kWh for about 4000 full-load hours per year, Fig. 6.

Finally, it is important to find an optimal balance between investment costs of electrolyser (depending on the plant size) and possible full-load hours per year. As an example, Fig. 7 shows the cost of hydrogen generation from small electrolysis systems depending on the full-load hours of the electrolyser and the costs of electricity used. The average electricity costs in Fig. 7, as well as Fig. 8, are obtained by dividing the average electricity price from Fig. 6 by the corresponding efficiency (according to Table 1), see also Eq. (1). The lowest cost of hydrogen could be reached from about 6000 full-load hours per year.

Fig. 8 show the total cost of hydrogen generation in large electrolysis system depending on the number of the full-load hours. In this

Fig. 6. Classified frequency of hourly marginal and average prices of electricity in the joint Austrian-German wholesale electricity market over a year (2016) (data source: EPEX, 2017).

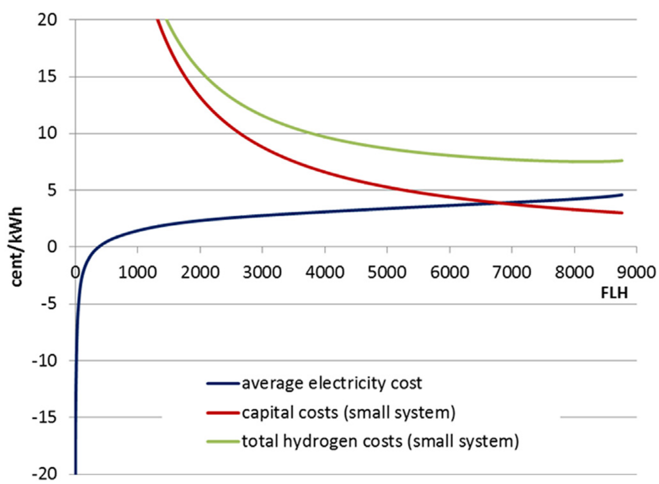

Fig. 7. The total cost of hydrogen from small electrolysis system (500 kW_{Ele}) depending on the number of the full-load hours.

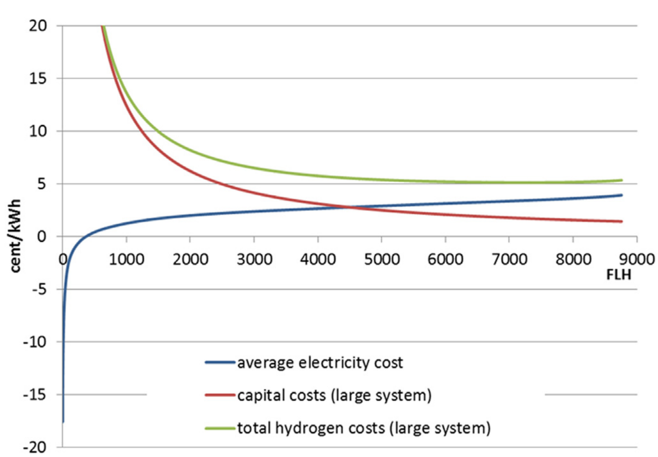

Fig. 8. The cost of hydrogen from large electrolysis system (10 MW_{Ele}) depending on the number of the full-load hours.

case, the lowest costs of hydrogen could be reached starting from about 4500 full-load hours per year.

Comparing the total production costs of small and large hydrogen-generation systems depending on the number of the full-load hours per year, it can be seen that the lowest costs are approximately 5 cents/kWh starting from about 4500 full-load hours in the large system, approximately 8 cents/kWh starting from about 6000 full-load hours in the small system. However, from practical lessons learned it is known that a maximum of 2800 full-load hours is realistic, leading to a hydrogen costs in the range from 7 cents/kWh to 12 cents/kWh.

4. Hydrogen chains based on renewable electricity

According to IEA (2015a) there are four major hydrogen chains based on renewable electricity:

(i) The first one is to convert surplus electricity into easy-storable energy carrier and, depending on needs, to convert it back to electricity.
(ii) Another option is to blend electrolytic hydrogen with natural gas or convert it to methane. In this case, hydrogen could be stored in the existing gas grid.
(iii) An additional option is to convert surplus electricity to hydrogen, which is then used as a feedstock for different industry processes.
(iv) Finally, of specific interest for the transport sector is the idea of using surplus electricity for hydrogen production and employing hydrogen as a clean fuel in fuel cell vehicles.

Regarding the first point, an example of such an energy supply chain is depicted in Fig. 9. Hydrogen is produced by electrolysis from variable renewables and it can be converted again to electricity (re-electrification). However, it is important to note that every conversion step in the energy supply chain involves energy loss, leading to low total efficiency of the system. Currently, the total conversion efficiency of different hydrogen-based systems involving electricity from RES and re-electrification is in the range from about 27–38%, see Fig. 9 (IEA, 2015a; Ajanovic and Haas, 2015).

Besides low efficiency, another problem is that compared to electricity market prices the costs of hydrogen are very high (e.g. about 6 cents/kWh even for 4000 full-load hours per year). Adding the re-electrification of hydrogen with a conversion efficiency of 58%, electricity generation costs would be about 10 cents/kWh, and consequently such an energy supply chain is not economically competitive at present.

To avoid energy losses during the re-electrification of hydrogen, we can use hydrogen as a fuel for FCVs in the transport sector, see Fig. 10. Already now, in comparison with other electric vehicles, FCVs show significant benefits such as a long driving range (about 500 km), as well as quick refueling (3–5 min).

Since current passenger car transport, which is mainly based on fossil fuels and internal combustion engine (ICE) vehicles, causes continuously increasing air pollutions and GHG emissions hydrogen systems based on renewables are seen as a possibility to contribute to the

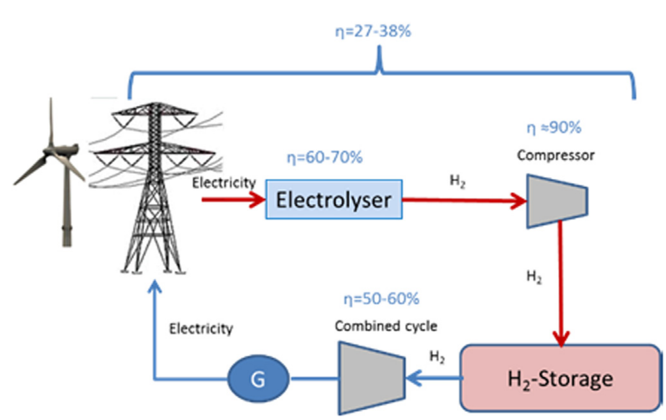

Fig. 9. Energy supply chains: electricity-hydrogen-electricity.

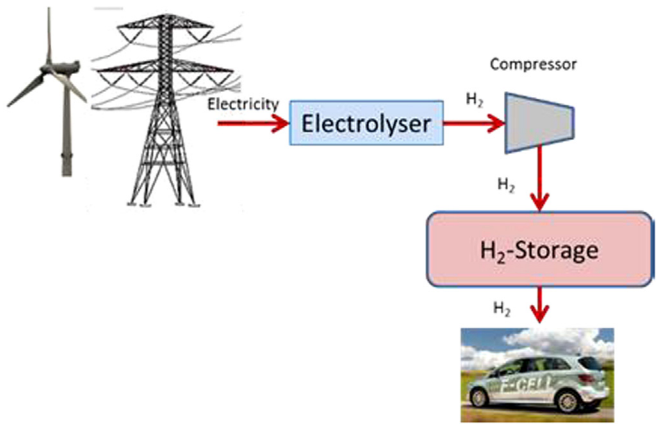

Fig. 10. Energy supply chains: Use of hydrogen from RES in FCVs.

decarbonization of the transport system. While the use of battery electric vehicles (BEVs) has been increasing over the last few years, FCVs are currently being discussed as a long-term option. However, the combination of such challenges as the integration of variable RES in power systems and the growing emissions from the transport sector could significantly accelerate the future deployment of hydrogen. The synergy between the transport and power sector should also accelerate investments in- and research on hydrogen and fuel cells.

5. Economics of hydrogen as an energy carrier in transport

One of the reasons for current negligible hydrogen use in the transport sector is the high price of FCVs. However, in contrast to other types of electric vehicles (such as hybrid electric vehicles (HEV), plug-in-hybrid (PHEV), and battery electric vehicles (BEV)), electricity in FCVs is produced on board from hydrogen. The current price of a mid-size FCV is about 72000 EUR (incl. VAT). The cost structure of FCVs is depicted in Fig. 11. As shown, the most expensive component of a FCV is the fuel cell system, about 50% (IEA, 2015a).

The total costs of mobility with FCVs per 100 km driven (C_{km}) are calculated according to the following equation:

$$C_{km} = \frac{IC \cdot \alpha}{skm} + P_e \cdot EI + \frac{C_{O\&M}}{skm} (€/100\ \text{km driven}) \tag{3}$$

where IC is the investment cost of vehicle (EUR/car), α is a capital recovery factor, $C_{o\&m}$ are operating and maintenance costs (EUR per car and year), skm is a specific number of vehicle kilometers driven per year (km), $P_e$is energy price incl. taxes (EUR/kWh), and EI is energy consumption of vehicle (kWh/100 km).

The total energy price (P_e) depends on the costs of the energy

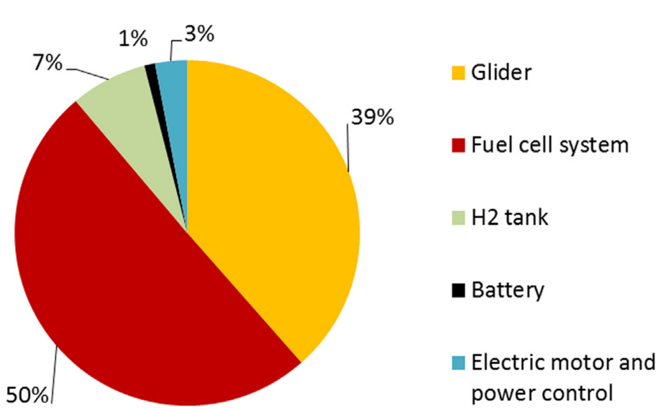

Fig. 11. Structure of investment costs of fuel cell vehicles.
data source (IEA, 2015a).

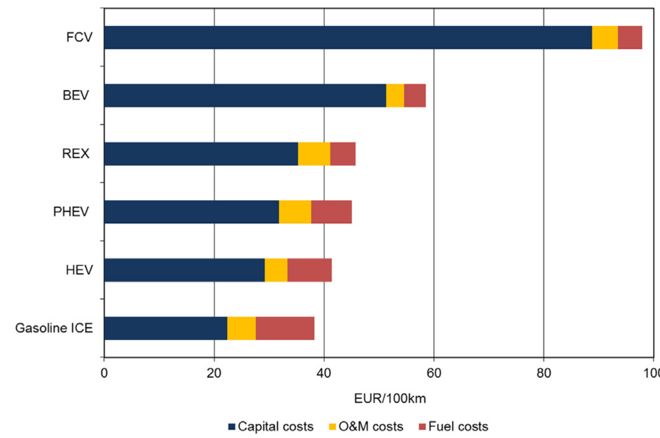

Fig. 12. The total costs of mobility with different fuel and powertrains, 2016.

carriers (C_e) used (e.g. hydrogen, electricity, gasoline, etc.) and the possible taxes (τ) implemented, such as e.g. value add tax, excise tax and CO_2 taxes:

$$P_e = C_e + \sum_{i=1}^{n} \tau_i (\text{EUR/kWh}) \tag{4}$$

The specific costs of mobility with hydrogen and FCVs compared to other electric vehicles, as well as conventional ICE vehicles powered by fossil fuels, are shown in Fig. 12. These costs are strongly dependent on the number of specific kilometers driven per year (see Eq. (3)). We have assumed 12,000 km driven per year for all types of cars.

The costs of hydrogen are taken from our calculation presented in Section 3. We have used the minimal hydrogen production costs considering plant size and associated number of 2800 full-load hours per year. These are 7 cents/kWh for large systems and about 12 cents/kWh for small systems (see Figs. 7 and 8). As currently mainly small electrolysers are operating, the figure of 12 cents/kWh has been taken for calculating the fuel cost of the FCV in Fig. 12.

Looking at the total costs of mobility with different fuels and powertrains, it can be noticed that the prospects of hydrogen in transport are not very convincing today. It is clear that the major economic barriers are the investment costs of the car. Whether hydrogen is produced in large or small plants has currently no significant impact.

Yet, since the cost and performance of fuel cell and hydrogen production systems have improved significantly over the last few years, cost parity with conventional cars can be expected in the future. In this context the full exploitation of economies-of-scale as well as of technological learning for electrolysis will play an important role.

With respect to the future development of the investment costs of alternative and new technologies, it is expected that they can be reduced through technological learning. Technological learning can be illustrated by learning curve which can be expressed using Eq. (5):

$$IC_{New}(t) = IC(t_0) \cdot \left(\frac{x_t}{x_{t_0}} \right)^{-b} \quad (EUR/kW) \tag{5}$$

where $IC_{New}(t)$ is investment cost of new technology (EUR/kW), b is a learning index, $IC(t_0)$ is investment cost at the time t_0 (EUR/kW), and x refers to cumulative capacities installed at time t and t_0.

Applying this approach to hydrogen production plants (electrolysers), Fig. 13 shows the perspectives of the developments of investment costs for small and large hydrogen plants with high and low learning rates (LR). It can be seen that over the period up to 2050 for both sizes the investment costs decrease by about 30% (for a low learning rate of 17% it is some percent less, for a high learning rate of 23%, some percent more). Based on these developments in investment costs, as next we calculate hydrogen generation costs up to 2050, see Fig. 14.

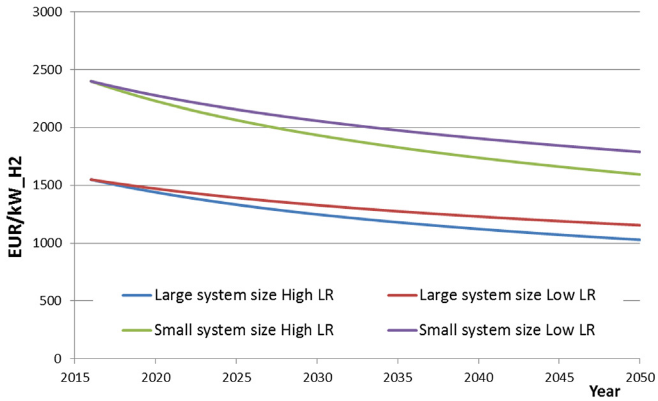

Fig. 13. Perspectives of development of investment costs of small and large electrolysis plants depending on learning rates.

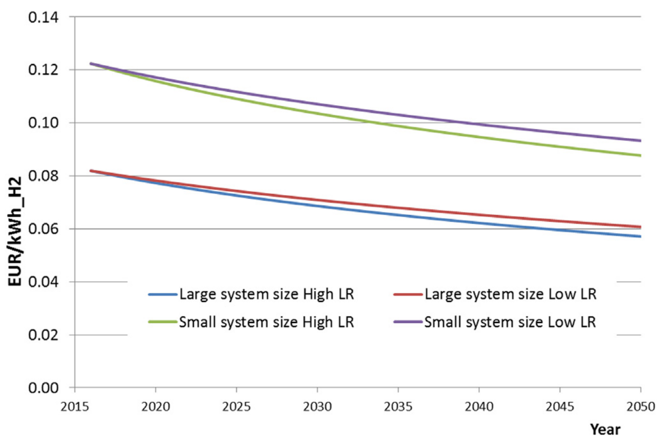

Fig. 14. Perspectives of development of hydrogen cost from small and large electrolysis plants depending on learning rates.

In addition, according to Eq. (1), the development of electricity prices is also important. In our scenario, due to higher quantities of surplus electricity in the future, electricity wholesale market prices decrease from 1.8 cents/kWh to 1.5 cents/kWh. Given these input parameters, by 2050 under most favorable learning conditions (IEA, 2010) the costs of hydrogen for 2800 full-load hours per year will be about 0.06 EUR/kWh, see Fig. 14.

Having estimated the hydrogen production costs for 2050 in our scenarios depending on technological learning and economies-of-scale, the next step is the analysis of the development of the investment costs of FCVs.

It is assumed that in the future cars driven by fossil fuel will become more expensive, mostly due to the better monetizing of negative environmental impacts. In contrast, fuel cell vehicles will become less expensive due to technological developments and learning, as well as the effects of economies-of-scale in production (IEA, 2015b). To capture the dynamic effects of changes in the investment costs of powertrains over time, the approach of technological learning has been applied.

For the cost reduction of FCVs, the cost development of fuel cells is of particular interest. The development of fuel cell system costs for a learning rate of 20% is shown in Fig. 15.

In recent years the costs of FCVs have decreased significantly, from about 120,000 EUR in 2010 to about 72,000 EUR (incl. 20% VAT) in 2016. Historical and possible future cost reductions of FCVs compared to battery and hybrid electric vehicles as well as conventional vehicles through technological learning is depicted in Fig. 16. As shown, in the future the mobility costs of FCVs could be much closer to that of conventional ICE vehicles, mostly due to a reduction in investment costs of vehicles.

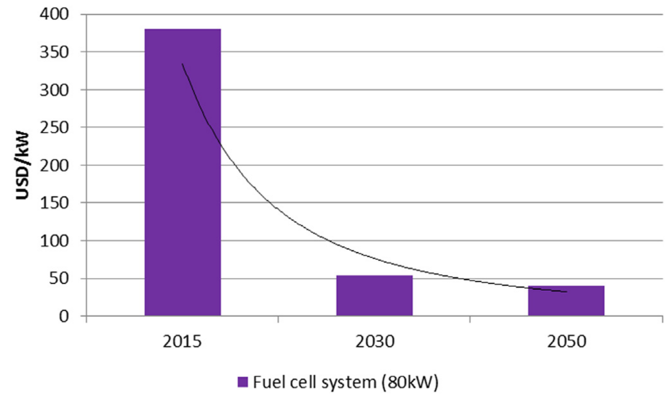

Fig. 15. Development of the costs of the fuel cell system.
data source (IEA, 2015a).

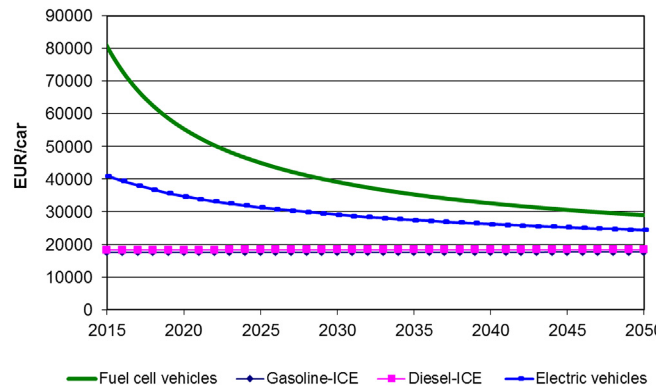

Fig. 16. Scenario for cost reductions of FCV compared to gasoline and diesel vehicles through technological learning (car size: 80 kW).

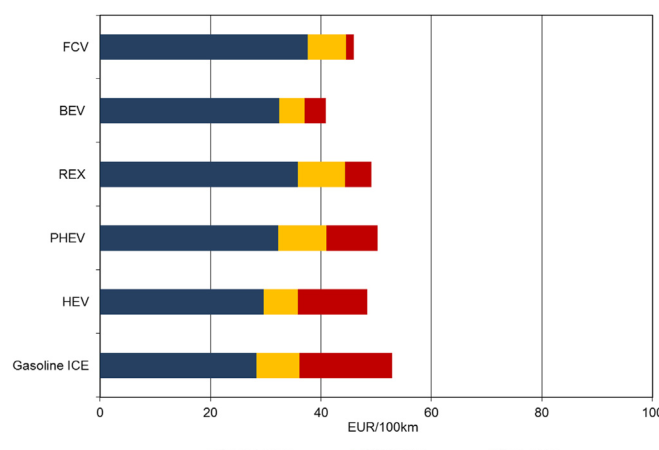

Fig. 17. The costs of mobility with different fuel and powertrains, 2050.

All these different issues added up could make FCVs economically competitive with other technologies by 2050, see Fig. 17. Since investment costs of vehicles have the largest impact on the mobility costs, the total costs per kilometer driven for all powertrains analyzed are in a very close range. Despite still higher capital costs of FCVs, in our scenario they become competitive by 2050 due to increasing costs of fossil fuels due to introduction of CO_2-tax on fuels

6. Policy implications

To accelerate the take-up of hydrogen and fuel cells, a number of obstacles need to be removed. In Fig. 1 we have shown the ambitious European proposal for a hydrogen-oriented economy. The core question is why it has failed so far. A major barrier is the lack of coordinated actions between stakeholders (such as car manufacturers, fuel suppliers and consumers) and technological standards, which could drive economis-of-scale. Since many investments in hydrogen energy systems require a long horizon of at least 10–20 years, this is a significant problem as all these issues increase the risks in long-term investments. In addition, the lack of clear and binding emission reduction targets discourages potential investors (HC, 2017).

However, there is already a broad portfolio of technology-neutral policies in Europe which indirectly support the use of hydrogen and fuel cells. Such policies are, for example, vehicle taxation schemes based on vehicle CO_2 emissions (such as registration taxes, ownership taxes, etc.), and purchase subsidies for low-emission vehicles. Besides, there are also some important non-monetary measures applicable to zero-emission vehicles, such as the free use of public parking spaces, the use of bus lanes, and free entrance to zero-emission zones in cities. Moreover, tighter fuel economy standards would support the introduction of FCVs as they are a low-emission automotive technology and contribute to the fulfillment of agreements between the European Commission and the automobile industry.

According to the European Energy and Climate Package (2020 and 2030) one of the major goals is to increase the amount of renewable energy in electricity generation, making the integration of variable renewable energy in the system more challenging. In this context hydrogen could be a link between the power and transport sector (as well as with other energy sectors). However, the success of this sector coupling is dependent on the annual availability of low-cost electricity from RES as well as the reduction of the investment costs of electrolysis system.

For the use of hydrogen in the transport sector the cost reduction of FCVs is crucial. At this very early stage FCVs and hydrogen require different tax exemptions as well as subsidies to become competitive with conventional cars. However, direct subsidies should be split between all stakeholders involved to avoid "the chicken and the egg" problem, to facilitate market stimulation and minimize investment risks (IEA, 2015a).

To enable hydrogen to play an important role in the decarbonization of the energy system, policy makers must provide stable, long-term policy and regulatory framework, guiding energy transition in all sectors. This transition requires coordination between all of the stakeholders involved. A harmonization of standards and safety codes for hydrogen production and its use across regions and sectors would create advantages of economies-of-scale and, consequently, a cost reduction in hydrogen technologies. In addition, an improvement and adaptation of existing policies and measures (such as CO_2 emission regulations, taxes, etc.), according to the long-term environmental goals, would support hydrogen use in the energy system.

7. Conclusions

For a long time hydrogen has been considered a clean energy carrier to be applied virtually universally. Already in 2003 the European Commission had the vision of heading towards a hydrogen-based economy by 2050. However, today we are far away from meeting the targets of this roadmap. In the real energy world hydrogen has not yet delivered. The major reason is that it has not become economically feasible.

With the increasing electricity generation from variable RES and its temporarily cheap surplus production, new prospects for hydrogen are on the horizon, thus meeting the rising need for the long-term storage of surplus electricity. Surplus electricity from variable RES could be converted into hydrogen, and re-electrified when needed. However, this would cause very long energy conversion chains leading to high energy losses at every conversion step, as well as high overall costs. Such energy supply chains are currently inefficient and uneconomical.

Increased efficiency could be reached by the direct use of hydrogen in the transport sector, which urgently needs environmentally-friendly technologies. However, with respect to hydrogen use in transport, the current major barrier is the high investment cost of FCV. In the future the economic performance of hydrogen could be improved due to (i) increasing end-use prices of fossil fuels, especially owing to increased taxes, (ii) reductions in hydrogen production costs, and (iii) a decrease in fuel cell production costs. The last two effects could be brought about by the full exploitation of economies-of-scale and technological learning.

While in this paper we have analyzed only the use of hydrogen for passenger vehicles, in the future it could also play a role in other modes of transport such as trains, trucks and busses. The commercial activities in fuel cell powered trams and light rail have increased in the past years, and after undergoing extensive demonstrations around the world, fuel cell buses fleets are ready to scale up. However, the future role of hydrogen in the transport sector is very dependent on policies implemented and regulatory framework provided.

References

Ajanovic, A., 2008. On the economics of hydrogen from renewable energy sources as an alternative fuel in transport sector in Austria. Int. J. Hydrog. Energy 33 (16), 4223–4234.

Ajanovic, A., 2013. Renewable fuels - a comparative assessment from economic, energetic and ecological point-of-view up to 2050 in EU-countries. Renew. Energy 60, 733–738.

Ajanovic, A., 2015. The future of electric vehicles: prospects and impediments. WIREs Energy Environ. 2015. https://doi.org/10.1002/wene.160.

Ajanovic, A., Haas, R., 2015. Hydrogen for mobility: an assessment from economic, energetic, and ecological point of view (Chapter 20). In: Sayigh, A. (Ed.), Renewable Energy in the Service of Mankind. Springer, pp. 215–223. https://doi.org/10.1007/978-3-319-17777-9.

Bakenne, A., Nuttall, W., Kazantzis, N., 2016. Sankey-Diagram-based insights into the hydrogen economy of today. Int. J. Hydrog. Energy 41 (2016), 7744–7753.

Ball, M., Weeda, M., 2015. The hydrogen economy - vision or reality? Int. J. Hydrog. Energy 40 (2015), 7903–7919.

Ball, M., Wietschel, M., Rentz, O., 2007. Integration of a hydrogen economy into the German energy system: an optimizing modelling approach. Int. J. Hydrog. Energy 32 (10–11), 1355–1368.

Bartels, J.R., Pate, M.B., Olson, N.K., 2010. An economic survey of hydrogen production from conventional and alternative energy sources. Int. J. Hydrog. Energy 35 (16), 8371–8384.

Burkhardt, J., Patyk, A., Tanguy, P., Retzke, C., 2016. Hydrogen mobility from wind energy – a life cycle assessment focusing on the fuel supply. Appl. Energy 181, 54–64.

EC, 2003. Hydrogen energy and fuel cells. A vision of our future. Final report of the High Level Group. EUR 20719 EN.

EPEX, 2017. 〈https://www.epexspot.com/en/〉 (Accessed 10 May 2017).

Haas, R., Lettner, G., Auer, J., Duic, N., 2013. The looming revolution: how photovoltaics will change electricity markets in Europe fundamentally. Energy 57, 38–53.

HC, 2017. How Hydrogen Empowers the Energy Transition. Hydrogen Council.

Hervey, L.D., 2018. Cost and energy performance of advanced light duty vehicles: implications for standards and subsidies. Energy Policy 114, 1–12.

IEA, 2010. Energy Technology perspectives. Scenarios & Strategies to 2050. International Energy Agency. OECD/IEA.

IEA, 2015a. International Energy Agency (IEA), Technology Roadmap Hydrogen and Fuel Cells, Paris.

IEA, 2015b. Technology Roadmap. Hydrogen and Fuel Cells. OECD/IEA.

IEA, 2017. Global trends and outlook for hydrogen. IEA hydrogen. December 2017.

James, B.D., Kalinoski, J.A., Baum, K.N., 2010. Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update. Directed Technologies Inc., Arlington, VA.

Liu, Z., Hao, H., Cheng, X., Zhao, F., 2018. Critical issues of energy efficient and new energy vehicles development in China. Energy Policy 115, 92–97.

Marchenko, O.V., Solomin, S.V., 2015. The future energy: hydrogen versus electricity. Int. J. Hydrog. Energy 40 (2015), 3801–3805.

Miotti, M., Hofer, J., Bauer, C., 2017. Integrated environmental and economic assessment of current and future fuel cell vehicles. Int. J. Life Cycle Assess. 22 (2017), 94–110. https://doi.org/10.1007/s11367-015-0986-4.

Ogden J., Yang C., Nicholas M., Fulton L., 2014. The hydrogen transition. Next steps white paper. UC Davis Institute of Transportation Studies; July 29, 2014.

Platts, 2018. ITM: hydrogen systems market 'at tipping point'. S&P Global. Power in Europe. Issue 767/2018.

Rahmouni, S., Negrou, B., Settou, N., Dominguez, J., Gouareh, A., 2017. Prospects of hydrogen production potential from renewable resources in Algeria. Int. J. Hydrog. Energy 42 (2017), 1383–1395.

Rifkin, J., 2003. The Hydrogen Economy. Tarcher/Penguin Book (ISBN 1-58542-254-1).

Sacramento, E.M., Carvalho, P.C.M., Lima, L.C., Veziroglu, T.N., 2013. Feasibility study

for the transition towards a hydrogen economy: a case study in Brazil. Energy Policy 62, 3–9.
Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., Thiel, C., 2016. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. Int. J. Hydrog. Energy 41 (2016), 19–35.
Shell, 2017. Energy of the future? Sustainable mobility through fuel cells and H2. Shell Hydrog. Study.
Sigal, A., Leiva, E.P.M., Rodrıguez, C.R., 2014. Assessment of the potential for hydrogen production from renewable resources in Argentina. Int. J. Hydrog. Energy 39 (2014), 8204–8214.
Singh, S., Jain, S., Venkateswaran, P.S., Tiwaria, A.K., Nouni, M.R., Pandey, J.K., Goela, S., 2015. Hydrogen: a sustainable fuel for future of the transport sector. Renew. Sustain. Energy Rev. 51, 623–633.
Sinha, J., Lasher, S., Yang, Y., Kopf, P., 2008. Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications. TIAX LCC, Cambridge, MA.
Specht, M., Staiss, F., Bandi, A., Weimer, T., 1998. Comparison of the renewable transportation fuels, liquid hydrogen and methanol, with gasoline e energetic and economic aspects. Int. J. Hydrog. Energy 23 (5), 387–396.
Steinmüller H., Reiter G., Tichler R., Friedl C., Furtlehner M., Lindorfer J., et al., 2014. Power to Gas – eine Systemanalyse. Markt- und Technologiescouting und –analyse. Endbericht.
Sweeting, W.J., Winfield, P.H., 2012. Future transportation: lifetime considerations and framework for sustainability assessment. Energy Policy 51, 927–938.
USDE, 2013. Report of the Hydrogen Production Expert. Panel: A Subcommittee of the Hydrogen & Fuel Cell Technical Advisory Committee. United States Department of Energy, Washington, DC 20585.
Usher, W., Strachan, N., 2012. Critical mid-term uncertainties in long-term decarbonisation pathways. Energy Policy 41 (0), 433–444.
Verne J., 1874. The mysterious island. first ed. Pierre-Jules Hetzel.
Veziroglu, A., Macario, R., 2011. Fuel cell vehicles: state of the art with economic and environmental concerns. Int. J. Hydrog. Energy 36 (2011), 25–43.