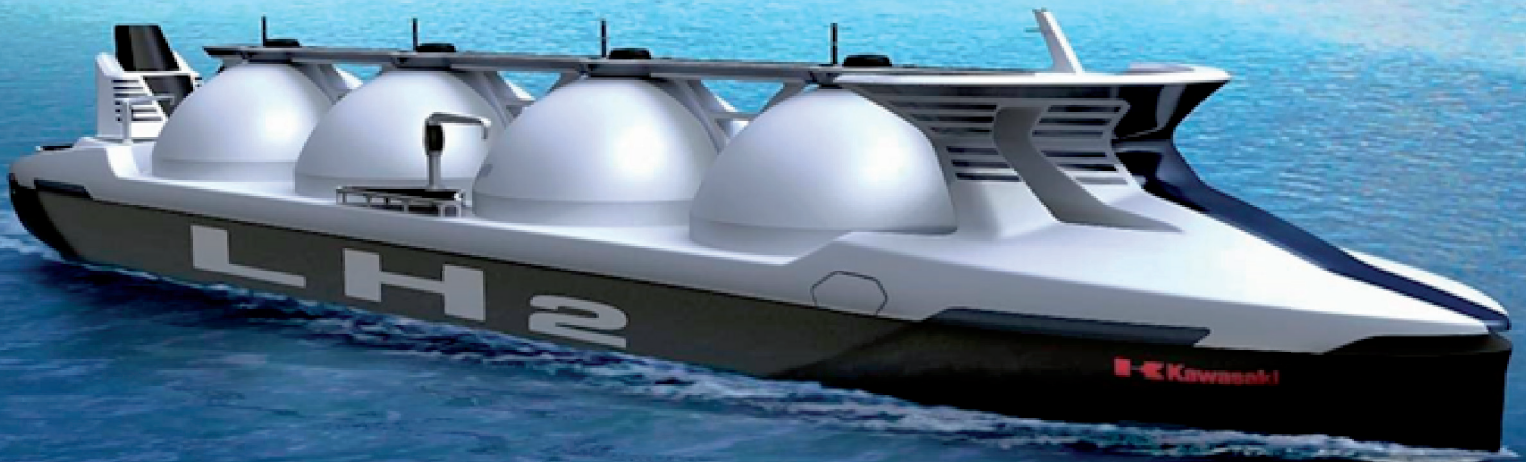


hydrogen

the key to the energy transition



 TU Delft

 TVVL

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Hydrogen – the key to the energy transition

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Foreword

Hydrogen – the key to the energy transition

Hydrogen – element number one in the periodic table and the smallest, most common atom on earth. The time has finally come to put it to good use on a large scale, for a more sustainable planet.

This is hardly a new idea. In 1874, in his novel *The Mysterious Island*, Jules Verne (1828-1905) wrote:

“Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen... will represent an inexhaustible source of heat and light.”

In the Netherlands, too, we have been here before. Some 60 per cent of what was known as ‘town gas’ in the 1950s and ‘60s was in fact hydrogen, made from coal.

Now hydrogen is back - with a devastating effect on fossil fuel production. Thanks to the plummeting prices of solar and wind energy, ‘green’ gas – yes, hydrogen – is set to push out current fossil fuel systems. You can store it, you can transport it easily over long distances and you can convert it into various forms of energy. Which means you need far less overcapacity built into your system. And it offers the added benefit of converting existing natural-gas distribution grids and appliances to hydrogen at relatively low cost.

This solution is many times more cost-effective than the ‘all-electric’ alternative, which would require substantial and basically unnecessary investments in additional infrastructure and back-up capacity. We would be far better off spending our money to turn the natural-gas grid into a hydrogen grid. In the meantime, locally generated electricity – perhaps even bolstered by a car park full of electric vehicles – can be linked to a DC network to play its part in the transition to sustainable energy. Later, hydrogen-powered fuel-cell electric cars could also be plugged straight into this system.

The decision to decommission the Groningen gas fields will have costly implications, but the transition to sustainable energy need not add that much to the price. Even more so when taking into account the financial benefits of an energy system without emissions, pollution, asset destruction and geopolitical costs.

With this paper, Professor Ad van Wijk and his colleague Chris Hellinga have made a valuable contribution to the energy transition. We as the TVVL Association for People, Technology and Society feel honoured by the privilege of publishing it.

Prof. P. G. Luscuere

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CHAPTER 1 - Introduction

In *The Hydrogen Economy* (2003), Jeremy Rifkind calls for hydrogen to become the principal energy carrier in a sustainable society. Hydrogen (H) is the most common element in our universe. The hydrogen molecule (H₂) is easy to extract from water, using (sustainably generated) electricity. Despite widespread initial enthusiasm for Rifkind's message, no real breakthrough ever came. Today, however, things appear to be changing. One of the many recent indicators is the establishment of the Hydrogen Council, a joint initiative by more than twenty multinationals with a total annual turnover of approximately €1300 billion, which have already invested over €10 billion in developmental hydrogen technologies [1,2,3]. In the Netherlands, too, there is increasing interest driven by the Green Gas Top consortium for Knowledge and Innovation (TKI Groen Gas) within the government-backed Topsector Energy. The very first key message in the consortium's *Outlines of a Hydrogen Roadmap* (May 2018) is that "We can achieve our climate objectives for 2050 with hydrogen" [4].

Various current developments strengthen the belief that hydrogen could fairly soon become available in vast quantities, with major implications for sectors such as transport, industry, ports and the built environment. Together with electricity, hydrogen may well be the principal energy carrier of the future. Not least because it is easily transported and can be stored underground on a massive scale. Hydrogen (or its derived energy carriers and raw materials) has the potential to become a connecting factor between the challenges facing the aforementioned sectors, and could thus provide a means to add more structure to our pursuit of a large-scale transition to sustainable energy.

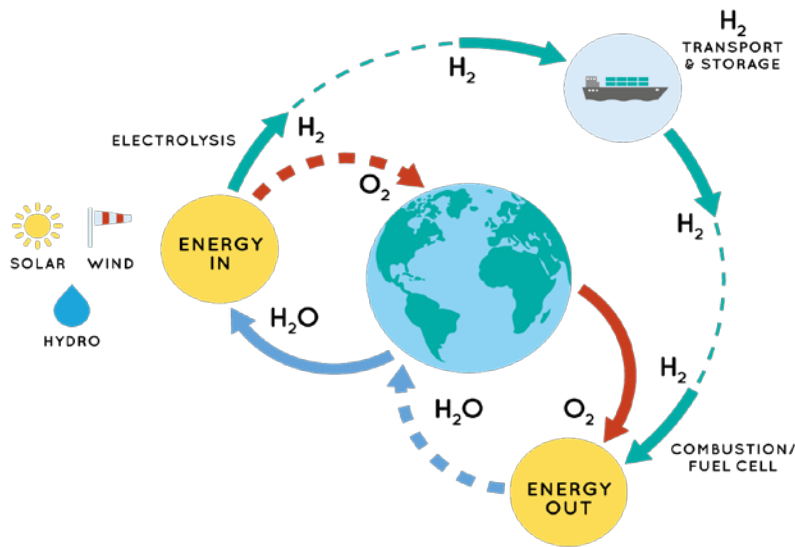
CHAPTER 2 - The hydrogen cycle


Figure 1. The global hydrogen cycle.
Source: van Wijk et. al. [5]

Figure 1 shows the global hydrogen cycle in simplified form. Electricity is used to convert water (H₂O) into hydrogen (H₂) and oxygen (O₂). At present, electrolysis is the dominant technology for this process. It transfers 70-80 per cent of the electrical energy to hydrogen. In the future, the bulk of hydrogen production will occur in regions with copious amounts of solar or wind energy, The end product is then cooled or compressed – and possibly converted into, say, ammonia – and shipped in tankers to places where there is a demand for energy. There it will be converted into a useable form of energy, such as steam, heat or electricity, used as a raw material or processed to produce fuels (not shown in the diagram). In the process chain – electricity produces hydrogen, from which electricity is later reproduced – about 60-70 per cent of the original sustainable energy is typically lost (assuming that the heat released during the conversions is not recovered and reused). But because electricity-production costs in particularly sunny and windy regions of the world are generally much lower than in temperate zones, this does not necessarily mean that the final price of the resulting electricity will be much higher than that of solar or wind power generated locally (see also figure 8).

Hydrogen is not a greenhouse gas, so the losses inevitably associated with such a process will not add to the greenhouse effect¹ (any hydrogen released into the atmosphere is converted back into water). The only possible negative environmental impact comes from the use of non-sustainable materials in the generation, conversion, storage and transport chain.

¹ For example, according to the IPCC, methane – the principal component of natural gas – is 28 times stronger than CO₂ in its contribution to the greenhouse effect over 100 years [10]. There is still considerable uncertainty about the extent of losses into the atmosphere during natural-gas production and consumption, but the Rhodium Group estimates them at 3 per cent of annual production. This represents a significant contribution to the greenhouse effect, over and above that resulting from the formation of CO₂ during natural gas combustion [11].

CHAPTER 3 - Hydrogen versus natural gas

Hydrogen gas differs from natural gas in a number of significant ways, but none of these present insurmountable technical or economic obstacles to large-scale introduction.

Hydrogen (H_2) is the smallest molecule on earth and by nature seeks to penetrate any other substance. For this reason, pipelines and storage tanks holding it have to be made of materials which ensure little or no leakage. Fortunately, practical and already widely available materials such as prevailing carbon steels and high-density polyethylene (HDPE) meet this requirement. They are therefore suitable for pipes to carry hydrogen gas instead of natural gas. A privately-owned 110-bar pipeline carrying hydrogen from Rotterdam via Antwerp to Northern France has been operating for decades without any problems. The existing Dutch high-pressure natural-gas distribution grid could be adapted to hydrogen quickly, easily and at relatively low cost [6]. The biggest challenge would be modifying the compressors. It has been estimated that this conversion would cost less than 10 per cent of the price of building an entirely new pipeline infrastructure [7].

Moreover, the energy content of hydrogen per unit of volume is relatively small. Compared to the low-calorific natural gas extracted from the Slochteren field in the province of Groningen, the Netherlands, it has three times less energy by volume at the same pressure. Hydrogen-powered cars therefore require high-pressure tanks to keep their size down to an acceptable level – 700 bar has now become the industry standard. These tanks contain about 5-6 kg of hydrogen, giving a fuel-cell electric vehicle (FCEV) a range of 500-600 km, comparable to the operating radius of a petrol or diesel car. During pipeline transport, the hydrogen flow rate has to be three times that of natural gas in order to convey the same amount of energy per time unit at the same pressure. But because of its lower density, this is possible with almost the same pressure differences over the pipelines seen today [6]. In other words, the energy conveyance capacity of the existing gas supply network is almost the same for hydrogen as it is for natural gas.

Hydrogen does have a public image problem, though. It is often seen as dangerous. Hydrogen-air mixtures can indeed ignite or explode over a wider range of concentrations than methane-air mixes. But because hydrogen is also much lighter than methane (natural gas), it rises and disperses very quickly in the event of a leak. Practical tests of this effect by KIWA Gastec as part of its HyHouse project showed that the risk of an explosive mixture forming after an indoor hydrogen-air leak is much lower than when natural gas escapes [8]. We should also remember that we already had hydrogen in our homes before the switch to natural gas in the 1960s: town gas consisted in fact for more than 50 per cent of hydrogen! Also, hydrogen has the important advantage that it does not produce carbon monoxide – the cause of most domestic gas-related deaths in the Netherlands – when burned. The Dutch 'Onderzoeksraad voor Veiligheid' (Dutch Safety Board) estimates the actual number of deaths from carbon monoxide poisoning to be three to five times higher than the five to ten reported each year, with hundreds more people injured [9].

CHAPTER 4 - Functions of hydrogen

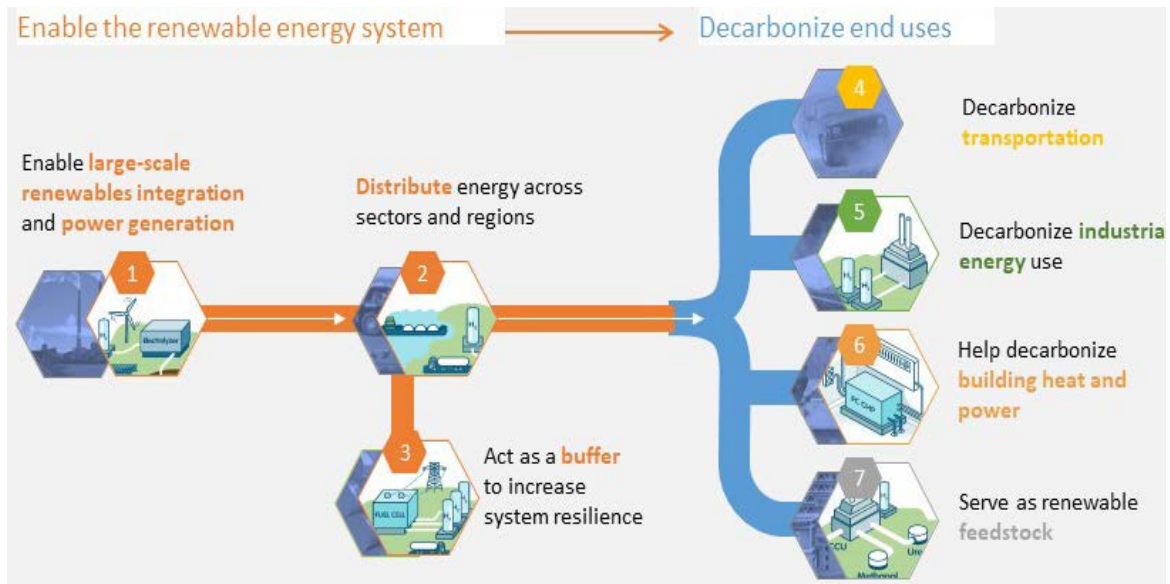


Figure 2. Hydrogen can fulfil seven important functions in a sustainable energy system.
Source: Hydrogen Council [3].

Figure 2 shows seven functions hydrogen could fulfil in a sustainable energy system dominated by wind and solar power [3].

1. In such a system, there is an imbalance between power supply and consumption. After all, solar and wind power are not available on demand. Moreover, the most economically viable new sources of this energy will be in sunny and windy regions, far removed from those places where demand is high. Hydrogen could bridge the gap in place and time between sustainable power generation and consumption, as well as satisfying demand for non-electrical energy and raw materials.
2. For this to happen, new links that cope as effectively as possible with discrepancies of supply and demand are needed between production and consumption zones. Hydrogen, or a chemical derived from it, is an energy carrier which can be transported cost-effectively and flexibly over long distances. We are also likely to see currently distinct sectors such as transport (oil products) and the built environment (electricity and gas) converging in their energy dependency. Not only can electric vehicles be charged at home, but if they run on hydrogen they could even supply it with electric power [12]. The combination of hydrogen and electricity is particularly powerful because it delivers 'high-quality' energy suitable for all types of use, from transport to communications and heating. By contrast, you cannot power light bulbs, for example, with relatively low-temperature heat energy.

3. Load balancing – reconciling asynchronous peaks and troughs in supply and demand – is one of the biggest challenges in the energy transition and will require affordable new forms of energy storage. For short-term fluctuations like the differences between day and night, options such as batteries should suffice. But to store energy in large quantities over long periods – from season to season, for example – hydrogen is probably the most compelling candidate. It can be stored in very large amounts in salt caverns or empty gas fields.

Large-scale hydrogen storage – a promising alternative

A recent German study predicts that, by 2050, sustainable solar and wind energy generation will exceed immediate demand by 20 per cent. The surplus can then be stored underground in the form of hydrogen, taking up one third of the gas fields currently in production in Germany [21]. These reserves could then be drawn upon at times when demand from primary exceeds supply.

Empty salt caverns and gas fields are also found in many other places across Europe [14,15]. Approximately 6,000 tonnes of hydrogen can be held in a typical salt cavern [16], worth 235 million kWh of energy. This is equivalent to about 17 million Tesla Powerwalls, each with a capacity of 14 kWh. A salt cavern is the empty space left after salt extraction and can relatively easily be integrated in a system which pumps in pressurized hydrogen gas and later recovers it with the required level of purity. Compared to electricity storage, it is a low-cost solution; according to a recent British study [17], the required investment varies depending on local surface and underground conditions but is typically in the region of €1 per kilowatt hour of storage capacity. For the Tesla Powerwall, this figure currently stands at about €400 per kWh. Meanwhile, the Hydrogen Council states an indicative price of USD 0.05-0.15 per kWh for hydrogen stored in salt caverns. Of the large-scale alternatives currently known, only pumped-storage hydroelectricity is cheaper – but its available capacity is limited, namely less than 1 per cent of global energy demand [3].

4. Hydrogen can take care of energy needs that are not covered efficiently – if at all – by electricity. For example, it is unlikely that batteries will ever be used for heavy-duty long-distance road, air or water transport, because the storage capacity required would make them too large, too heavy and too expensive. Hydrogen, or another form of fuel derived from it, would be a better option here.
5. Industrial energy usage often involves achieving high process temperatures, with combustion sometimes being essential. But existing gas turbines, for example, could also run on hydrogen. This gives it an important potential role in the efficient production of high-temperature steam or heat (combined heat and power) [18].
6. Hydrogen is also a viable option for heating the built environment, especially areas or buildings which are not well-suited to sustainable alternatives such as residual heat use, geothermal heat or heat pumps. In our climate zone in particular, energy storage is set to play an important role for indoor heating, as energy demand for space heating in winter is high but negligible in summer. The total demand for electricity and natural gas in the Netherlands in the coldest months of the year is more than double that in the hottest months (figure 3). To achieve a more sustainable society, we therefore need to stockpile wind and solar energy in the summer for use in the winter, in order to make optimum use of production capacity over the course of the year. Hydrogen would be a perfect storage medium.

- From the petrochemical and fertiliser industries there is already considerable demand for hydrogen as a raw material and auxiliary agent. At present, it is still being made using fossil fuels. ‘Greening’ that production could substantially reduce carbon dioxide (CO₂) emissions. Many forms of chemical manufacture require raw materials containing carbon (C) atoms, such as methanol or ethylene used in making plastics. Biomass could provide these – through gasification, for example –, as well as closed raw-materials cycles. The alternative of direct extraction of carbon from the highly diluted CO₂ in the atmosphere remains an expensive process. This makes biomass important as a viable source of carbon for industrial raw materials, meaning that large quantities are going to be required worldwide. Moreover, it is also required to help meet the ever-growing global demand for food and for sustainable building materials. For these reasons, for the time being at least, it would not be a good idea to commit to biomass for energy functions not requiring the presence of carbon atoms – for example, the production of methane (CH₄) from hydrogen and biomass to heat homes or generate high-temperature steam. For these uses, ‘straight’ hydrogen would be a more rational alternative.

Yearly natural gas and electricity use

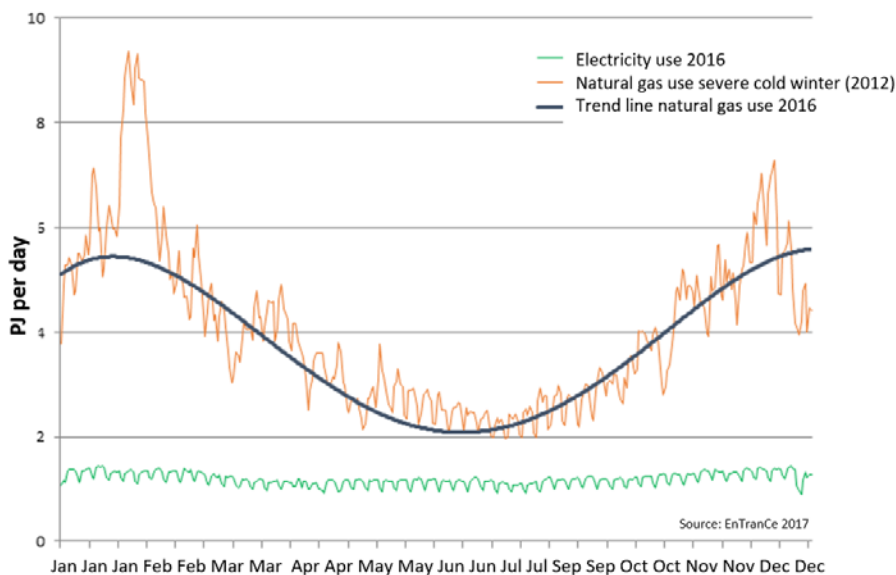


Figure 3. Electricity and gas consumption in the Netherlands. Source: Entrance, 2017 [19].

CHAPTER 5 - Dutch fuel, raw material and auxiliary agent needs

One thing we do not always realise is that there is a very high demand in the Dutch economy for fuels to serve heavy-duty long-distance road, water and air transport, as well as for industrial raw materials (plastics, fertilisers) and auxiliary agents (for steel manufacturing). And that, in all likelihood, this will remain so.

Figure 4 shows where the demand for the almost 4,000 petajoules² of energy currently consumed in the Netherlands each year comes from. This includes the fuels used for international aviation and international shipping (686 PJ) [13]. After deducting 20 per cent for conversion, distribution losses and the energy sector's own consumption³, the blue segment (1,690 PJ) shows transport fuels (1,121 PJ) plus raw materials and auxiliary agents for industry (non-energy use, 569 PJ). On the left, in orange, is the demand for heat from the built environment, greenhouse horticulture and industry, totalling about 1,000 PJ [20]⁴. Finally, in yellow, we see that only 10 per cent of the total energy demand reaches the end user in the form of electricity.

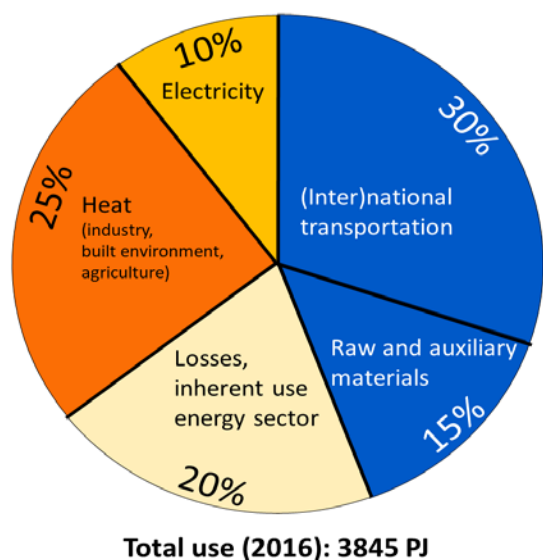


Figure 4. Dutch demand for energy in five domains.
Source: CBS [13].

The blue segment, representing 'molecules', is thus many times larger than the yellow segment ('electrons'). If all light road transport (passenger cars and light freight vehicles) were to become fully electric, powered by batteries, this would require around 100 PJ of electricity – a quarter of the total current electricity consumption – and demand for fossil fuels would drop by about 300 PJ. This is because electric motors are far more efficient than internal combustion engines. Nevertheless, the share of demand for fossil fuels and raw materials would still be much greater than that for electricity. Naturally, this 'prediction' is overly simplistic: to achieve any real degree of accuracy, we also need to take

² One petajoule (PJ) is the amount of energy needed to run 29,000 cars on petrol for one year, or to meet the annual gas demand of 21,000 households.

³ Losses during electricity production and other forms of conversion: 549 PJ. Consumption by the energy sector itself: 178 PJ. Distribution losses: 23 PJ [13].

⁴ About 40 per cent of this is high-temperature heat for industry, with the remaining 60 per cent being low-temperature heat for the built environment and greenhouse horticulture [20].

other factors into account, such as greater overall energy savings and the ‘closing’ of raw-material cycles. Nevertheless, there can be no denying that demand for liquid/gaseous fuels and raw materials will remain substantial, even beyond the middle of the century – *possibly around three times the direct demand for electricity*. Hydrogen will undoubtedly play an important role in their production, not to mention as a raw material for other chemical compounds. Moreover, producing this hydrogen will require much more electricity⁵ than we now consume as end users.

Offshore wind power is set to make a significant contribution to satisfying the energy needs of the ten countries closest to the North Sea,⁶ which are collectively planning to have turbines with a total generating capacity of 180,000-250,000 MW installed by 2050 [21]. This works out at 18,000-25,000 large, modern 10 MW turbines, capable of producing 3,000-4,000 PJ of electricity a year.⁷ This total capacity is roughly equivalent to the Netherlands’ entire annual demand for energy! It should be noted, however, that these existing plans are partly driven by financial and investment forecasts drawn up some years ago, in line with the subsidy arrangements in place at the time. In fact, the North Sea has more to offer: those 25,000 turbines will take up only about 5 per cent of its surface area. Since modern wind farms no longer require public funding to be economically viable, it seems likely that even more will be planned over the next few years.

Even with such raised offshore wind ambitions, however, we will still have to import large quantities of energy into north-western Europe in the future. One excellent way of doing this is in the form of hydrogen or ammonia⁸ produced elsewhere, using renewable energy, and shipped in by sea. Such imports should therefore be integrated into our strategy for a sustainable energy supply.

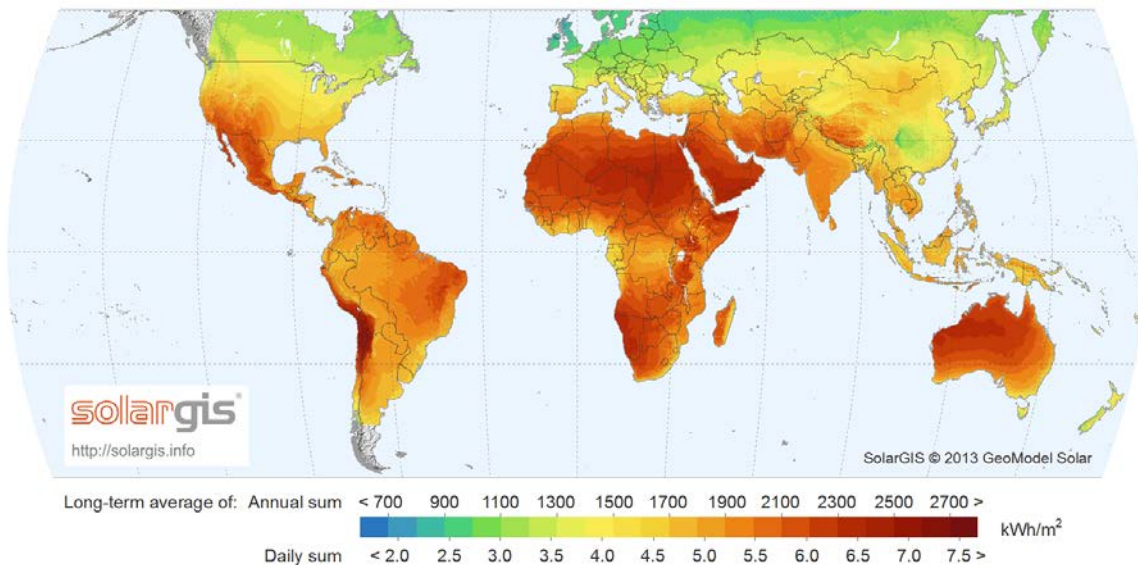


Figure 5. Global photovoltaic power potential. Source: SolarGis.

⁵ Work is also being conducted on alternative forms of sustainable fuel and raw material production, other than electrolysis, but its large-scale application will require still several decades to come.

⁶ Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Norway, Sweden and the United Kingdom have signed an energy co-operation contract to this effect [21].

⁷ At 4,500 full load hours annually.

⁸ Ammonia (NH₃) is made from hydrogen and nitrogen, with the latter extracted from the air. This can be done anywhere in the world.

CHAPTER 6 - Sustainable electricity is very cheap – or it will be!

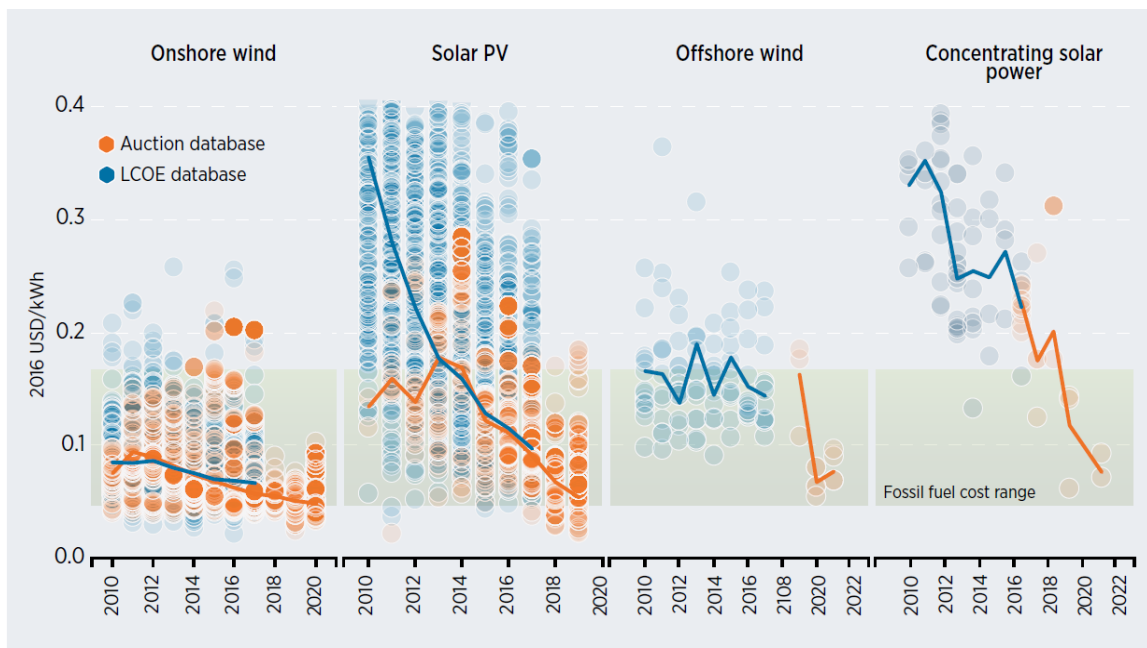
Thanks to technical improvements and upscaling, the prices of wind and solar power have fallen sharply in the past ten years. At the end of 2017, MASDAR/EDF put out a tender bid to build a 300 MW photovoltaic (PV) solar plant in Saudi Arabia which will supply electricity for just under USD 0.018 (€0.015) per kWh [22] – a price two to three times lower than for power generated from gas or coal. In southern Europe, too, it is now becoming more attractive to build solar parks. In April 2018, Statkraft announced a 170 megawatt peak (MWp) project near Seville in Spain – one of the first in Europe to be built without public funding [23].

Leading financial services provider Bloomberg expects solar PV electricity prices to drop by around 66 per cent between now and 2040 [24], meaning that a price of less than USD 0.01 per kWh is within reach.

The most favourable production zones for this power source are in the worldwide 'solar belt' (see figure 5), where the annual photovoltaic power potential (solar radiation) is two to three times greater than the 1,000 kWh per square metre per year, seen in the Netherlands. Combined with the cost benefits achieved by very large installations,⁹ production prices per kWh there are typically five to nine times lower compared to Dutch rooftop solar panels (see also figure 8) [5].

Offshore wind energy prices have also been falling recently. Commercial operators in the Netherlands, Germany and Denmark are already prepared to develop wind farms without external funding. For example, Vattenfall announced in March 2018 that it will be building an unsubsidised 700 MW farm off the Dutch coast, due to enter service in 2022[25]. For onshore wind, prices of USD 0.02-0.03 are already being achieved in Texas and other areas of the American Mid-West [29]. Bloomberg New Energy Finance expects prices of onshore wind energy to have dropped by 47 per cent by 2040, and offshore by 71 per cent [24].

⁹ Utility-scale installations (typically 100+ MW) are currently 2.5-3 times cheaper per Wp than small private ones.[32]



Source: IRENA Renewable Cost Database and Auctions Database.

Figure 6. Overall production costs (levelized cost of electricity, LCOE) for solar PV, concentrating solar power, onshore and offshore wind, historical and projected.[26]

Electricity production costs are monitored by IRENA, the International Renewable Energy Association (see figure 6). Its data shows that the levelized cost of energy (LCOE: all essential costs divided by total energy production over the depreciation period) for solar and wind power has dropped sharply in recent years, to a level comparable to or even below that of electricity production from fossil fuels [26]. Indeed, sustainable energy has already become so attractive that two-thirds of global investments in electricity generation in 2016 went into renewable sources – primarily solar and wind [27].

CHAPTER 7 - Conversion system costs also falling

When sustainably generated electricity is passed through water in a so-called electrolyser, hydrogen and oxygen are produced. There are two main types of electrolyser: proton exchange membrane (PEM) and alkaline-based electrolysers. Both consist of a 'stack' of small electrolysing cells, which makes the systems easily scalable and facilitates the cheap mass production of their functional components. Whereas the CAPEX¹⁰ for PEM systems was still around €2,000 per kW in 2013 [30], by April 2018 it had fallen to just €400-450 for large-scale projects in the 100 MW-plus range [28]. The same applies to alkaline electrolysers: their CAPEX was around €1400 per kW in 2013, but had dropped to €300-350 per kW [28] for large-scale projects by April 2018. The electrical conversion efficiency of both types of system are currently at 70-80 per cent, a figure expected to rise to 80-85 per cent in the further future, with the CAPEX for gigawatt-scale projects dropping to €250 per kW [31].

Technically speaking, fuel cells are the very opposites of electrolysers: they produce electricity from hydrogen and oxygen, with a peak conversion efficiency of 60 per cent now being achieved. The US Department of Energy expects it to increase to 70 per cent in the long term [33]. Fuel cells are also made up of small functional parts, and in the case of both PEM electrolysers and PEM fuel cells, in particular, improvements in membranes to increase their lifespan and reduce their cost of production have made them much cheaper in recent years. Fuel cells are a crucial component of hydrogen-powered vehicles, of course, but can also be used in the built environment for simultaneous heat and power generation.

The price of fuel cells in 2006 was USD 124 per kW, but has since dropped to about USD 53 when mass-produced at the rate of 500,000 units annually. The US Department of Energy expects a further price decrease to USD 40 in 2020, and USD 30 in the long term [35]. As with solar PV systems, which also consist of small modular units, these decreases will be driven by the upscaling of production volumes as well as by technical improvements.

¹⁰ Capital expenditures. That is, investment costs.

CHAPTER 8 - Long distance energy transportation: cheaper by molecule

The costs of electricity generation and conversion seem set to drop dramatically in the most suitable production zones for wind and solar energy, while the north-western countries of Europe still have to import large amounts of fuel. The transport of energy over large distances (hundreds or thousands of kilometres) in the form of chemical energy carriers (molecules) is cheaper than carrying it by power cable (electrons) [20]. Liquid hydrogen or ammonia produced from hydrogen would be particularly viable options.

For transmission from – the more distant parts of - the North Sea, it also holds that pipelines, whether carrying natural gas or hydrogen, are cheaper than power lines. A simple comparison between the BritNed cable and the BBL gas pipeline, both connecting the Netherlands with the UK, clearly demonstrates this [16].

	BritNed cable	BBL gas pipeline
Capacity	1 GW	15 GW
Length	276 km	225 km
Construction costs	€500 million	€500 million
Annual volume	8 TWh	120 TWh

In return for a similar investment, the pipeline can transport between ten and twenty times more energy than the cable. If offshore wind turbines are built far out in the North Sea, it may therefore be cheaper to convert the power they generate into hydrogen and to modify an existing natural gas pipeline to bring it ashore. The necessary adaptation would cost only 5-10 per cent of the price of building a new pipeline [7]. In the case of the BBL pipeline, for instance, an investment of €25-50 million would create an energy conveyance capacity of 15 GW. Overall, then, this option would make energy 100-200 times cheaper to carry per unit of energy than if a new electricity cable had to be laid. Then again, the cost of producing hydrogen at sea also needs to be taken into consideration. And as well as selecting the best form of transport per se, the total cost structure of the price of hydrogen needs to be considered: electricity generation, electrolytic conversion (offshore or onshore, including distribution losses), compression, possible storage and transport. However, the general message here is that the hydrogen route is gaining more and more appeal – with an increasingly pronounced difference in transport costs – as the generation of offshore wind power becomes cheaper and moves further out to sea.

For the geographical planning of energy production in the North Sea, it is therefore important to consider the existing gas grids (figure 7).

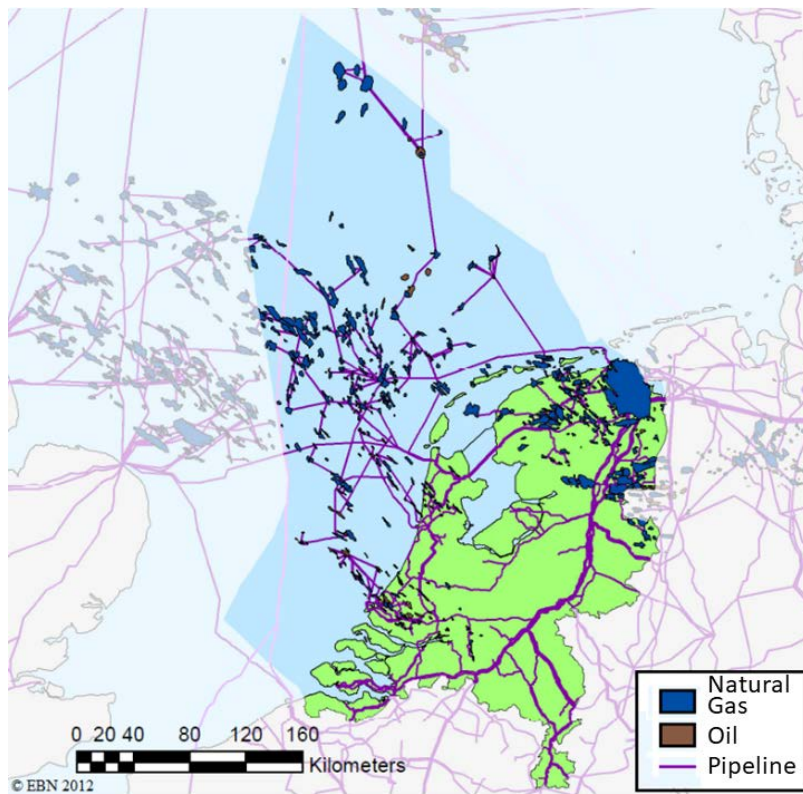


Figure 7. Natural gas pipelines in the Dutch sector of the North Sea. Source: EBN, 2012 [35].

CHAPTER 9 - The price of hydrogen from the desert

Assuming a generation cost of €0.01 per kWh in the ‘solar belt’ and an electrolytic conversion price of €350 per kW, in the long term it should be possible to produce hydrogen at less than €1 per kg¹¹ before compression or cooling and transport. Van Wijk et al. [5] calculate that, once this hydrogen is converted back into electricity in the Netherlands using a fuel cell, its final price is comparable to that of power generated locally from rooftop solar panels. Naturally, this calculation also takes into account distribution losses incurred during the entire process, the cost of liquefaction for shipping¹² and the transport costs themselves (figure 8). One important advantage of electricity derived from hydrogen is that it is always available – day and night, and in every season.

Using hydrogen from the major production zones, or made closer to home in times of wind or solar energy surpluses when electricity prices are low, would then become attractive for buffering energy on a large scale for periods when not enough wind and solar power can be generated.

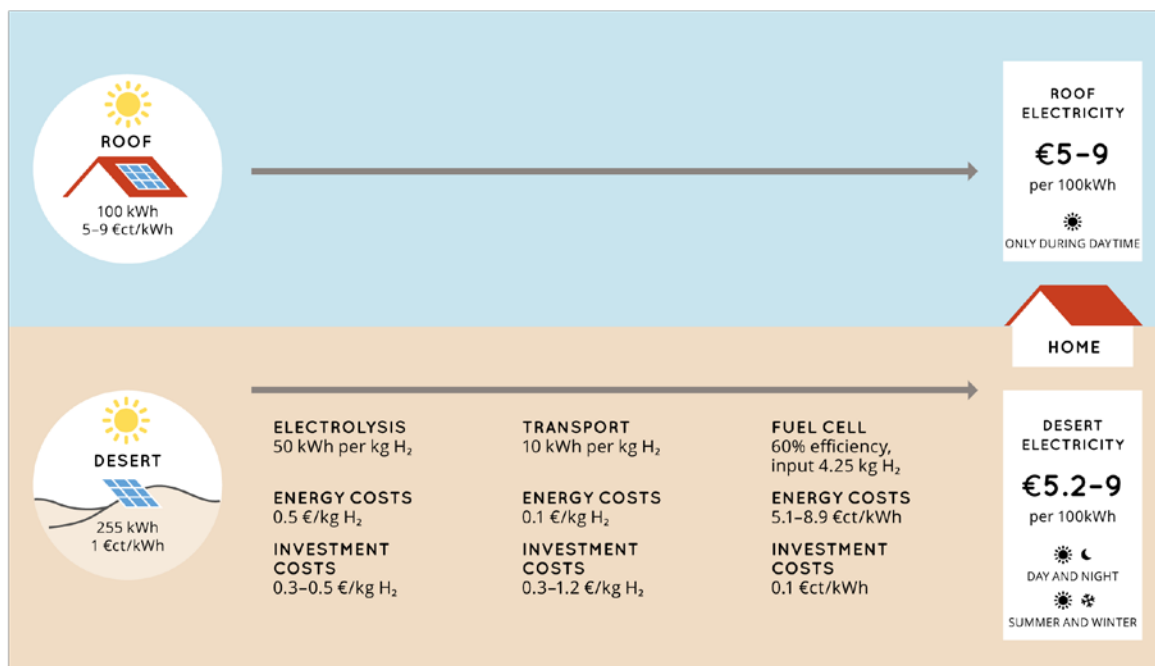


Figure 8. Price comparison of Dutch-generated solar PV power and electricity derived from

¹¹ 1 kg of hydrogen contains 121 MJ of energy (lower heating value) equalling 141.8 MJ – as the higher heating value. A price of €1 per kg for H₂ is equivalent to €0.26 per m³ for low calorific natural gas (31.65 MJ per m³) or €51 per barrel for oil (6,100 MJ per barrel). The current cost of the conventional production of ‘grey’ hydrogen by steam methane reforming is €1.5 per kg of H₂. It is expected that ‘green’ hydrogen will in time become competitive, at a price level of €2-3 per kg of H₂, due to rising gas prices and carbon taxes – at which point it could supersede current Dutch ‘grey’ production for sale to industry (volume estimated by ECN at approximately 8 billion m³ of H₂ per year).

¹² Transport under high pressure is another option. Because ammonia is easier to transport, hydrogen could first be converted into ammonia at the production site using nitrogen from the atmosphere. Liquid hydrogen and liquid ammonia transport, pipeline transmission and transport of hydrogen bound to a carrier are all under development and may become viable options in the future.

CHAPTER 10 - Hydrogen transport in the Netherlands

DNV-GL, together with Gasunie Transport Services, has investigated the extent to which the existing high-pressure gas infrastructure in the Netherlands could be used for hydrogen transport. Whilst this will obviously present some issues, the overall conclusion is that it is quite feasible [6]. In principle, hydrogen from offshore wind farms or imported by ship from other production zones could be pumped into a converted natural-gas pipeline network in the north of the country for nationwide distribution. Similarly, 'industrial hydrogen' produced in or imported through Rotterdam could replace the current local production of 'grey' hydrogen (from natural gas, 8-10 billion m³ hydrogen per annum) and be fed into the existing hydrogen pipeline system to Antwerp and northern France. Other options are conversion at Rotterdam's Port Industrial Complex into products such as ethylene or methanol, for pipeline transportation to the Ruhr region and other destinations, or the establishment of central back-up facilities for electricity generation using imported or stored hydrogen.

CHAPTER 11 - Hydrogen to heat the built environment?

Driven by the strong desire to decommission the Groningen gas fields as soon as possible, dissociating the built environment from natural gas has become a pressing issue in the Netherlands. Many people envisage heat pumps taking over our future demand for heat energy, or district heating networks distributing residual heat from incineration or industry or from geothermal sources. Naturally, these last options require the presence of heat sources somewhere near the point of demand, as well as the availability – or installation – of heating networks. In this case, gas pipes would no longer be needed.

For well-insulated new homes, heat pumps are an excellent solution. In fact, a significant proportion of the building stock of 2050 – many estimates put it at 80 per cent – is already in place. To equip existing homes and other buildings with heat pumps, they will also have to be insulated, heavily in a lot of cases, to prevent electricity bills from becoming too high. Under the current ‘Stroomversnelling’ programme, the target budget to convert a typical terraced house into a ‘net zero energy retrofitted’ home with solar panels supplying all its electricity all year round, would be €60,000 – although in recent pilots that amount was exceeded by some €20,000 [36]. According to the Urgenda Foundation, these costs could eventually be cut to about €35,000 [37], but that is still a large sum given that the annual energy bill for an average family is around €2,000. With a thousand homes per working day to be covered if we were to start today, how could we finance this type of investment between now and 2050?

The large-scale introduction of heat pumps would also require a far more resilient power grid, to cope in particular with early-morning peaks in demand – for showers and so on – at a time when the sun is hardly shining, if at all. Moreover, a lot of energy is required to heat buildings in the winter (see figure 3) when rooftop solar panel productivity is at its lowest. Security of supply during the winter period therefore requires massive seasonal energy storage capacity. Practically speaking, it means using a lot of hydrogen, some of which could be provided by the surplus of solar energy available in the summer months.

Assuming that hydrogen will become available in large quantities for sustainable energy supply, one interesting question is whether we might also be able to supply the built environment with an immediately available sustainable alternative to natural gas, and so perhaps need to be cautious about dismantling our existing natural gas distribution infrastructure. When making the gas supply more sustainable, it is important that existing equipment (central heating systems, gas hobs and cookers) can still be used in the short term. In the longer term, new conversion systems are likely to be introduced. For example, domestic fuel cells which simultaneously produce heat and electricity. Or hybrid heat pumps, which normally run on electricity but also burn hydrogen, say, at peak times.

Logically, the most obvious alternative gas is sustainably produced methane (CH₄). After all, this is already the main component of natural gas and would therefore require the least disruptive modification of infrastructure and domestic equipment. Methane can be made from hydrogen by adding a carbon atom, but as mentioned above, there are good arguments for avoiding the use of this atom in future energy supplies in situations where it is not really needed (see also footnote 1). Whilst this option – either permanently or in a transitional situation – cannot be excluded, we should also look seriously at whether it is possible for hydrogen alone to meet the heating needs of our buildings.

The H21 project in Leeds

In this respect, an interesting project has been under way in Leeds (UK). Called H21, this project aims to convert the entire city of 600,000 people to hydrogen by 2026. One key motivator is that such a switch requires only minor adjustments in the home – replacing cooker and boiler burners – a level of conversion comparable to that from town gas to natural gas in the Netherlands in the 1960s.

The key conclusions of the study into the conversion to hydrogen in Leeds were as follows [38].

- The city's gas network has the right capacity for full conversion to hydrogen.
- It can be converted incrementally, with minimal disruption to customers.
- The average cost per home of domestic modifications (labour and materials) is an estimated €3.500.
- Full conversion to hydrogen will have minimal impact on customers' gas bills.
- Minimal new energy infrastructure will be required compared to alternatives.
- The city's existing heat demand can be met through steam methane reforming, with the CO₂ being stored in empty gas fields under the North Sea.
- Seasonal demand fluctuations can be managed through salt cavern storage of the hydrogen.
- All the necessary technology is already in place and has proved itself successful.

It is certainly to be recommended that the Netherlands also investigate the role that hydrogen could play in the transition process to a sustainable energy supply for the built environment. Not only in urban areas – particularly old city centres – but also in the countryside and smaller villages, hydrogen would appear to represent an appealing and relatively quick-to-implement alternative or addition to other energy-transition measures.

CHAPTER 12 - Hydrogen for light road transport?

It is not unlikely that hydrogen-powered cars will play an important role in making the transport sector more sustainable, although their development still lags behind that of electric vehicles. As mentioned earlier, leading motor manufacturers from the US, Europe and Asia have joined efforts in the Hydrogen Council to boost their development. Japan sees itself as the first country to develop a hydrogen economy, with one of its ambitions to have 800,000 fuel-cell electric vehicles (FCEVs) on the road by 2030 [39]. Meanwhile, the US Department of Energy predicts that FCEVs will cost less to run per kilometre than battery-operated electric vehicles (BEVs) by 2040 [40]. In addition, their short refuelling times and long operating range will appeal to the consumers. FCEVs also consume fewer primary materials than BEVs, due to their much smaller battery packs. Kiyotaka Ise, Head of Advanced R&D at Toyota, stated to the press that the FCEV should be seen as ‘the ultimate eco-car’ [41].

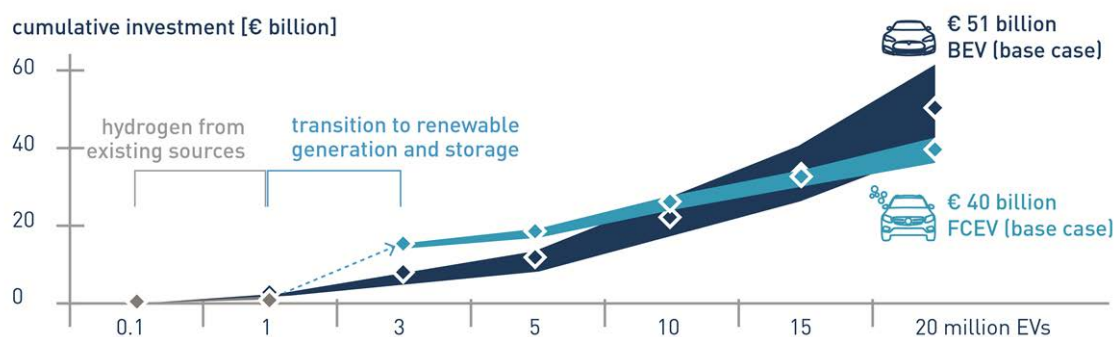


Figure 9. Cost projection for hydrogen fuelling versus electric charging infrastructure in Germany, as a function of the size of the vehicle fleet to be serviced [42].

The potential breakthrough for FCEVs should therefore be taken seriously. Obviously, this has major consequences for our thinking about urban design and, in particular, the level of demand for BEV charging points. The Jülich Research Institute has calculated for Germany that, with a total fleet of 20 million cars, the rollout of a hydrogen-fuelling infrastructure would be cheaper than national coverage with electric charging points (see figure 9) [42]. One important point here is that a single hydrogen filling point can serve many more cars per day than one electric point. Whether similar conclusions can also be drawn for the Netherlands, with its smaller vehicle fleet of about 7 million cars, is an interesting question. But here, too, we have to be careful with preconceived ideas such as, ‘Electricity is everywhere, but for hydrogen a complete new infrastructure will have to be rolled out’. That is true now, but it does not mean that going electric will remain either the cheapest or the best option in the long run.

CHAPTER 13 - The car as power plant

However, the potential implications of the widespread introduction of FCEVs go well beyond the issue of how to provide enough electric charging points if BEVs were to become dominant. If 7 million battery-powered vehicles were to take to the road in the Netherlands, each covering 15,000 km annually and consuming 1 kWh of electricity per 5 km covered, they would require almost 100 PJ a year in total. Most of which, given their relatively long charging times, would have to be delivered in built-up areas. That is half the total amount of electricity currently supplied in the built environment. With overnight charging likely to be the rule rather than using locally produced solar energy, that power will have to be generated elsewhere and put pressure on the grid. And if there is also a shortage of wind power at night, stored energy will have to be converted to meet the demand. If this storage is hydrogen-based, then even BEVs will end up running indirectly on hydrogen.

By contrast, vehicles powered directly by hydrogen are refuelled more or less in the traditional way, at filling stations. This means they transport energy, in the form of hydrogen, into the city. And in periods of power scarcity, they could even supply electricity to local buildings. This option has already been demonstrated at Delft University of Technology, using a Hyundai FCEV ‘plugged into’ a local power network. A single car can supply dozens of homes with electricity for several hours [12]. Car parks might become viable sources of back-up power for electricity suppliers – rather than investing in their own expensive fixed assets. They would instead pay vehicle owners for each kWh delivered.

If and when sales of FCEVs start to take off, we should realise that they could also quickly provide significant reserve power-generation capacity. Almost 420,000 new cars were sold in the Netherlands in 2017 [43]. Had all of them been FCEVs, each fitted with a 100 kW fuel cell, they would have given us the potential to produce about an additional 42,000 MW of electricity. That is approximately double the nation’s current total installed generating capacity [31, 12].

CHAPTER 14 - Conclusion

Thinking in terms of ‘the hydrogen and electric power combination’ brings structure and coherence to our search for solutions to the big questions surrounding the energy transition. Realistic perspectives for the transition process in the transport sector, the built environment, industry and energy storage are now beginning to emerge, but there is still much work to be done. The real challenge is to adopt an all-embracing approach to the possible routes in order to identify ‘no-regret’ investments in infrastructure and other developments to be made in the short term.

Once there is enough confidence to proceed with the conversion of the natural-gas infrastructure to hydrogen, for example, with associated storage in salt caverns, this will of course have far-reaching consequences with respect to issues concerning the back-up of electricity supplies, modifications to the built environment and the transport sector.

Even though sometimes at odds with the current trend for ‘decentralised energy thinking’, the international context – energy produced cheaply in wind and sun-rich regions, then shipped out in the form of hydrogen – has an important role to play here. Not least due to its economic implications for port activities, employment and so on. Our huge demand for energy in north-western Europe will continue to require imports, but it is the form they take that will have great impact on our ability to create a sustainable energy supply and economy.

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