MASTER'S DEGREE PROGRAMME

Sustainable Energy Systems

Hydrogen sector coupling of Innere Stadt Linz

SUBMITTED AS A MASTER THESIS

to obtain the academic degree of

Master of Science in Engineering (MSc)

by

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September 2022

Thesis supervisor

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Contents

1. Preface / Acknowledgements

Firstly, I would like to thank WIVA P&G for providing me with the chance to write my master thesis on the hydrogen-related subject during these uncertain post-lockdown times. Receiving immediate help from my university staff and professors regarding any issue assured me that I am studying at one of the most considerate international programs in Austria. Also, I wanted to give special thanks to Dr. Erwin Reichel, coordinator at WIVA P&G, and my company supervisor for providing help, sending me valuable articles to improve the quality of my thesis, and being constantly available for all the questions. Additionally, I wanted to show my gratitude to all the developers of "City Energy Analyst" software who helped me with my project, especially Mr. Mathias Niffeler, who offered me to have a video call and cleared many of my questions regarding the software and my project. Also, I would like to thank Dipl. Ing. Dominik Kreil and Mr. Dominik Matheisl for taking the time to answer my interview questions for the qualitative analysis section. I have learned much new information, which will be helpful in my future career. Lastly, I wanted to thank FH-Prof. DI Dr. Michael Steinbatz, Head of studies of the Sustainable Energy Systems program, helped me with the regulatory side of all the processes and was very responsive to all the problems I had. Under his attentive supervision, all the work of the master thesis became very structured and organized.

2. Abstract

This paper thoroughly reviews the role of hydrogen nowadays, new technologies invented in the last 1-2 years, and leading countries and companies in this direction. It overviews different parts of the hydrogen field, like logistics and global perspectives. Also, recent, and most important regulations, the use of hydrogen on all ends like household, industry, mobility, and sector coupling is part of this research. Additionally, as a practical side of this research, the calculation of parameters for sector coupling of Innere Stadt district of Linz with Hydrogen technology was conducted. With software estimation of the region's energy demand and consideration of 3 thousand buildings. This paper seeks to estimate the capacities of electrolysers and storage required for an effective sector coupling of a modern city. Hence, this further pushes the idea of simulating city-scale estimations and developing this niche for creating decarbonized and seasonally flexible cities. Since there is a heavy concentration on the increase of renewable energy potentials to decarbonize the world, the seasonality of the generation will only increase. Hydrogen is one of the best solutions for seasonal energy storage now. Therefore, in the future, more and more cities will need to be sector couples to ensure seasonal energy stability and utilize the energy without any greenhouse gas emissions. This research will contribute to it by adding another district simulated and sector coupled via utilization of modelling tools.

3. Kurzfassung

Dieses Papier gibt einen gründlichen Überblick über die Rolle von Wasserstoff heutzutage, neue Technologien, die in den letzten 1-2 Jahren erfunden wurden, und führende Länder und Unternehmen in diese Richtung. Es gibt einen Überblick über verschiedene Teile des Wasserstoffbereichs, wie Logistik und globale Perspektiven. Auch die jüngsten und wichtigsten Regulierungen zur Nutzung von Wasserstoff an allen Enden wie Haushalt, Industrie, Mobilität und Sektor Kopplung sind Teil dieser Forschung. Zusätzlich wurde als praktische Seite dieser Forschung die Berechnung von Parametern für die Sektor Kopplung des Linzer Bezirks Innere Stadt mit Wasserstofftechnologie durchgeführt. Mit Softwareschätzung des Energiebedarfs der Region und Berücksichtigung von 3.000 Gebäuden. Ziel dieser Arbeit ist es, eine grobe Abschätzung der Kapazitäten von Elektrolyseuren und Speichern zu geben, die für eine effektive Sektorenkopplung einer modernen Stadt benötigt werden. Daher treibt dies die Idee weiter voran, Schätzungen im Stadtmaßstab zu simulieren und diese Nische für die Schaffung von dekarbonisierten und saisonal flexiblen Städten zu entwickeln. Da eine starke Konzentration auf die Steigerung der Potenziale erneuerbarer Energien zur Dekarbonisierung der Welt besteht, wird die Saisonabhängigkeit der Erzeugung nur zunehmen. Wasserstoff ist heute eine der besten Lösungen für die saisonale Energiespeicherung. Daher müssen in Zukunft immer mehr Städte Sektorenpaare sein, um die saisonale Energiestabilität zu gewährleisten und die Energie ohne Treibhausgasemissionen zu nutzen. Diese Forschung wird dazu beitragen, indem ein weiterer simulierter und Sektor hinzugefügt wird, der durch die Verwendung von Modellierungswerkzeugen gekoppelt ist.

4. Introduction

Climate change, rising world population, urbanization trends, and increased demands on residents' living standards necessitates a response from city planning regarding energy generation, supply, and consumption. Despite only making up 2% of the Earth's surface, urban metropolises account for around 80% of global oil, gas, and coal consumption and are the most significant greenhouse gas producers. By 2050, 70% of the world's population is projected to reside in urban areas (United Nations, 2015), and cities are among the top emitters of greenhouse gases and consumers of energy (IEA, 2016). As a result, cities present a huge opportunity to increase energy efficiency and reduce greenhouse gas emissions. Urban regions must quickly shift to energy efficiency and adjust to the problems brought on by climate change. District heating and cooling show high potential for contributing to future energy systems, and the harvest of solar energy and wind is an already fast-growing contribution to the energy transition.

In accordance with EU rules, Austria has pledged to reduce greenhouse gas emissions in industries not included in the European emissions trading scheme by 36% by 2030 compared to 2005. The share of energy from renewables in gross final energy consumption is to be increased from just under 34 % to 46–50 % (National Climate and Energy Plan 2019). The goal is to cover 100% of power demand with renewable sources by 2030, with a current high baseline of over 70%. There will be serious efforts to increase the renewable energy capacity of the whole country.

However, because natural resources are intermittent and are classified as variable renewable energy (VRE) sources, the increased variability that these sources provide to the electricity system has an impact on the energy system during the day and the course of the year's seasons. Existing technical solutions must be developed further to provide the necessary system flexibilities. Due to the need to replace significant amounts of gaseous and liquid fossil fuels, flexible hydrogen (H2) production through electrolysis can significantly contribute to this. Furthermore, gas networks can be essential in transporting large amounts of energy.

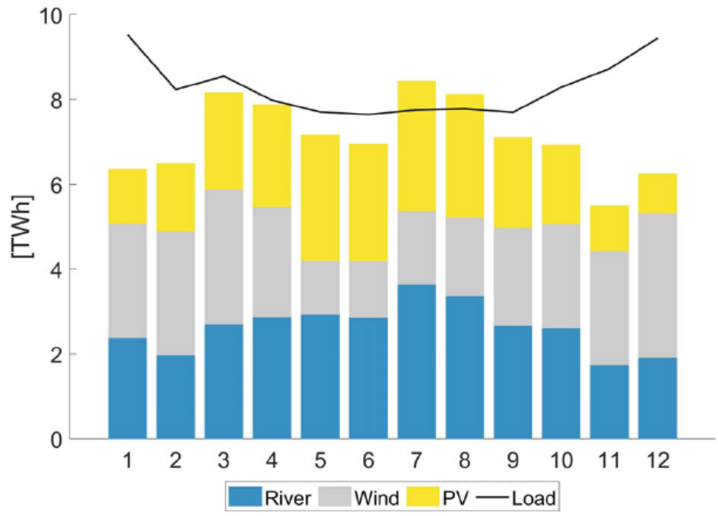


Figure 1: Monthly electricity generation in a 100% VRE 2050 scenario for Austria

Source: EEG TU Wien

Figure 1 provides Austria's renewable energy generation in a 2050 scenario, together with the relative shares of hydro, wind, and solar power, as an illustration of the seasonal fluctuation of continental Europe. Long-term seasonal storage is required to achieve decarbonization of the power sector These capacities, however, are spatially constrained, making the need for alternative flexibility strategies like chemical gas storage necessary. On a good summer day, the amount of excess generation from the sun and wind peaks during low energy demand, as shown in Figure 2. Only some of this generation can be balanced through short-term pumped hydro storage.

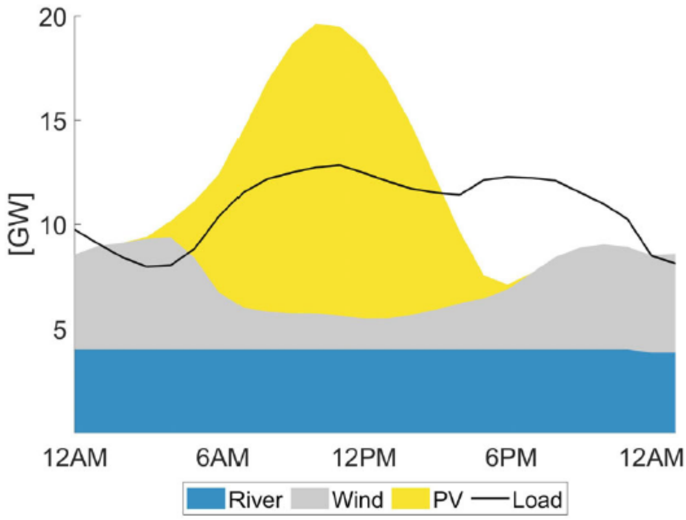


Figure 2: Exemplary summer day 2050: Surplus VRE electricity generation, Austria

Source: EEG TU Wien

Managing the energy system is made more difficult by these changes in how electricity is generated. There are concerns about how to control these uncontrollable sources, deal with excess power production, and utilize it effectively regarding economic, ecological, and social well-being. In addition to frequently discussed solutions like grid extension or new electric storage alternatives, VRE power surplus can be employed in other end-use sectors, such as transportation, domestic heating, or industry, as a potential solution for seasonal balancing and increased integration of VRE. A strategy to replace fossil fuels with energy from renewable electrical sources in all end-consumption sectors, such as transportation, industry, and home heating/cooling, is known as sector coupling (SC) or sector integration (SI). It advocates for developing 100% renewable energy systems, improving flexibility and storage choices, and distributing renewable electricity more flexibly (Schaber et al., 2013).

Modelling can be used to explain the creation of potential routes for municipal or district energy systems. In this regard, virtual 3D city models that store geometrical and semantic information on entire cities have demonstrated significant promise in the disciplines of city planning, the environment, and energy, from flood risk simulations to solar potential analyses (Solar Atlas Berlin, 2010). Parallel to this, as new automatic data collection technologies like LiDAR, a remote sensing technique that measures distance by illuminating surfaces with a laser, are developed, the number of cities represented in 3D city models is growing exponentially. At the same time, the investment costs and construction time for these models are also getting smaller. Some urban energy analyses based on a virtual 3D city model have already been realized at a local scale for some city districts like Berlin (Carriòn et al., 2010, Kaden et al., 2013), Karlsruhe and Ludwigsburg (Nouvel et al., 2013). These city models' data quality varies considerably based on the publicly accessible database (often provided by the municipality) and the information data gathered onsite.

The first part of this paper introduces the role of hydrogen nowadays, new technologies invented in the last 1-2 years, and leading countries and companies in this direction. It overviews different parts of the hydrogen field like logistics and global perspectives. Also, recent, and most important regulations, the use of hydrogen on all ends like household, industry, mobility, and in sector coupling is part of this research. Recent research only gives up-to-date information about one specific field of Hydrogen technology, and this research is planned to do that in all fields of the technology for readers to read one article and be updated with all sides of this field.

The second half presents the practical calculation of sector coupling needed for the district Innere Stadt of Linz with hydrogen technology. The simulation was carried out using the City Energy Analyst software, a platform for simulating urban buildings and one of the earliest open-source initiatives for creating highly effective and low-carbon cities. The considered case for calculation will be the replacement of energy for district heating systems generated by fossil-fuelled engines with hydrogen fuel cells and calculating the CO2 savings.

5. Theoretical Background

5.1 Global overview

5.1.1 Global perspectives / zero emission scenarios / markets

In the universe, hydrogen is the lightest, oldest, and most abundant element. Hydrogen occurs naturally in many compounds, such as water and fossil fuels.

The (petro)chemical industry uses hydrogen gas primarily for refining crude oil, synthesizing ammonia (mostly for the production of fertiliser), and producing methanol (used for a wide range of products including plastics).

Approximately 120 million tonnes of hydrogen are produced worldwide (IEA, 2019a), of which two-thirds are pure hydrogen and one-third is hydrogen mixed with other gases. China is the world's most significant producer and user of hydrogen. It produces nearly 24 million tonnes of pure hydrogen every year, accounting for almost one-third of all hydrogen produced worldwide.

Hydrogen can also be used as a fuel. Hydrogen produces heat when it burns at more than 1000 degrees without emitting CO2. Fuel cells can also use it to produce electricity when it chemically reacts with oxygen without emitting pollution or greenhouse gases. Water vapour is the only by-product of this chemical process.

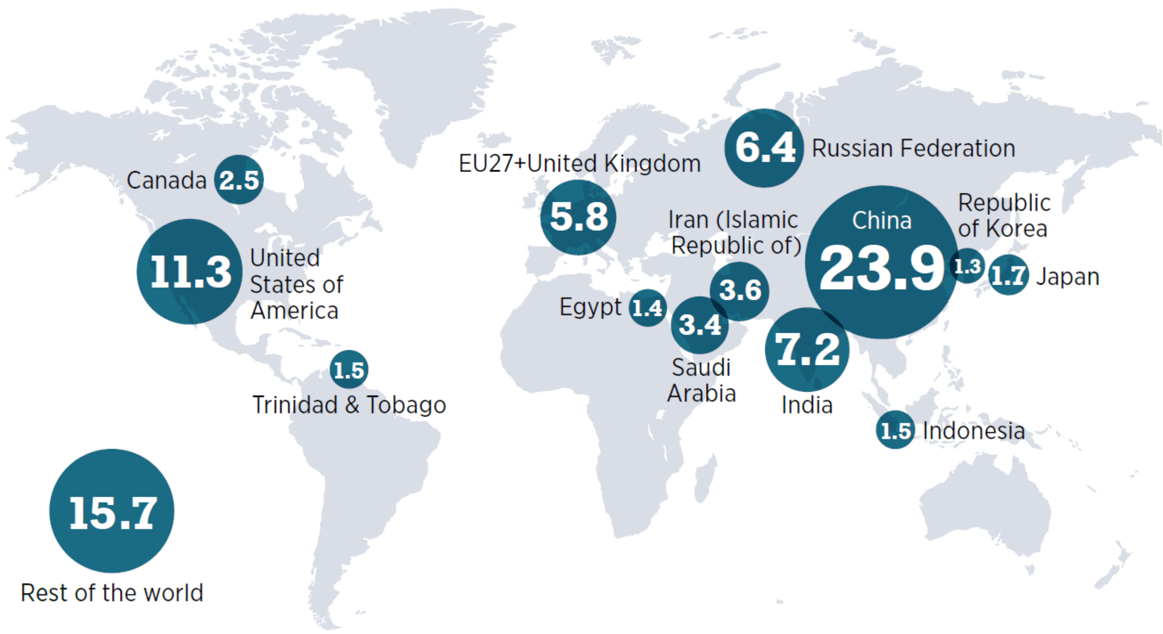


Figure 3: Hydrogen consumption in 2020 (million tonnes per year)

Source: IRENA (2022), Geopolitics of the Energy Transformation: The Hydrogen Factor

Hydrogen is a very adaptable fuel that can be made using all kinds of energy sources (coal, oil, natural gas, biomass, renewables, and nuclear) via a very broad variety of technological techniques like reforming, gasification, electrolysis, pyrolysis, water split, etc. The words "safe," "sustainable," "low-carbon," and "clean" are now being discussed. In recent years, various hydrogen production methods have been denoted by various colours (e.g., green for hydrogen from renewable sources and blue for synthesis from natural gas with CCUS). There is not yet an international agreement on the use of these terms, and their meaning in this context has not been clearly defined.

The environmental implications of each production route might vary significantly due to the numerous energy sources that can be utilized; also, the geographic region and process design used have an impact. Recognizing that hydrogen's ability to cut CO2 emissions is highly dependent on how it is produced, this project emphasizes the importance of low-carbon hydrogen production methods in the clean energy transition. Low-carbon hydrogen in this report includes hydrogen generated from renewable and nuclear power, biomass, and fossil fuels with the CCUS.

Production from fossil fuels with CCUS is only included if upstream emissions are low enough if all CO2 streams associated with the production route are captured – at high rates – and if all CO2 is permanently stored to avoid release into the atmosphere. The same principle applies to low-carbon feedstocks and hydrogen fuels manufactured from low-carbon hydrogen and a sustainable carbon source (biogenic or directly captured in the atmosphere).

There has been a growing number of countries announcing targets for achieving net zero emissions by 2050 before the 26th Conference of the Parties to the UN Framework Convention on Climate Change (COP 26). As a result, more than 100 companies that consume large amounts of energy or produce goods that consume energy have adopted similar policies. To achieve these targets by 2050 we need to maximize clean energy expansion in the 2020s.

As we transition to net zero emission, hydrogen will play a key role. Many governments and companies have been developing goals and plans for hydrogen since the first Hydrogen Energy Ministerial (HEM) meeting in Japan in 2018.

In 2019, G20 leaders emphasised the importance of hydrogen in enabling clean energy transitions at the Osaka Summit. In addition, the Hydrogen Initiative (H2I) was launched during the 10th Clean Energy Ministerial meeting in Vancouver to accelerate hydrogen deployment, and the Clean Hydrogen Mission was announced at the 6th Mission Innovation Ministerial to reduce the cost of clean hydrogen.

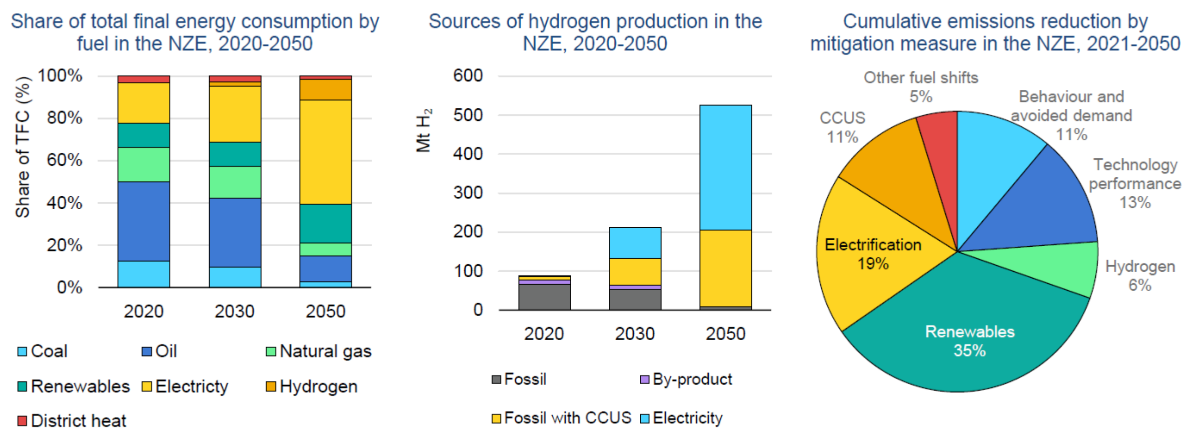


Figure 4: Hydrogen is an important part of the Net zero Emissions Scenario but is only one piece of the Puzzle.

Source: IEA (2021), Net zero by 2050.

A broad spectrum of technologies will be required to alter the energy system to achieve net-zero emissions by 2050. Energy efficiency, behaviour change, electrification, renewable energy, hydrogen and hydrogen-based fuels, and the CCUS are the fundamental pillars of the decarbonization of the global energy system. The growing share of hydrogen and hydrogen-based fuels in total final energy consumption (TFC) shows how vital hydrogen is becoming in the Net-zero Emissions Scenario: in 2020, hydrogen and hydrogen-based fuels accounted for less than 0.1 percent of TFC, but by 2030, they will be increased to 2 percent, and by 2050, they will be increased to ten percent.

But this growth in demand alone is not enough to make hydrogen a key pillar of decarbonisation. Hydrogen production also needs to become much cleaner than it is at present. For example, of the ~90 Mt H2 used in 2020, about 80% were produced from fossil fuels, most of the time non-stop. Almost all the rest is from residual gases produced in refineries and the petrochemical industry. As a result, over 900 Mt of CO2 was released during the creation of hydrogen, which is equal to the combined CO2 emissions of Indonesia and the United Kingdom.

Under the net-zero scenario, hydrogen production is going through an unprecedented transformation. When the overall output reaches 200 Mt H2 in 2030, low-carbon technologies will account for 70% of that production (electrolysis or fossil fuels with CCUS). Hydrogen production will increase up to 500 Mt H2 by 2050, mainly all based on low-carbon technologies. To meet these targets, installed electrolysis capacity must rise from 0.3 GW today to nearly 850 GW by 2030 and nearly 3 600 GW by 2050, with CO2 captured in hydrogen production rising from 135 Mt today to 680 Mt in 2030 and 1 800 Mt in 2050.

Strong hydrogen demand growth and the deployment of cleaner hydrogen production technologies in the Net Zero Emissions Scenario allow hydrogen and hydrogen-based fuels to avoid up to 60 Gt CO2 emissions in 2021-2050, accounting for 6.5 percent of overall cumulative emissions reductions. Hydrogen consumption is particularly important to reduce emissions in hard-to-decarbonise sectors where direct electrification is difficult to implement mainly in heavy industry (mainly iron and steel and chemicals), heavy road transport, maritime transport, and aviation. Hydrogen can also offer flexibility in the energy sector by balancing the rising shares of fluctuating renewable energy output and facilitating seasonal energy storage.

5.1.2 State-of-the-art in H2 technology: electrolysers, fuel cells, storage

Hydrogen does not exist in great numbers in its pure form in nature, despite its abundance on Earth. There are no large reserves of hydrogen that can be obtained in the earth. Compounds containing hydrogen are almost exclusively water molecules (hydrogen and oxygen) and fossil fuels (hydrogen and carbon). These compounds can release hydrogen, but it takes energy to do so.

A colour-coding system is commonly used to describe hydrogen production methods [see Fig. 5 on page 13]. Most of the hydrogen produced today is "grey" hydrogen, which comes from fossil fuels such as natural gas steam methane reforming or coal gasification. These fossil fuel-based production techniques, which make up 95% of the hydrogen available today, emit a lot of CO2 and are therefore incompatible with reaching net-zero emissions.

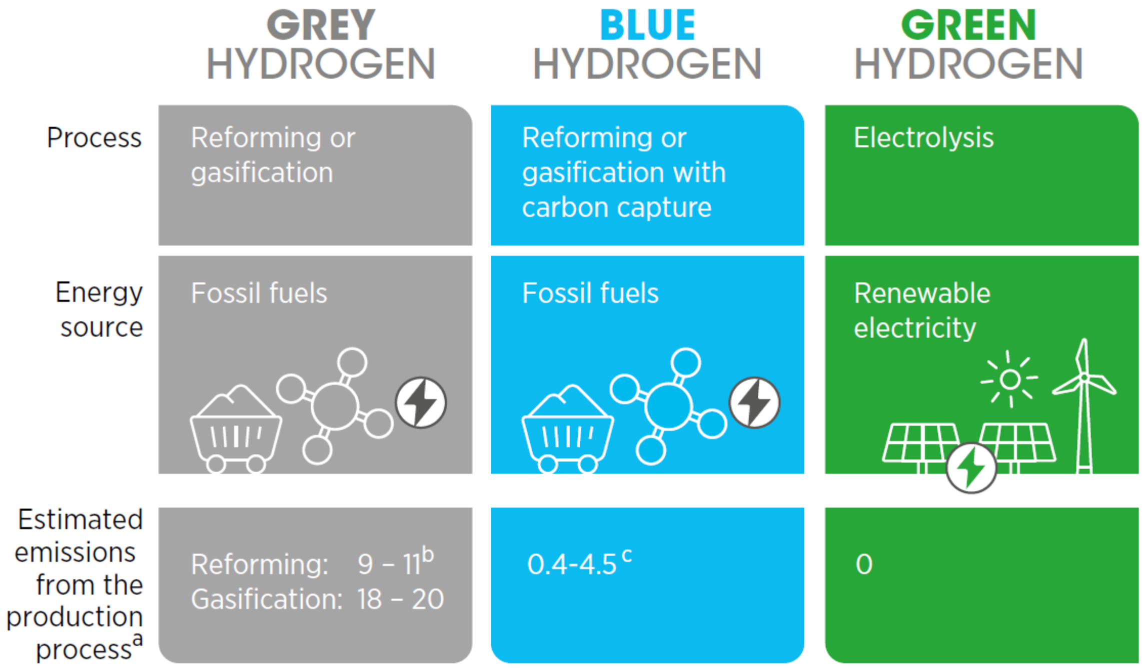


Figure 5: Selected colour-code typology of hydrogen production.

Source: IRENA (2022), Geopolitics of the Energy Transformation: The Hydrogen Factor

Green and blue hydrogen are the two main ways being considered to replace grey hydrogen with a clean type of generation. Green hydrogen production is completely compatible with a net-zero strategy. It is based on long-established technology, such as water electrolysis powered by renewable electricity. Hydrogen generation from renewable sources is currently limited, but this is expected to change as the world becomes more focused of its potential.

Facilities for producing grey hydrogen may continue functioning while generating fewer greenhouse gases if CCS is retrofitted. However, because blue hydrogen is based on fossil gas, there is a chance that methane, which is a much more potent greenhouse gas than CO2, could leak upstream or in the middle of the process. As a result, blue hydrogen can produce very low greenhouse gas emissions only if methane leakage emissions do not exceed 0.2%, with almost 100% carbon capture. Such rates must be demonstrated in a large-scale setting (Bauer et al., 2021; Howarth and Jacobson, 2021; IEA, 2021b; IRENA, 2020b; Saunois et al., 2016).

Blue hydrogen has several other drawbacks that have limited widespread application. It relies on fossil fuels, which means it is subject to price fluctuations, as was the case in late 2021 in Asia and Europe (Collins, 2021a), and does not support energy security or climate resilience goals. It also raises CO2 transport and storage prices and necessitates CO2 storage monitoring.

Nonetheless, if blue hydrogen can meet strict emissions criteria, it could play an important role in increasing hydrogen volumes in the short-to-medium term and accelerating the development of related technologies and infrastructure. Furthermore, blue hydrogen may provide more flexibility in the hydrogen market. On the other hand, green hydrogen is a long-term zero-carbon alternative and should be the target.

There are other ways of producing low-carbon hydrogen. One alternative is "turquoise" hydrogen, which relies on CO2-free pyrolysis of methane (natural gas). The solid material "carbon black" is the only by-product of this technique, and there is a market for it, though a small one. Another alternative is nuclear-generated "pink" hydrogen. Biomass gasification with carbon capture and storage (CCS), the third choice, may result in dangerous CO2 emissions. This report does not include any of these types of hydrogen, giving priority to more developed methods of production.

Almost all the worldwide hydrogen demand of 90 Mt was met by fossil fuels in 2020, with 72 Mt (79%) coming from dedicated hydrogen plants. Most of the remaining hydrogen (21%) is created by facilities designed to produce other products, such as refineries, where naphtha is reformatted into gasoline and hydrogen is produced. A total of 72 Mt of hydrogen was used as a pure gas for ammonia production and oil refining, while 18 Mt H2 was mixed with other gases for use in methanol and steel production.

The most popular technique for generating hydrogen from natural gas is steam methane reformation, which is used in the ammonia and methanol industries and refineries. Natural gas accounted for 60% of annual global hydrogen production using 240 bcm (6% of global demand in 2020), while coal (2% of global demand) accounted for 19%. This is indicative of coal's dominant role in China. The remaining committed output was provided by oil and electricity.

Because fossil fuels lead in hydrogen generation, the sector will produce over 900 Mt of direct CO2 emissions in 2020 (2.5 % of the world's energy and industrial CO2 emissions), which is equal to the UK and Indonesia's emissions. Emissions from hydrogen production must be decreased to achieve a clean energy transition.

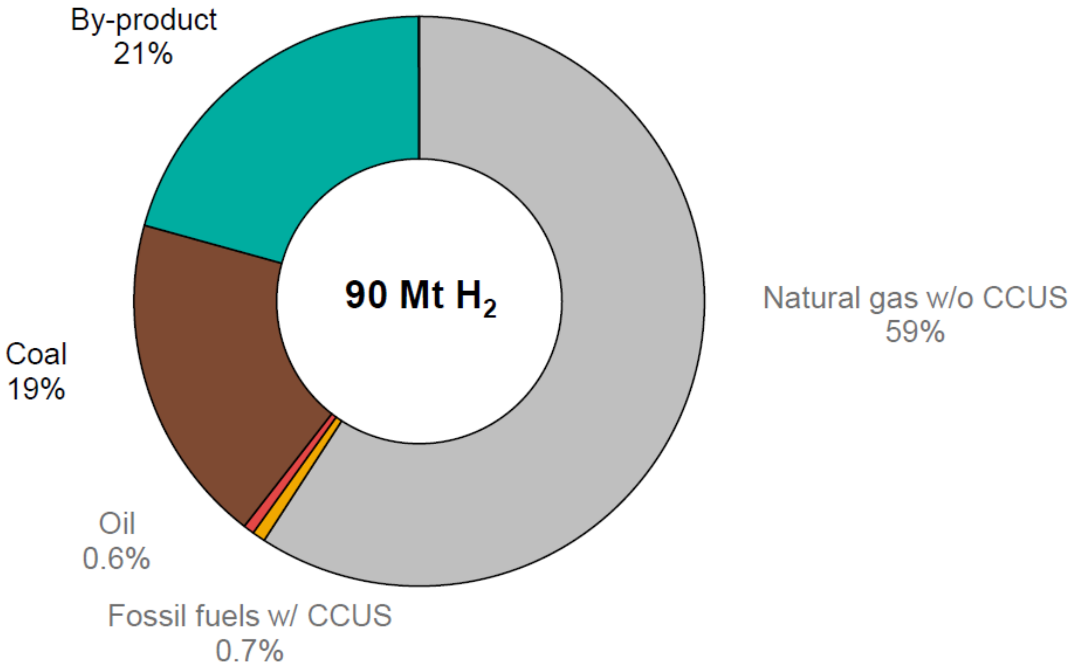


Figure 6: Sources of hydrogen production, 2020.

Source: IEA (2021) Global Hydrogen Review

There are several technologies available for producing low-carbon hydrogen: electrolysis, using water and electricity; carbon capture, use, and storage (CCUS) from fossil fuels; and biomass gasification from bioenergy. However, these sources account for very small shares of global production: while the proportion of water electrolysis at 30 kt H2 was 0.03%, and 16 fossil fuel CCUS plants produced just 0.7 Mt H2 (0.7%).

The chemical process of electrolysis creates hydrogen from water and electricity. Over 200 years ago, electrolysers — devices that split water into oxygen and hydrogen – were invented.

There are multiple water electrolyser technologies. The four promising types are alkaline, proton exchange membrane (PEM), solid oxide electrolyser cells (SOEC), and anion exchange membranes (AEM). Either alkaline or PEM technologies are used in all of the electrolyser capacity that has been deployed. Electrolysers made using AEM technology are relatively new and have little deployment; however, they have the advantage of using no precious metals and using a less expensive membrane than PEM technology.

Type	Commercial Status	Considerations
Alkaline	Mature	• Simple system design. • Have other applications with existing supply chain that can be scaled up. • Slower dynamic response; less suited for variable renewable energy (VRE) support.
Proton exchange membrane (PEM)	Commercial, fast growth	• Platinum and iridium are required. Current global iridium production could support annual deployment of up to 3-7.5 GW a year. • Faster dynamic response; well suited to VRE and voltage regulation.
Solid oxide electrolyser cells (SOEC)	Demonstration plants	• No cycling (ramp up or down); well suited for constant base load hydrogen production.
Anion exchange membrane (AEM)	Limited deployment	• Does not use any precious metals. • Membrane is less expensive than that used for PEM.

Table 1: Main electrolyser technology comparison

Source: IRENA (2020a, 2020b).

Electrolysers have been used for decades. Alkaline water electrolysers with more than 100 megawatts (MW) were built many times during the 20th century, close to hydropower dams that generated cheap electricity. Fertilizers were mostly made from renewable hydrogen. In real life, until the 1960s, the majority of fertiliser delivered in Europe originated from Rjukan and Vemork, Norway's hydropower-based electrolysis and ammonia industry (Philibert, 2017). Therefore, electrolysis was essential for food production.

Plant location (country, city)	Capacity (MW)	Commissioning year
Norway (Rjukan)	165	1929
Canada (Trail)	90	1939
Norway (Glomfjord)	160	1953
India (Nangal)	125	1958
Peru (Cuzco)	25	1958
Egypt (Aswan)	160	1960
Zimbabwe (Que Que)	95	1974

Table 2: Historic examples of large-scale electrolysis hydrogen production plants

Source: Smolinka, Günther and Garche (2011); Godula-Jopek (2015).

Despite more than a century of expertise and thousands of installed plants worldwide, the water electrolysis sector was described as small and fragmented in 2014 (FCH JU, 2014). Despite its maturity, electrolytic hydrogen production has been unable to compete with fossil fuels (Godula-Jopek, 2015).

The electrolyser sector is experiencing a rebirth thanks to the falling cost of renewable energy and the need to reduce global emissions to net-zero. In 2018, the annual global electrolyser manufacturing capacity was about 135 MW (IRENA 2020a). By 2024, it is expected to reach 16 GW. [see Fig. 7 on page 18]. Several gigafactories (factories with gigawatt production capacity) have announced plans to produce electrolysers at large scale, including Australia, France, Germany, Israel, Norway, Spain, and United Kingdom (IRENA, 2021b; Bullard, 2021; Brisbane Times, 2021; La Repubblica, 2021). The cost of electrolytic hydrogen is projected to be considerably reduced by projects of this size, achieving economies of scale through mass production and fully automated production lines.

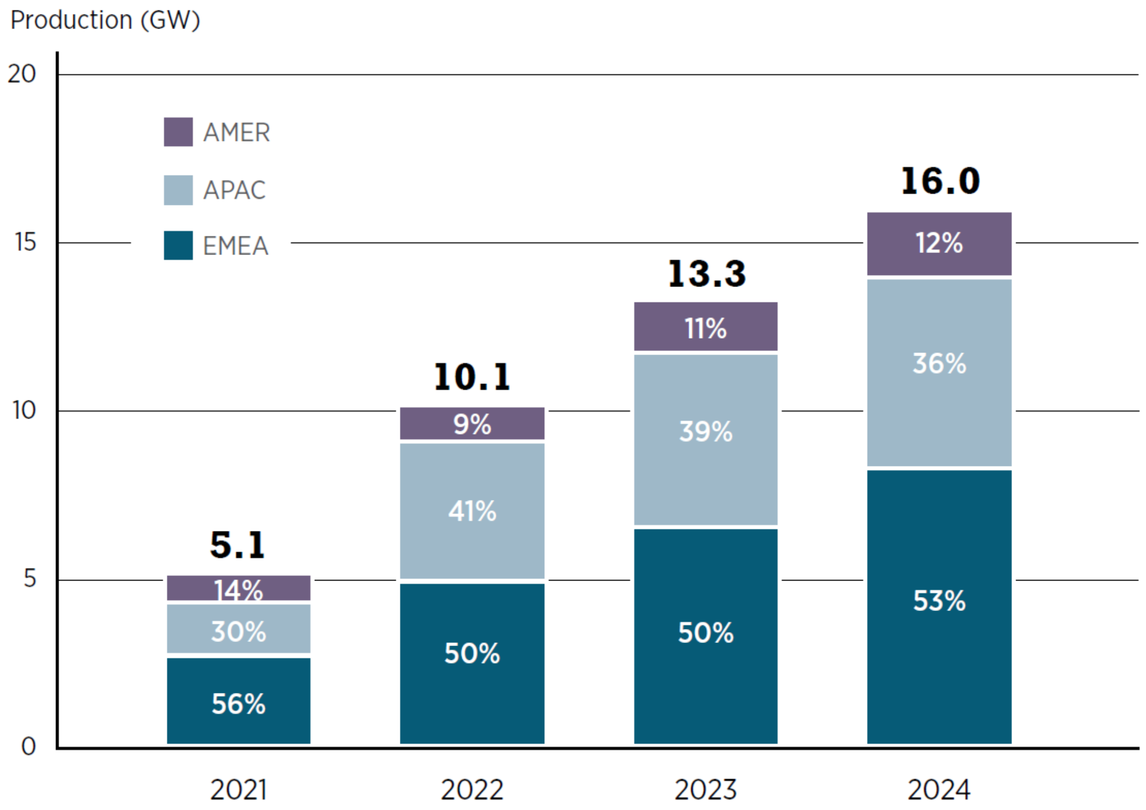


Figure 7: Estimated global electrolyser manufacturing capacity 2021-2024, based on investment plans

Source: BloombergNEF (2021b).

In the electrolyser manufacturing industry, Europe has gained considerably dominant position. Even now, about half of all electrolyser manufacturers are based in Europe, and so are the majority of their component suppliers (Fraunhofer ISE, 2020). Europe, the Middle East, and Africa (EMEA) will produce half of the world's electrolyser capacity in the following years, according to projected investment plans [see Fig. 8 on page 19]. The European hydrogen strategy is aimed primarily at retaining the region's electrolyser manufacturing competitiveness. European hydrogen industries are determined not to follow the path of the continent's solar PV sector, in which Europe, particularly Germany, once held a dominant position, but which lost ground due to cheaper Chinese solar modules (Amelang, 2020).

Even though Europe has the most manufacturing capacity, China leads the world in electrolyser shipments (BloombergNEF, 2021b). Electrolysers made in China are also substantially cheaper than those made in Europe. Standard alkaline electrolysers are said to be supplied for USD 300 per kilowatt in China, which is 75 percent less than similar machines built in the West (BloombergNEF, 2021b). Several firms, particularly from the West, are investing in more novel technologies including proton exchange membranes, solid oxide, and pressurized alkaline electrolysers. These technologies have advantages, despite their higher cost.

For example, proton exchange membrane electrolysers are more compact and better adapted to operate with fluctuating renewable electricity generation than typical alkaline electrolysers. Companies in China, Europe, and Japan have a head start when it comes to manufacturing and selling electrolysers, but the sector is still young. Market shares could vary rapidly as hydrogen production plants ramp up from megawatts to gigawatts to fulfil the expected substantial growth for clean hydrogen. The electrolyser market, as well as the current manufacturing landscape, could be reshaped by innovation and upcoming technologies.

Electrolysis was responsible for around 0.03 % of hydrogen production for energy and chemical feedstocks in 2020. Moreover 40% of the installed global electrolyser capacity of 290 MW is based in Europe, with Canada (9%) and China following closely after (8 percent).

Alkaline electrolysers accounted for 61% of installed capacity in 2020, while PEMs accounted for 31%. The remaining capacity is composed of SOECs (installed capacity of 0.8 MW) and an undisclosed electrolyser technology. Additionally, alkaline electrolysers have a wide operating range, from a 10% load to full design capacity.

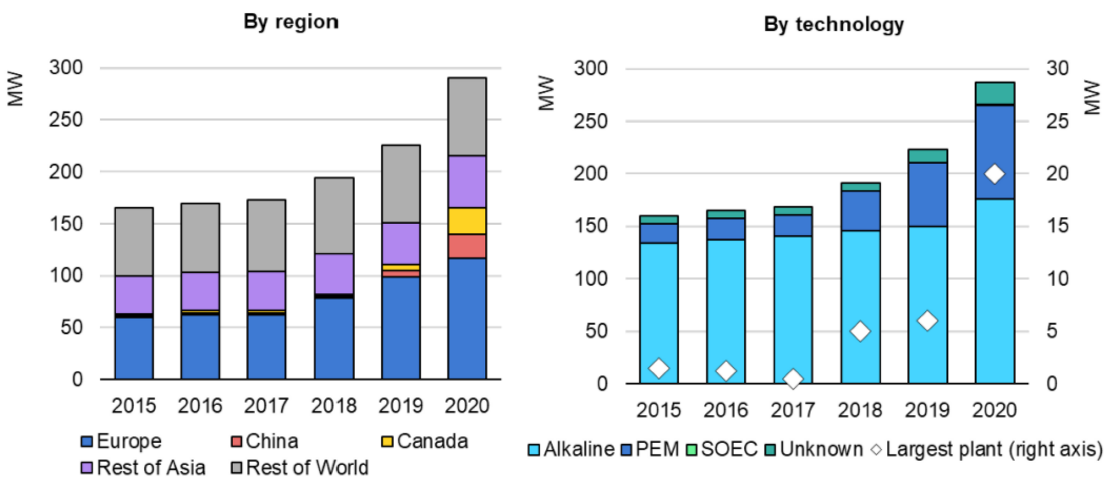


Figure 8: Global installed electrolysis capacity by region and technology, 2015 – 2020.

Source: IEA (2021), Hydrogen Projects Database.

PEM electrolyser systems are more compact than alkaline ones, making them more desirable in urban or industrial settings. Nevertheless, since platinum, iridium catalysts, and titanium plates, as well as membrane materials, are relatively expensive, the costs are higher for PEMs (USD 1,750/kW) than for alkaline electrolysers (USD 1 000-1 400/kW). PEM systems also have a lower lifespan now.

Given the capacity under building and projected, global installed electrolyser capacity might reach 54 GW by 2030. By 2030, capacity could reach 91 GW if all projects in the early development stages are counted. Europe and Australia are at the top of the list, with 22 GW and 21 GW of projects now under construction or planned, respectively. Latin America (5 GW) and the Middle East follow (3 GW).

Numerous initiatives use renewable energy as their primary electricity source, and about a dozen demonstration initiatives (with a combined electrolyser capacity of 250 MW) investigate the use of nuclear energy to produce hydrogen (Canada, China, Russia, the United States, and the United Kingdom). However, not all these plans will come to reality. 50 GW are in various early stages of development. However, only 4 GW (about 7%) of the total are currently being built or have made a final investment decision (e.g., at the front-end engineering design, feasibility study, and concept phases).

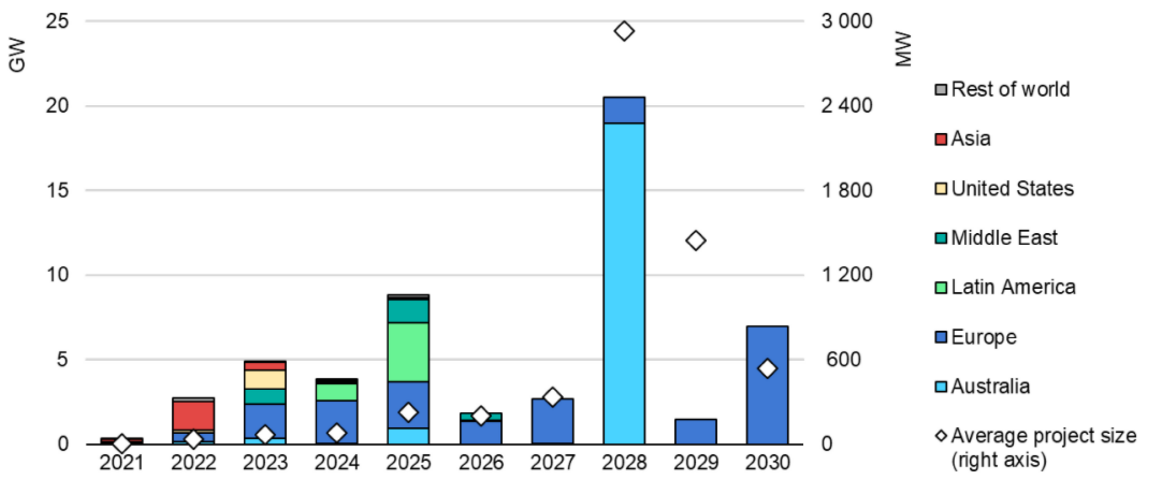


Figure 9: New installed electrolyser capacity based on projects under construction or planned, 2021 – 2030.

Source: IEA (2021), Hydrogen Projects Database.

The average project size grows as worldwide electrolyser capacity expands. The industrial Cachimayo facility in Peru, with a capacity of 25 MW, and the world's largest PEM electrolyser using allotted renewable energy (20 MW powered by hydropower in Bécancour, Quebec, which was opened in 2020 by Air Liquide), each had an average of 0.6 MW in 2020.

Currently, 80 projects with a capacity of more than 100 MW are under construction or in the planning stages. Eleven projects with more than 1 GW have been announced. The proposed Western Green Energy Hub (Australia) will bring 3.5 Mt H2/yr for conversion into 20 Mt of ammonia for exportation with a solar PV and wind capacity of up to 50 GW. Economies of scale and learning effects are predicted to lower electrolyser costs when the average project sizes grow to 230 MW by 2030.

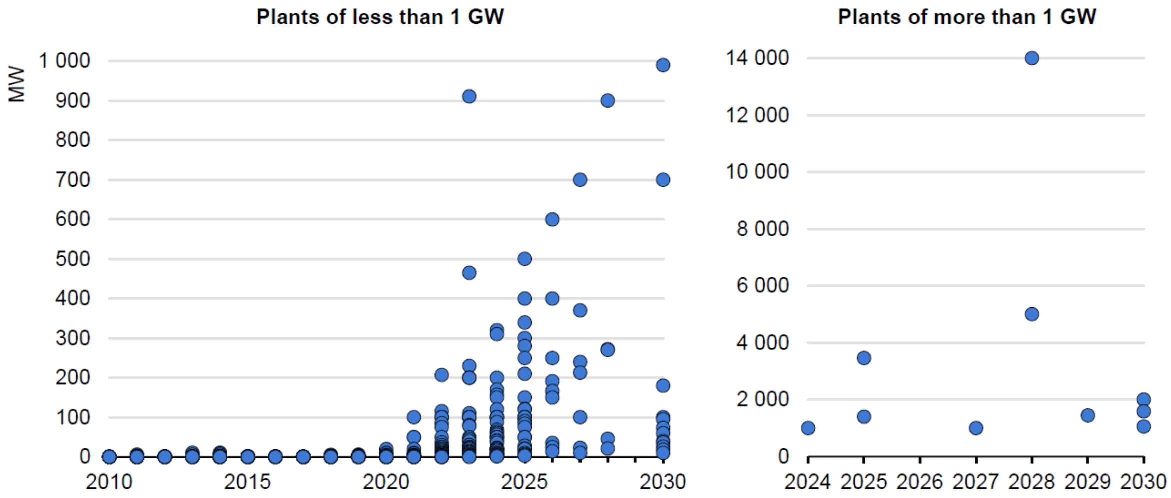


Figure 10: Size of electrolyser projects (existing, under construction and planned), 2010-2030.

Source: IEA (2021), Hydrogen Projects Database.

The European Union and several other nations' hydrogen deployment strategies include electrolyser capacity deployment objectives. These commitments could result in 75 GW of installed capacity by 2030, with the majority tied to European Union (40 GW) and Chile (25 GW). However, planned initiatives may or may not align with national or regional goals. Only 22 GW are now under construction or planned in the EU, which is only a half of the objective of 40 GW by 2030.

Using the Announced Pledges Scenario, installed electrolyser capacity exceeds 180 GW by 2030, more than twice the national targets. Project capacity also increases by three times in the Projects case, and still by 70 percent when including early-stage projects.

When early-stage projects are taken into account, the capacity requirements in the Net-zero Emissions Scenario in 2030 are 850 GW, which is more than nine times the existing project pipeline. While there are significant gaps, the current efforts serve as a good springboard for expanding and accelerating deployment while raising ambitions as more hydrogen projects are developed and more countries include hydrogen in their national strategies.

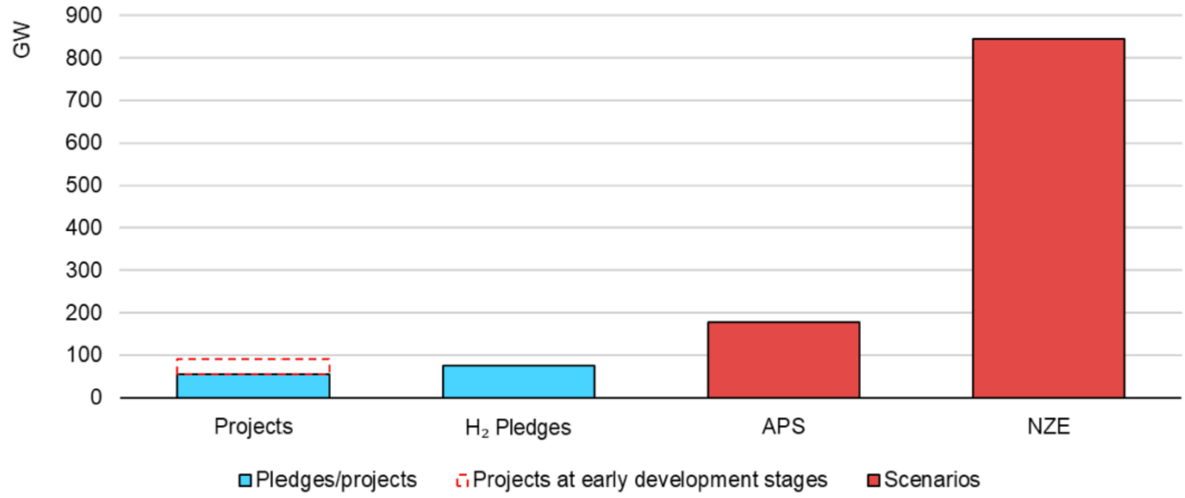


Figure 11: Electrolysis capacity in the Announced Pledges and Net-zero Emissions scenarios in 2030 compared with the current project pipeline and government deployment pledges.

Source: IEA (2021) Global Hydrogen Review

Alkaline electrolysers cost between USD 750 and USD 1 300 per kW in China, with some sources suggesting as low as USD 500/kW, which is much less than the USD 1 400 per kW average for the world. Chinese electrolysers have been questioned for their dependability and endurance, yet manufacturing is snowballing. Chinese manufacturers had to import key components only a few years ago, limiting their capacity to decrease costs through industrial clustering and economies of scale. However, because local component manufacture is growing, cost savings should be seen soon.

Electrolyser costs will also be driven down by manufacturing learning effects and economies of scale. Future electrolyser costs as a function of cumulative capacity deployment were analysed using a component-wise learning-curve technique. A learning rate of 15% is assumed for the electrolyser stack based on a literature study, which also takes into account learning rates for fuel cells that use the same electrochemical processes.

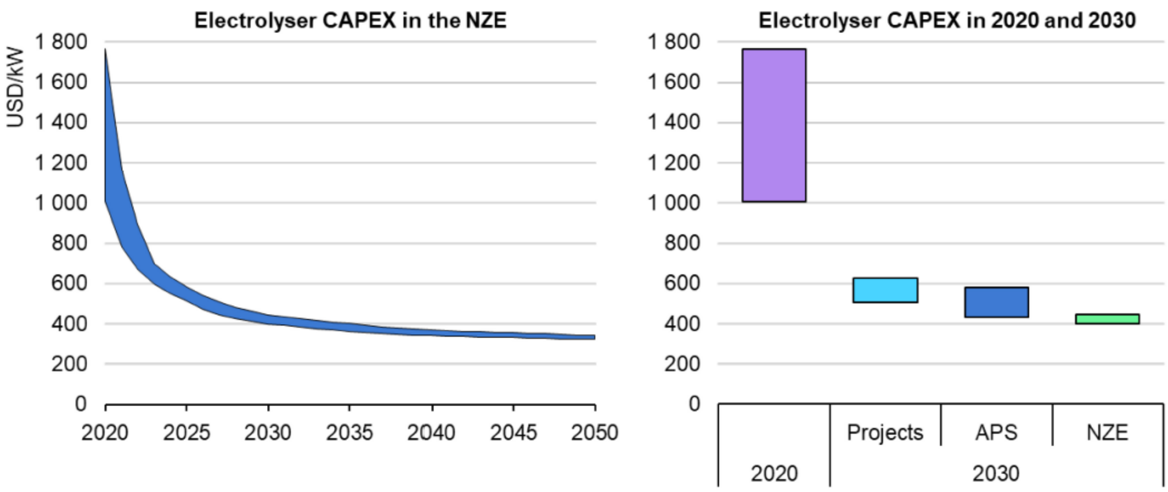


Figure 12: Evolution of electrolyser capital costs under the Projects case, Announced Pledges and Net-zero Emissions scenarios.

Source: Based on data from McKinsey & Company and the Hydrogen Council.

The demand for minerals, particularly nickel and platinum group metals, will be impacted by an increase in electrolyser output (depending on the technology type). Although alkaline electrolysis does not necessitate the use of precious metals, modern designs utilize 800-1000 t/MW of nickel. Even if alkaline electrolysis dominates the market by 2030, a nickel demand of 72 Mt would be required in the Net-zero Emissions Scenario (which is much lower than the amount needed for batteries).

PEM electrolysers need 300 kg of platinum and 700 kg of iridium per GW for their catalysts. As a result, in the Net-zero Emissions Scenario, assuming PEMs supplied all electrolyser production in 2030, demand for iridium would surge to 63 kt, nine times present global production. However, experts think that in the future decade, demand for both iridium and platinum can be cut by a factor of 10. PEM electrolyser cell recycling can help to lessen the primary demand for these metals and should be a key component of cell design.

Meanwhile, nickel (150-200 t/GW), zirconium (40 t/GW), lanthanum (20 t/GW), and yttrium (5 t/GW) are required for SOEC manufacturing. Better design is predicted to halve each of these quantities over the next decade, with the technical capability to reduce nickel concentration to below 10 t/GW. Mineral needs for SOECs are not directly similar to those for alkaline and PEM electrolysers due to SOECs' superior electrical efficiency.

Hydrogen is electrochemically converted into electricity using fuel cells. They're basically reverse electrolysers: instead of using water and energy to create hydrogen, they utilize hydrogen and air to create electricity and water. Both stationary applications, including large-scale power plants, and transportation applications (fuel cell electric cars, trucks, buses, forklifts, ferries, ships, and aircraft) can use fuel cells.

The fuel and electrolyte in fuel cells distinguish them. Fuel cells are available in six different types in the renewable energy sector today.

1) Proton exchange membrane fuel cell (PEMFC)

2) Alkaline fuel cell (AFC)

3) Phosphoric acid fuel cell (PAFC)

4) Molten carbonate fuel cell (MCFC)

5) Solid oxide fuel cell (SOFC)

6) Direct methanol fuel cell (DMFC)

They also work at different temperatures. Some of them operate at high temperatures (for example, MCFC and SOFC), whereas others operate at low temperatures (examples: PEMFC, AFC, and PAFC).

In the past, fuel cell electric vehicles and hydrogen refuelling stations have received the majority of policy support for hydrogen (IRENA, 2020b). The price of car fuel cells decreased by almost 70% between 2008 and 2020 (Kleen & Padgett, 2021), and more price drops are anticipated if production is scaled up. However, global fuel cell shipments have expanded at a rather slow pace. Globally, 1.3 GW of fuel cells was sold by 2020. The majority of the capacity was allocated to automobiles, buses, and trucks in Asia [see Fig 13 page 25]; in 2020, about 8000 FCEVs were sold (E4Tech, 2021). Despite being the biggest number ever, it pales in comparison to the 3 million electric automobiles sold worldwide in the same year (IEA, 2021e).

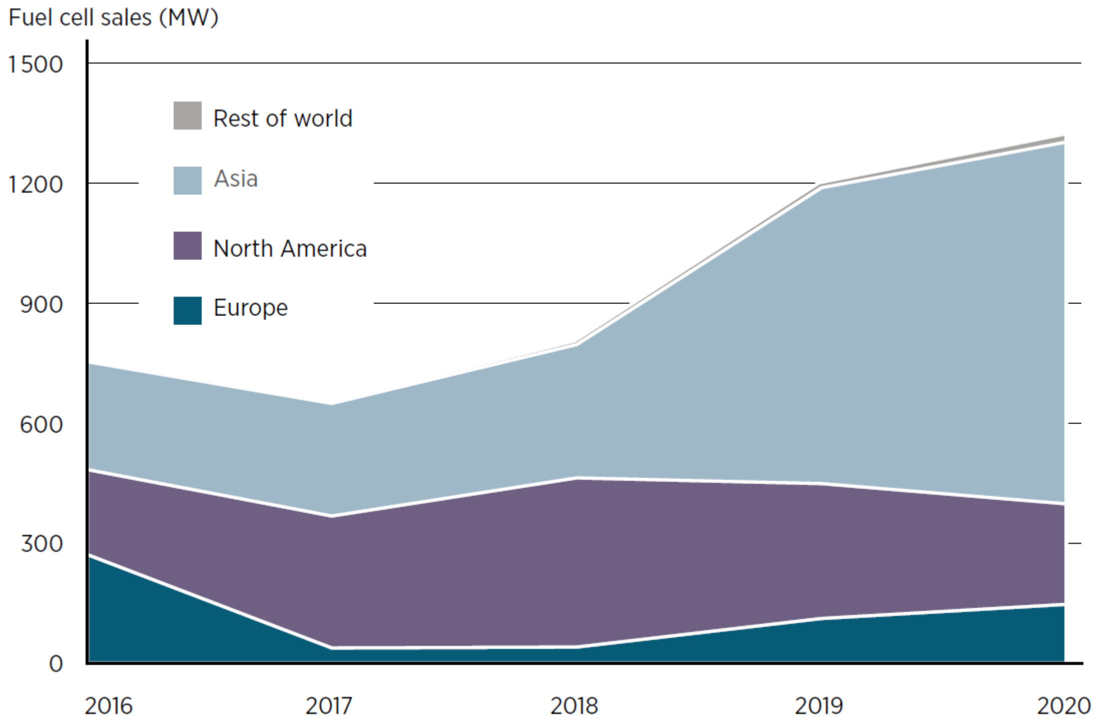


Figure 33: Fuel cell sales, by region of adoption, 2016-2020

Source: E4Tech (2021).

Nonetheless, numerous countries are moving forward with fuel cells in a variety of applications. As of this year, China is targeting deployment of 1 million FCEVs by 2030; Japan has installed 400 000 residential fuel cell systems, with a goal of 5.3 million by 2030; By 2040, South Korea intends to produce 15 GW of fuel cells, of which 7 GW will be exported. In Europe, a group of businesses hopes to put 100.000 hydrogen fuel cell heavy-duty trucks into service by 2030. California has set a goal of 200 hydrogen refuelling stations by 2025 (CARB, 2019), with vision documents predicting that by 2030, there will be up to 1000 such stations serving 1 million FCEVs (CACFP, 2018).

Fuel cells, in comparison to electrolysers, are still establishing their position in the energy transition. Fuel cell innovation could shift markets and focus on the next years. In any case, the market will most likely be less than electrolysers in terms of overall size.

Hydrogen can also add flexibility and resiliency to an energy system that is likely to become increasingly electrified over the next few decades. To determine the optimal ways to deliver hydrogen, careful planning is required. It can be deployed, for example, in regions with high shares of variable renewable energy sources and high levels of excess power that cannot be stored in batteries or transmitted through power lines (such as Northern Chile or offshore wind production in the North Sea) (IRENA, 2021b). Even though domestic electrolysis targets would advance energy security and industrial policy objectives, governments would want to avoid undermining climate mitigation goals or diverting attention from other priorities, such as universal access to energy.

The underlying competitive advantage of hydrogen is its prodigious capacity for long-term energy storage. As clean hydrogen replaces fossil fuels in some applications, hydrogen storage, like natural gas storage, might become more important for energy security in many areas. However, natural gas and hydrogen storage are not the same. Natural gas is mostly stored to satisfy demand fluctuations (seasonal). However, the hydrogen market is likely to be more stable, at least in the early years when industrial users are likely to make up most of the demand (primarily steel, ammonia, and high-value chemicals).

Because green hydrogen is produced using fluctuating renewable energy sources, hydrogen storage will be required mainly to address variations in supply rather than demand. This might be a basis for storing hydrogen near production facilities rather than demand centres. Having both production and storage in exporting countries could increase energy security concerns in importing countries that don't have the buffer capacity to deal with supply disruptions. The availability of adequate underground facilities will, of course, influence the actual location of storage locations.

Salt caverns are now seen to be the most promising method for long-term hydrogen storage. Those now used to store natural gas might be modified to store pure hydrogen. Due to hydrogen's lower energy density than natural gas, a modified natural gas storage site can only hold about 24% of the original energy quantities (GIE and Guidehouse, 2021). To put it differently, four times the amount of space is required to maintain existing energy storage capability. Only six salt caverns in the world have been used to store hydrogen: three in Teesside, United Kingdom, and three in Texas, United States. Accelerating geological storage of hydrogen requires careful planning because specific geological storage locations are likely to be used for storing methane, biomethane, or even CO2 throughout the transition and maybe in the long run.

Hydrogen can also help distant communities, like as settlements deep in the mountains or islands far from the mainland, become more resilient. These communities have particular problems in terms of energy security. Their electricity infrastructures are usually modest and rely on diesel generators for backup power, making them excessively reliant on external fossil fuels. Remote and isolated communities, on the other hand, enjoy some of the world's best renewable energy resources (IRENA, 2016a). Hydrogen (typically in combination with batteries) provides resiliency in this situation as well. For example, two water electrolysers on the small Scottish archipelago of the Orkney islands transform wind and tidal energy into hydrogen. The hydrogen is consequently used to heat and power local schools, harbour structures, ferries, and fuel-cell cars (FCH JU, n.d).

For the electrical sector, hydrogen-based fuels (such as ammonia and liquid organic hydrogen carriers) and hydrogen offer extensive and seasonal storage options. While significantly cheaper, these solutions have low round-trip efficiency (about 40%) as compared to batteries (approximately 85%), limiting their usage for long-term energy storage.

Salt caverns are already being used to store pure hydrogen underground due to their well-sealed nature and little chance of contamination. As an alternative, hydrogen-based fuels (such as ammonia) can be used as storage in places without access to salt caverns. Ammonia, which can be used in power plants when solar PV and wind energy decrease, can be produced from excess electricity.

Another possibility is big, refrigerated liquid ammonia tanks (e.g., 50-m diameter and 30-m height) commonly used in the fertiliser sector, which can store 150 GWh of energy, about equivalent to a city of 100,000 people's yearly electricity use. In the United Kingdom, Siemens tested the use of ammonia for electricity storage in 2018, utilizing electrolysis to transform wind electricity into hydrogen and subsequently into ammonia for storage. The stored ammonia was then used, to generate energy in an internal combustion engine.

Having hydrogen available for use as an energy vector could, like natural gas, improve overall energy system flexibility by balancing short-term supply variability and meeting seasonal demand swings, making energy supplies more secure. Low-carbon hydrogen deployment will need to be paired with the development of cost-effective, large-scale, and long-term storage systems in order to fulfil this function.

In 2020, global gas storage capacity was estimated to be >400 bcm (10 percent of total consumption), with porous reservoirs (depleted fields and aquifers) accounting for >90 percent of total storage capacity and the remainder in salt and rock caverns. In the Net-zero Emissions Scenario, the amount of hydrogen that has to be stored by 2050 might exceed 50 Mt (550 BCM), assuming that the worldwide demand for hydrogen reaches 530 Mt and that the storage-to-consumption ratio stays the same.

Hydrogen storage underground in salt caverns has been a proven method in the petrochemical sector since the early 1970s. Because large injection and withdrawal rates are achievable in salt caverns, storing hydrogen there can give short-term energy system flexibility. Their development, on the other hand, is dependent on geological conditions, such as the presence of salt deposits. Furthermore, the petrochemical industry's usage of subterranean hydrogen storage may have a different injection-withdrawal periodicity than other applications, which may require faster cycles.

In Europe, many pilot projects are being developed. The first cavern is anticipated to be operational in 2026 in the Netherlands, where testing for hydrogen storage in the borehole of a future cavern near Zuidwending began in August 2021. In Germany, EWE started construction of a smaller-scale salt cavern storage complex near Rüdersdorf in early 2021, with first test results expected in mid-2022. A rock cavern hydrogen storage facility is being built in Sweden, with pilot operations set to begin in 2022. In France and the United Kingdom, several pilot projects are in various phases of development.

The anticipated large-scale Advanced Clean Energy Storage (Utah) project in the United States is aiming for start-ups in the mid-2020s. Although there is no real-world experience with methane caverns being converted to hydrogen storage, it is anticipated that the process would take about as long as creating a brand-new salt cavern.

However, demonstration projects in Argentina (HyChico) and Austria (Underground Sun Storage project) show that they can store 10% hydrogen and 90% methane in porous reservoirs without harming the reservoirs or machinery. In geological storage, water aquifers are the least mature, and there is conflicting evidence regarding their suitability. Pure hydrogen must still be proven to be a cost-effective and viable storage medium in depleted reservoirs and aquifers. Further research will be needed.

Another potential big obstacle is public opposition based on reason to worry about subsidence and induced seismicity, both of which should be thoroughly examined to mitigate hazardous situations. Meanwhile, public concerns should be addressed by proper and transparent communication before large-scale storage site development starts.

Name	Country	Project start year	Operator/ developer	Working storage (GWh)	Type	Status
Teeside	United Kingdom	1972	Sabic	27	Salt cavern	Operational
Clemens Dome	United States	1983	Conoco Philips	82	Salt cavern	Operational
Moss Bluff	United States	2007	Praxair	125	Salt cavern	Operational
Spindletop	United States	2016	Air Liquide	278	Salt cavern	Operational
Underground Sun Storage	Austria	2016	RAG	10% H_2 blend	Depleted field	Demo
HyChico	Argentina	2016	HyChico, BRGM	10% H_2 blend	Depleted field	Demo
HyStock	The Netherlands	2021	EnergyStock	-	Salt cavern	Pilot
HYBRIT	Sweden	2022	Vattenfall SSAB, LKAB	-	Rock cavern	Pilot
Rüdersdorf	Germany	2022	EWE	0.2	Salt cavern	Under construction
HyPster	France	2023	Storengy	0.07-1.5	Salt cavern	Engineering study
HyGéo	France	2024	HDF, Teréga	1.5	Salt cavern	Feasibility study
HySecure	United Kingdom	mid-2020s	Storengy, Inovvn	40	Salt cavern	Phase 1 feasibility study
Energiepark Bad Lauchstädt Storage	Germany	-	Uniper, VNG ONTRAS, DBI Terrawatt	150	Salt cavern	Feasibility study
Advanced Clean Energy Storage	United States	mid-2020s	Mitsubishi Power Americas Magnum Development	150	Salt cavern	Proposed

Table 3: Existing hydrogen storage facilities and planned projects

Source: IEA (2021) Global Hydrogen Review

5.1.3 Main companies in the market

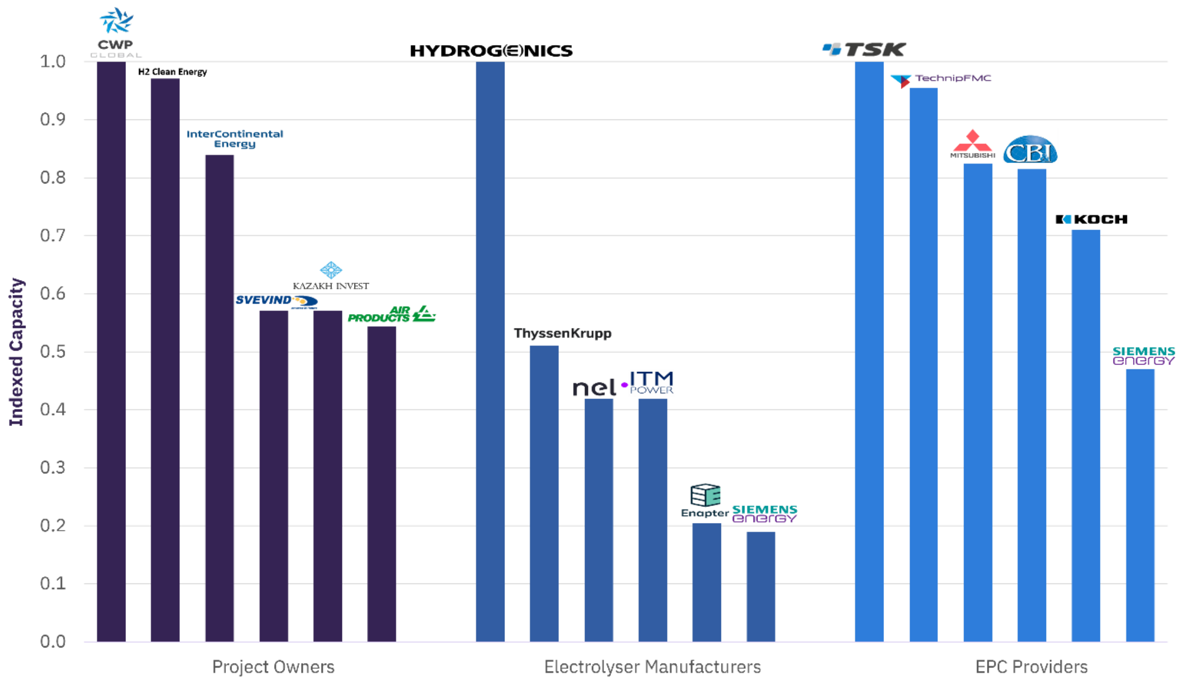


Figure 14: Green Hydrogen Leaders – Q1 2022

Source: GlobalData

Highlights:

- Green hydrogen pipeline capacity is presently at 38 mtpa, accounting for over 90% of the entire planned low-carbon hydrogen capacity. CWP Global, H2 Clean Energy, InterContinental Energy, Svevind, Kazakh Investment, and Air Products are the top firms aiming to build the most capacity.

- With electrolysis being the critical method for producing green hydrogen from renewable energy and 295 GW of electrolyser capacity on the way, manufacturers like Hydrogenics, ThyssenKrupp, Nel, ITM, Enapter, and Siemens Energy are leaders in winning work to deliver the capacity required.

- Many EPC contractors are looking to expand their position in this market as energy corporations take initiatives to benefit from a hydrogen economy. TSK, TechnipFMC, Mitsubishi, CBI, KOCH, and Siemens Energy are the main EPC companies for green projects.

The hydrogen economy is a critical area for growth. Many businesses scramble to seize this long-term vision and establish themselves as market leaders along the hydrogen value chain.

For a long time, hydrogen, particularly green hydrogen, has been a hot topic in the renewable energy industry. It is becoming a gamechanger with its significant contribution to renewable energy transitions, thanks to its critical applications across industries.

The momentum that has been developed along the entire value chain is speeding the cost reduction in hydrogen generation, transmission, distribution, retail, and end uses, thanks to strong investments from enterprises to develop green hydrogen projects. To decarbonize their business portfolios, several important firms have chosen to invest in potential green hydrogen projects as well as other components of the hydrogen economy, such as fuel cells and refuelling stations.

Last year, compared to 2020 levels, partnerships and collaborations between companies across several industries nearly tripled, allowing corporations to participate in many projects, ranging from pilot to large-scale projects.

Betting on green hydrogen development now will position companies as market leaders in the future, when the market matures. In addition to completing the energy transition, achieving the decarbonization goals, and establishing leading enterprises as industry authorities, the upcoming years will be necessary for developing a low-carbon hydrogen economy.

5.1.4 Regulations

Governments must take the lead in transforming the energy sector. The IEA listed several recommendations for immediate action in its report The Future of Hydrogen. The analysis goes into deeper levels on how policies might assist boost hydrogen's adoption as a clean fuel:

- Set targets and road maps for hydrogen's involvement in energy systems: Developing hydrogen strategies and road maps that include specific targets for low-carbon production and, particularly, stimulation of significant demand, is an important first step towards establishing stakeholder confidence in the potential market for low-carbon hydrogen. This is a critical first step in building momentum and attracting further funding to scale up and speed adoption.

- Create incentives for people to use low-carbon hydrogen instead of unlimited fossil fuels: Demand generation is falling short of what is expected to help the world achieve net-zero emissions by 2030. To successfully achieve hydrogen's potential as a clean energy vector, it is important to take more tangible steps in this direction. Hydrogen, including low-carbon, is currently more expensive than unabated fossil fuel hydrogen in areas where the fuel is already being utilized - and more expensive than fossil fuels in areas where the fuel could eventually replace fossil fuels. Carbon pricing is already being used in certain countries to close the cost difference, but it is insufficient. When paired with additional policy measures like auctions, mandates, quotas, and hydrogen requirements in public procurement, wider adoption can assist de-risk investments and enhance the economic feasibility of low-carbon hydrogen.

- Increase production, infrastructure, and factory investment: A demand-stimulating policy framework can encourage investment in low-carbon production facilities, infrastructure, and industrial capacity. This process, however, will not proceed at the necessary speed to accomplish climate targets unless more governmental action is taken. Through tailor-made support for shovel-ready flagship projects, low-carbon hydrogen can be scaled up as well as infrastructure to connect supply sources to demand centres and manufacturing capacities, which will ultimately benefit later projects. To avoid delays or the development of assets that could become stranded in the near or medium-term, proper infrastructure planning is essential.

- To ensure that key technologies achieve commercialization as quickly as possible and provide significant innovation support: Continuous innovation is required to reduce costs and improve the competitiveness of hydrogen solutions. Over the next decade, strong demonstration efforts will be required to unlock the full potential demand for hydrogen. To ensure that essential hydrogen technologies reach commercialisation as quickly as possible, an increase in R&D funds and support for demonstration projects is urgently required.

- Create suitable certification, standards, and regulatory frameworks: The adoption of hydrogen will lead to the emergence of new value chains. To remove the obstacles holding back wider adoption, current regulatory frameworks will need to be modified, as well as new standards and certification schemes. To ensure that hydrogen generation is truly low-carbon, international agreement on methods for calculating the carbon footprint of hydrogen production is essential. It will also be essential for the growth of a global hydrogen market.

Integrating hydrogen as a new vector into energy networks is a difficult task that will not be accomplished at the rate required to satisfy climate goals without government assistance. As a result, many governments are already collaborating with a wide range of stakeholders to address critical difficulties and develop wise policies to assist this transformation. Policies and actions must be based on applicable goals and limits, such as resource availability and existing infrastructure, because needs vary by country and industry.

The world that emerges from the transition to renewable energy would be substantially different from the world based on fossil fuels, the Global Commission on the Matters of Geopolitics of Energy Transition stated in its 2019 report (IRENA, 2019a). The exact scope and rate of the energy change could not be anticipated, according to the report. The rise of hydrogen is a good example of this. Only a few years ago, hydrogen was seen as a minor player in the global energy debate. It is now at the centre of decarbonisation initiatives for harder-to-abate sectors, with an increasing number of countries and industries counting on its universal adoption.

In many ways, the energy revolution is still in its development. The use of renewable energy is increasing, causing systemic changes. End-use electrification is already changing demand in terms of size and scope. The future function of hydrogen is unclear, as the majority of it is still produced using fossil fuels. Green hydrogen generation is expected to boom, but not just in today's oil and gas areas. As hydrogen markets grow, different economic, social, environmental, and geopolitical consequences may emerge. Despite a number of unknowns, hydrogen deployment should make significant progress by 2030 in the pursuit of a carbon-free energy system by 2050. Some of the things to consider in policymaking are discussed below.

1. Hydrogen development and deployment plans should not be pursued in isolation because it is part of a bigger energy transformation picture.

Countries should evaluate how hydrogen fits into their long-term economic, social, environmental, and political plans. As nations work to position themselves in the new energy economy, they must consider the state of their energy sector, their level of economic competitiveness, and any potential socio-economic implications of their choices. For example, a country with abundant renewable energy resources and inexpensive electricity may decide to use electrolysis to make green hydrogen affordable. In other circumstances, policymakers may find it more beneficial to concentrate on other technologies that support the energy transition (IRENA, 2020b).

Suppliers, supply channels, and the types of energy carriers that may be imported are all diversifying as a result of the energy revolution. Consequently, given the long-term nature of these decisions and the significant risks (and costs) of stranded assets, infrastructure plans and investments will need to be closely examined. Pipelines, for example, should be able to be repurposed to transport green gases like hydrogen and biomethane. The technical difficulties and financial expenses of such repurposing should be considered in from the start.

2. Setting the proper priorities for hydrogen use will be critical for its quick scale-up and long-term contribution to climate change efforts.

Global efforts should concentrate on applications that ensure the highest immediate benefits and allow for economies of scale, especially in the short term. Hydrogen trade will most likely be shaped in the early stages by bilateral agreements that carry the possibility of one or both parties defaulting. Prioritizing high-demand applications where hydrogen is obviously the best alternative is more cost-effective and less vulnerable to the uncertainties associated with emerging markets. Supporting and then speeding up the transition to green hydrogen in industrial applications where hydrogen is already used, such as refining and ammonia and methanol synthesis, is one example. (IRENA, 2020b).

Before diverting renewable energy to manufacture green hydrogen, it is prudent to examine the amount of electricity generated for productive purposes from renewable sources. (IRENA, 2020b). Otherwise, indiscriminate usage of green hydrogen could halt the energy transition by reintroducing fossil fuels into the mix. If countries prioritize the deployment of renewables for green hydrogen export, failure to observe the principle of additionality could suppress progress in expanding energy access to those who currently lack it.

3. To create a transparent hydrogen market with consistent standards and norms that contribute meaningfully to climate change efforts, international cooperation will be required.

Clean hydrogen could be a key piece of the deep decarbonisation puzzle, contributing to geopolitical stability by increasing positive economic and political opportunities for countries and regions while reducing climate risks and losses. However, if hydrogen plans prolong fossil fuel demand and supply while obstructing energy efficiency and electrification, there is a risk of carbon lock-in. To ensure that blue hydrogen makes a substantial contribution to decarbonisation, an agreed-upon threshold for carbon capture and methane emissions will be required.

The efficient functioning of a worldwide hydrogen market will require transparency in how emissions are calculated. The ability to develop consistent and transparent regulations, standards, and norms to allow clean hydrogen deployment across countries, regions, and industries is critical to the success of clean hydrogen markets. Shaping these may be a battleground for geopolitical competition, but strong international partnership and constructive political and economic involvement can gain a lot.

4. Supporting renewable energy and green hydrogen development in growing countries is crucial for decarbonizing the energy system and can help to ensure global equity and stability.

A wide hydrogen market would open up new trade and collaboration opportunities, minimize supply chain risks, and increase overall energy security. Countries' ability to convert renewable energy potential into energy production is reliant on their ability to manufacture required equipment and the intellectual property that supports innovation. Manufacturing capacity is currently concentrated in a few countries. As a result, most countries rely on equipment imports from a small number of locations. Future importers should foster diversification by allowing renewable-rich countries in the developing world to establish local value chains and job-creating green sectors in the interest of geopolitical stability and a just energy transition. The full potential of hydrogen to decarbonize the global energy system and contribute to global justice and stability will require access to technology, training, capacity building, and affordable funding.

5. Reduced unnecessary energy use across various end applications can be mitigated geopolitical concerns.

Making the transition to a truly sustainable sector involves not only switching energy sources but also determining how to use energy more efficiently and fairly. This entails minimizing needless energy usage across a wide range of final uses and shifting away from a consumer-driven system. Nations may manufacture hydrogen throughout the transition to a decarbonized energy system, for example, to strengthen national energy independence, although only a small number still supply resources. Mineral and metal bottlenecks can be addressed by innovation, efficiency, recycling, and a circular economy. However, in the long run, decreasing demand will be vital for material security.

6. To ensure positive, long-term outcomes, policymakers should take into account the broader effects of hydrogen development on sustainable development.

One of the root causes of geopolitical instability is the concept of "human security". According to the 2030 Agenda and the Sustainable Development Goals, the concept extends the security agenda to include poverty and disease as threats to peace and stability within and among countries. Depending on how it is produced, hydrogen could either have a beneficial or harmful effect on results for sustainable development. Hydrogen's water requirement, for example, is not generally viewed as a barrier to its deployment from a technical perspective. Nevertheless, climate change is expanding water risks at some of the most promising hydrogen production sites. We will be able to minimize or reduce some problems that could come along with the large-scale deployment of hydrogen by comprehending the diverse nature of global threats and vulnerabilities.

A new generation of hydrogen is on the horizon, and governments have a unique opportunity to direct it, avoid the flaws and inefficiencies of the current system, and shape geopolitical outcomes. Certain economic and political alliances and partnerships will be disrupted by hydrogen technology adoption. These technologies offer the opportunity if pursued with due care and caution, to demonstrate the positive aspects of disruption and enhance regional and national sovereignty, resilience, and cooperation. As the race for clean hydrogen accelerates, the experience of fossil fuel use may be instructive. A policymaker can also draw early lessons from pioneers in the hydrogen sector and incorporate their successful practices into their policies. A key element to navigating the unknowns, mitigating risks, and overcoming obstacles will be international cooperation.

5.2 Technology Applications

5.2.1 Industrial use

Although hydrogen is rapidly emerging as a viable alternative energy solution, these applications make up less than 10% of global hydrogen usage. The world is reconsidering how hydrogen is produced, transferred, and used as the hydrogen economy grows.

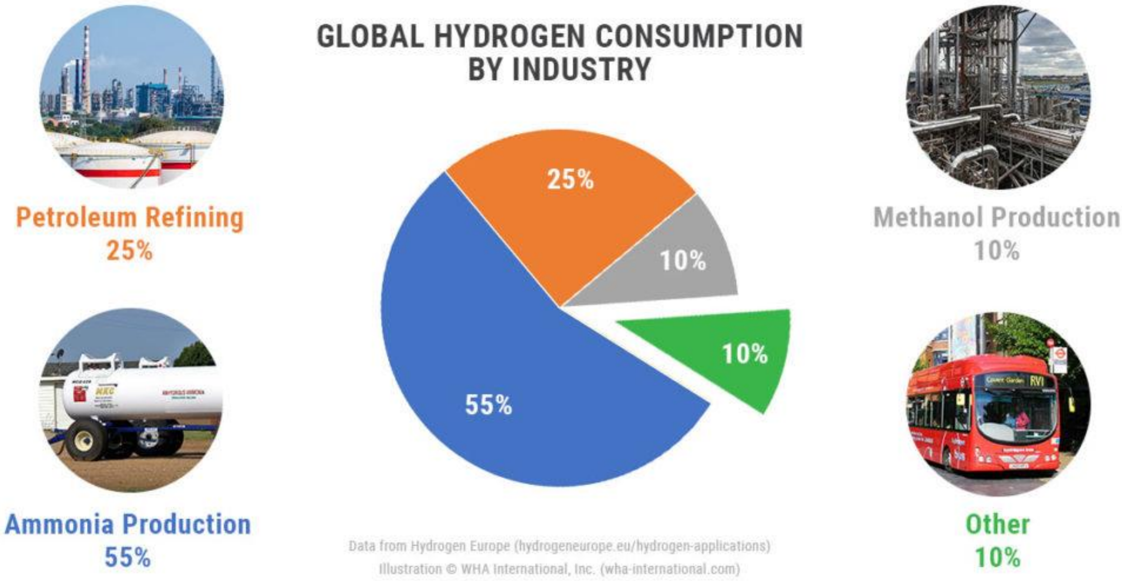


Figure 15: Global Hydrogen Consumption by Industry.

Source: Hydrogen Europe

Hydrogen is now considered a premium product, with produced purities of 99.999 %. Hydrogen has mostly been applied in the chemical and refining sectors for decades. End applications include:

Petroleum Refining Industry: Hydrogen is extensively utilized in the hydrocracking process to make petroleum products like gasoline and diesel. In the presence of hydrogen and a catalyst, hydrocracking takes heavier refinery products and fractures the large molecules into smaller ones (distillate like diesel or petrol). It's also used to get rid of impurities like sulfur and produce methanol (CH_3OH).

Agricultural/Chemical Industry: Ammonia (NH_3), also known as azane, is an essential component of fertilizers used in agricultural businesses all over the world. Hydrogen is a key raw element in the production of ammonia. The Haber-Bosch method, which involves the direct mixing of hydrogen and nitrogen at pressure and temperature in the presence of a metal catalyst, is the most used industrial procedure for producing ammonia today. Ammonia is a component of numerous household cleaning products and is used to make ammonium nitrate, a fertilizer. Ammonia is currently the leading application of hydrogen, second only to oil refineries. Ammonia is also a cost-effective and ecologically sustainable refrigerant (R-717).

Food: Unsaturated fats, like hydrogenated vegetable oils such as margarine and butter spreads, are converted to saturated fats and oils using hydrogen.

Metalworking: Hydrogen is employed in a variety of applications, including metal alloying and the production of iron flash.

Welding: A type of arc welding that uses a hydrogen environment is known as atomic hydrogen welding (AHW).

Flat Glass Production: In order to prevent oxidation and, consequently, manufacturing flaws, a mixture of hydrogen and nitrogen is used during manufacturing.

Electronics Manufacturing: Hydrogen is used to make semiconductors, LEDs, displays, photovoltaic modules, and other devices because it is an efficient reducing and etching agent.

Medical: Hydrogen peroxide (H_2O_2) is produced from hydrogen. Hydrogen gas has recently been explored as a treatment gas for a range of diseases. It is a powerful oxidizing agent that is very useful for cleansing wounds, cuts, and other injured tissue. Additionally, it is used to bleach hair, whiten teeth, and get stains out of clothes. H_2O_2 is also utilized in studies to evaluate the anti-oxidant capacity of enzymes like catalase.

Notable growth areas include:

Space Exploration: Since NASA's Apollo program, when it was initially utilized in the secondary stage of Saturn rockets, liquid hydrogen (LH_2) fuel has played a significant role in space exploration. United Launch Alliance, Boeing, and Blue Origin are among the government and commercial companies that are now using it.

Aviation: Hydrogen fuel cells have been deployed on many test flights for programs like the Pathfinder and Helios crewless long-duration aircraft. Airbus recently released ideas for "ZEROe" hydrogen-fuelled aircraft that use liquid hydrogen to power modified gas turbine engines.

Global Logistics: Several large warehouse and distribution corporations are using hydrogen fuel cells to power trucks, forklifts, and other equipment. Nikola Motors, Hyundai, Toyota, Kenworth Truck Company, and UPS all have high hopes for hydrogen-powered trucks, vans, and semis.

Backup Power Generation: Stationary fuel cells are implemented in uninterruptible power supply (UPS) systems at the local level, where uptime is crucial. Hospitals and data centres are turning to hydrogen to cover their uninterruptible power supply requirements.

5.2.2 Domestic applications

Space and water heating in buildings account for almost 55% of global energy use in buildings and 4.3 Gt CO2 emissions, consuming nearly 70 EJ. In buildings in very cold climates like Russia, the Caspian Sea, and Iceland, heating can make up more than 80% of the overall energy requirement. To decarbonize heating in buildings, enhancing the thermal performance of building envelopes and incorporating clean, efficient low-temperature equipment are top priorities. Heat pumps and clean district energy are two of the available choices for efficient heating currently available.

Hydrogen's potential in this sector is constrained by the exceptional efficiency of electricity-based solutions and the energy losses associated with converting and transporting it. PV-powered heat pumps, for example, use 5-6 times less electricity to deliver the same amount of heat as a boiler driven by electrolytic hydrogen. Furthermore, maintaining safe operations and transforming gas infrastructure is both financially and socially difficult.

Existing (old) multifamily buildings and very cold climates are in particular difficult to decarbonise, since integrating efficient low-temperature solutions is dependent on space availability, design of energy systems, and the building's overall performance, as well as logistical and economic costs for building occupants.

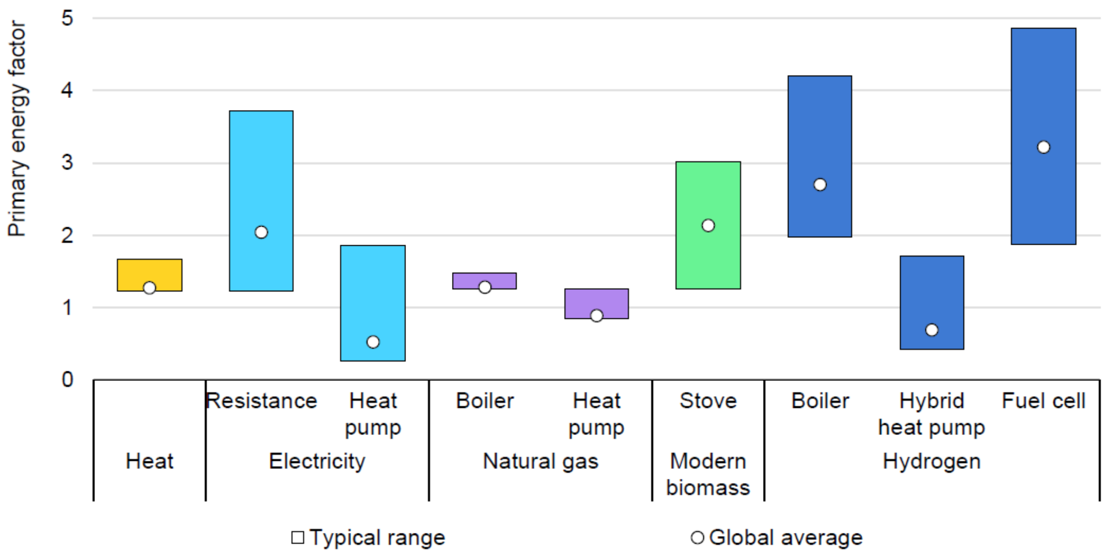


Figure 16: Primary energy factors of heat production by equipment and fuel, 2020.

Source: IEA (2021) Global Hydrogen Review

Localised hydrogen uses, however, could promote decarbonisation in very particular situations where gas infrastructure already exists, because hydrogen equipment is compatible with existing building energy systems. In addition to providing flexibility to the power grid, the cohabitation of hydrogen and other heat-generating technologies can also enable demand-side response, particularly in extremely cold areas where BEVs and other storage devices would probably fall short.

Natural gas, which now covers 35% of world energy demand for heating, can be combined with or replaced in part with hydrogen. Depending on the region, such blending (around 5-20 percent) can take advantage of existing natural gas infrastructure without requiring large network changes.

Blending hydrogen at 20% would only reduce carbon intensity by 7%, well short of the level required for long-term decarbonization of the building sector. It would also have an impact on end-user fuel prices. While decarbonizing existing hydrogen consumption is still a goal, blending alternatives could help ensure low-carbon hydrogen demand.

In the long run, hydrogen-specific infrastructure might be developed (either by creating new networks or upgrading existing ones) to further the substitution of natural gas. Equipment for space and water heating will also need to be improved or replaced and then tested for performance.

It takes about five days to adapt a building's energy system, and deployment of hydrogen technology must be precisely targeted to situations where it is cost-effective compared to alternative possibilities.

At the building level, four primary types of technologies can work on hydrogen:

- Because consumers are familiar with the basic concept and its upfront capital requirements, hydrogen boilers can be practicable where gas networks exist. However, the increased fuel consumption of this option compared to more efficient technologies makes it less appealing for most buildings in the long run.

- Solid oxide fuel cells (SOFCs) and polymer electrolyte membrane fuel cells (PEMFCs) are examples of fuel cells that produce both heat and electricity. When compared to PEM cells, which operate at a lower temperature (60-80°C) on periodic load schedules, but offer poorer electrical efficiency, SOFCs demand a higher temperature but also give a more stable load. Because SOFC efficiency suffers when run with pure hydrogen, optimizing the system layout to solve this problem is a major research target. Micro-cogeneration units have an electrical efficiency of 35-60% for SOFCs and 35-38% for PEMFCs, according to field testing carried out in Europe in the field of natural gas, with corresponding cogeneration system efficiencies of 80-95% (SOFCs) and 85-90%. (PEMFCs).

• A boiler is combined with an electric heat pump in hybrid heat pumps. The boiler comes on only when the heat pump cannot meet the heating demands. Hybrid heat pumps are an appealing choice in cold locations where hydrogen can be utilized to replace peak demand during extremely cold periods, but they come with higher upfront costs and need both electricity and hydrogen connections.

• Heat pumps driven by gas employ a gas engine to produce energy. Thousands of units, mostly in non-residential buildings, are already in use in Asia and Europe.

Status of hydrogen and fuel cells for buildings

Even though countries began financing demonstration projects and programs to deploy hydrogen-compatible technology, spark market acceptance, and cut upfront consumer prices as early as the 2000s, hydrogen's share of heating energy consumption was extremely small (less than 0.005 percent) in 2020. These programs, which have primarily focused on stationary fuel cells and employed natural gas, can also be applied to pure hydrogen. These projects are located in countries that collectively cover 40% of global heat demand, have significant heating seasonality, and where natural gas accounts for a large portion of building heat output.

Stationary fuel cells

The largest number of micro-cogeneration stationary fuel cells (*1 kW of energy output per unit of resistance [kWe] for residential applications, and up to 5 kWe) have been deployed in Japan (over 350 000 units) and Europe, especially in Germany (15 000), Belgium and France. According to CEM H2I studies, Korea has 15.7 MWe (units of 100 kWe) installed in houses, but the US has mostly industrial-scale units (>100 kWe).

Fuel cells have been used to supply primary or backup power or co-generation in practically all building types, from residential to commercial/public building uses, including military sites, hospitals, and data centres. Most run-on natural gas. PEM fuel cells are most commonly used in residential applications, and they are typically small (0.7-1.5 kWe, sometimes up to 5 kWe), with several governments providing financial incentives to encourage their adoption.

When installing residential units bigger than 0.5 kWe, US homeowners may qualify for federal tax credits (over USD 3 300/kWe). Other government programs, such as New Jersey's Clean Energy Program for micro-cogeneration technology, provide subsidies for fuel cell technologies. Korea is one of the countries that subsidizes renewable energy certificates. Support typically covers installation expenses or rewards power generation rather than heat generation.

Hydrogen blending and pure hydrogen applications.

Around the world, many projects are in various stages of development to look into the impact of hydrogen blending on present gas networks. The frontrunner, which debuted on the Dutch island of Ameland in 2007, tested injection volumes of up to 20% for heating and cooking with standard appliances. In France, the GRHYD project evaluated injection (max. 20%) for >100 residences from June 2018 to March 2021, while the three-phase UK HyDeploy project intends to verify the safety of blending up to 20%. The first phase, which ended in 2021, featured a real demonstration in the Keele gas network to determine how much blending is safe with existing household appliances.

Other projects, mainly in north-western Europe, are also in the works to show hydrogen use in dedicated networks in a few hundred homes. H100 Fife in the United Kingdom (300 households starting in 2022), and Hoogeveen and Stad aan 't Haringvliet in the Netherlands (600 households starting in 2025). Larger projects, like H21 in the United Kingdom, are still in the planning stages.

The Hy4Heat project, which examines the technological, economic, and safety issues of substituting natural gas with hydrogen in residential and commercial buildings and gas uses, is also supported by the UK government. A Worcester Bosch 100% hydrogen-ready prototype boiler received Best Heating Innovation in the 2021 Green Home Awards under this program, which can be converted to run on hydrogen by altering just two or three components.

In the first trial in single-family, semi-detached, and terraced homes, the investigation found that utilizing 100 percent hydrogen for heating and cooking is as safe as using natural gas. More research is needed to determine the safety of providing homes through gas networks, as well as multi-family residences and houses with limited natural ventilation. The initiative is also evaluating the first hydrogen-powered home (in Low Thornley, Gateshead), from boilers to cookers.

WaterstofWijk Wagenborgen is a pilot project in the Netherlands that will connect 1970s houses to a hydrogen network. Wagerborgen hybrid heat pumps will be put in each house, running on electricity as much as possible and switching to hydrogen exclusively during cold months; solar panels and induction cooking will also be installed.

Region	Share of global heating consumption (%)	Share of water heating in heating consumption (%)	Share of natural gas in:		Initiative details
			Heating (%)	Cooking (%)	
United States	17	19	65	60	New Jersey's Clean Energy Program provides financial incentives for co-generation and fuel cell installations.
United Kingdom	2.5	21	70	50	HyDeploy for hydrogen blending applications. H21 Leeds City Gate and H21 Network innovation for 100% hydrogen application. Hy4Heat project.
Korea	1.5	22	48	63	Announced intentions to create three hydrogen power cities by 2022, in line with hydrogen roadmap goal of providing households and other buildings 2.1 GW of power from fuel cells.
European Union	15	20	40	32	Ene.field project, Europe-wide field trials for residential fuel cells, concluded in 2017. PACE (Pathway to a Competitive European Fuel Cell micro-Cogeneration Market), ends in 2021. ComSos, (Commercial-scale SOFC systems), ends in 2022. National innovation Programme for hydrogen and fuel cell technology (Germany), 2007-16. KfW433 (Germany), dedicated fuel cell programme since 2016; overall impact: >15 000 fuel cells deployed in EU. GRHYD (France): power-to-gas testing with hydrogen blending rates of up to 20% per volume, 2018-21. WaterstofWijk Wagenborgen planned project (Netherlands): demonstration project for hybrid heat pumps for 40 residents.
Japan	3	35	32	39	Ene.Farm project, >350 000 commercial fuel cells deployed.

Table 4: Natural gas use in the buildings sector and selected key projects, initiatives, programmes, announcements for deploying hydrogen or hydrogen-compatible equipment by country or region, 2020.

Source: IEA (2021) Global Hydrogen Review

5.2.3 Mobility

By the end of June 2021, there were more than 40 000 FCEVs on the road around the world. Stocks increased at a 70% annual rate from 2017 to 2020. However, stock growth slowed to 40% in 2020, and the number of new fuel cell vehicle registrations fell by 15% (10,000 new vehicles), matching the general decline in the auto market brought on by the Covid-19 epidemic. However, over 8000 FCEVs were purchased in the first half of 2021, with monthly sales in California (759 in March) and Korea reaching new highs (1 265 in April).

Passenger light-duty vehicles (PLDVs) have accounted for the majority of global FCEV deployment, accounting for 74% of registered FCEVs in 2020. Hyundai NEXO, Honda Clarity14, and second-generation Toyota Mirai are the three commercial fuel cell PLDV vehicles on the market, with other original equipment manufacturers (OEMs) declaring plans to launch variants in the next years.

Despite being deployed earlier and having a bigger number of fuel cell types (12, according to Calstart's Zero-Emission Technology Inventory tool), buses account for only 16% of total FCEV stock. Nearly 95% are in China, which has also taken the lead in the deployment of fuel cell trucks, with over 3100 in service by 2020.

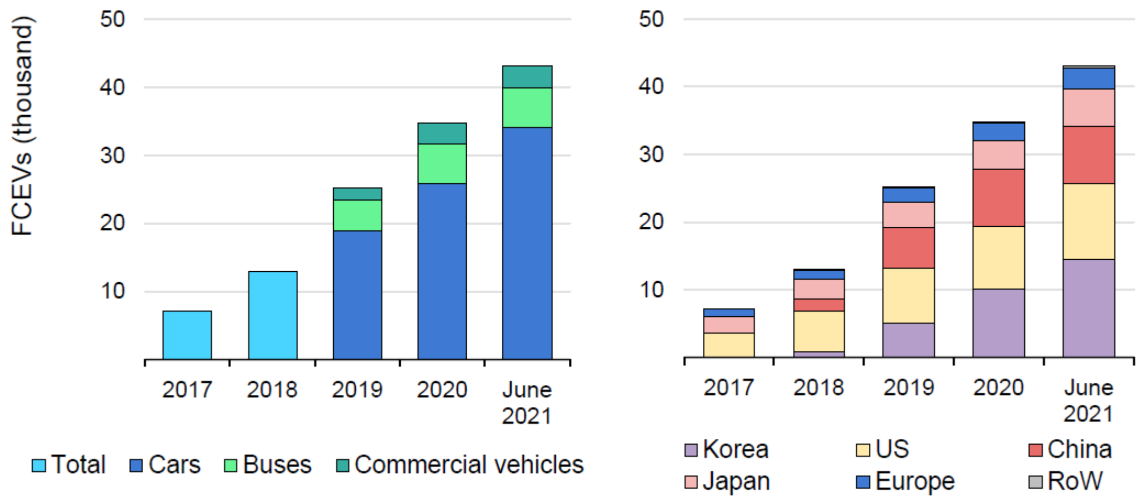


Figure 17: Fuel cell electric vehicle stock by segment and region,2017-June 2021.

Source: IEA (2021) Global Hydrogen Review

There are now just five fuel cell truck models available, but 11 are projected by 2023. With a focus on long-haul trucking, among other uses, Cellcentric, a joint venture between Daimler Truck AG and Volvo Group, will research, manufacture, and market fuel cell systems. Both businesses joined the H2Accelerate agreement to roll out large-scale hydrogen trucks in Europe, along with IVECO, OMV, and Shell.

Although less ready technologically than hydrogen fuel cells, some OEMs, like Cummins and MAN, are developing and testing prototype hydrogen-fuelled internal combustion engines for commercial vehicle use.

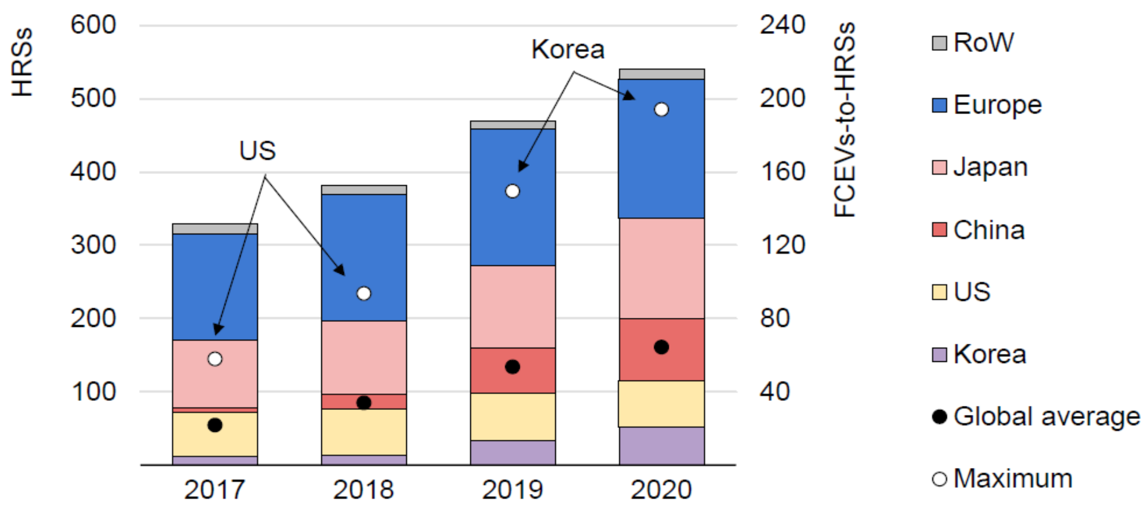


Figure 18: Hydrogen refuelling stations by region and ratio of hydrogen refuelling stations to fuel cell electric vehicles, 2017-2020.

Source: AFC TCP Deployment Status of Fuel Cells in Road Transport: 2021 Update.

Compared to FCEVs, the number of hydrogen refuelling stations (HRSs) is growing more slowly, with an average annual increase of over 20% between 2017 and 2020. As a result, especially in areas where FCEV sales are the highest, the ratio of FCEVs to HRSs is increasing. In 2020, this ratio in Korea was about 200:1 and in the US was 150:1, compared to only 30:1 in Japan. This is due to surplus HRS capacity, as stations are planned with FCEV development in mind.

The capacity of recent stations is higher than that of original ones. California unveiled a 1200 kg/day station in 2020 and announced financing for up to 1620 kg/day stations, which is 2.5-3.5 times the average station capacity funded since 2012. The world's largest hydrogen station, with a daily capacity of 4,800 kg, was inaugurated in Beijing in July 2021.

The refuelling pressure at each station varies depending on the vehicle market served. To serve fuel cell cars, most stations in most countries deliver hydrogen at 700 bars. In China, most stations serve bus and truck fleets with 350 bars. Station and component design, as well as fuelling protocols, are now being worked on to enable high throughput dispensing for vehicles with 700-bar internal storage, which will support a range of 800 km, nearly double that of current fuel cell trucks (400 km). To enable vehicle ranges of more than 1000 km, businesses including Daimler, Hyzon, and Chart Industries are investigating internal liquid hydrogen storage and refuelling.

5.2.4 Sector coupling

The concept of "sector coupling" (or "sectoral integration") was created in Germany to address the problem of rapid decarbonization in the electrical sector but slower decarbonization in other sectors (buildings, transportation, and industry). Sector coupling is described as "a strategy to provide greater flexibility to the energy system so that decarbonization can be achieved more cost-effectively" by the European Commission (DG Energy). Sector coupling aims to replace fossil fuels in many applications with decarbonized electricity or energy carriers derived from decarbonized sources. End-use sector coupling and cross-vector integration are the two main ways.

End-use sector coupling refers to the electrification of end-use sectors on a broad scale. Most studies agree that in a decarbonized energy system, carbon-free electricity will play a larger role. End-use sector coupling attempts to electrify as many industries as possible that now rely on fossil fuels (transport, heating and cooling, industrial processes). This might be achieved in the transportation industry by using electric and hydrogen-powered vehicles and a modal shift from road to rail transit. Electric heat pumps can be used to replace fossil-fuel furnaces in the heating sector. The cost of energy generation, storage, and extension of the electricity transmission and distribution networks to handle increased demand and demand peaks would all increase as a result of this proposal, as would the cost of electric vehicles, heat pumps, and other electrical end-use equipment.

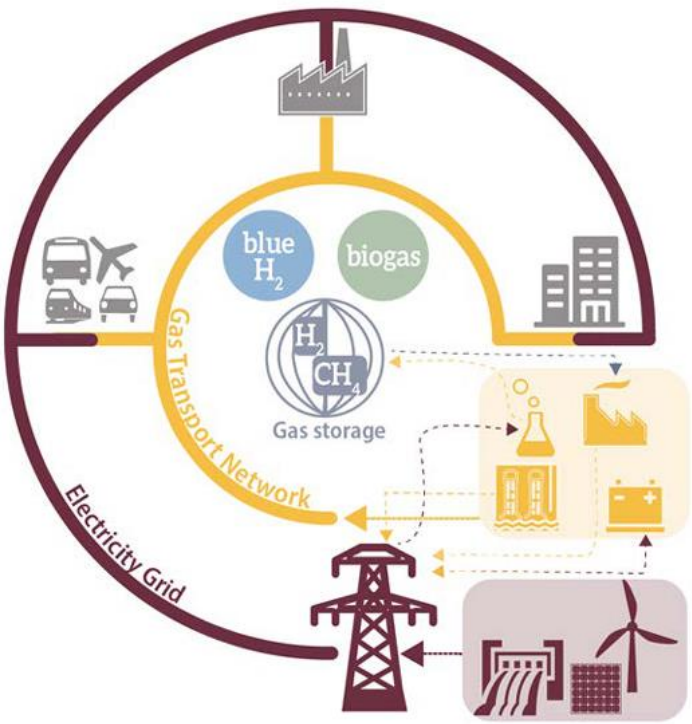


Figure 19: Sector Coupling.

Source: European Parliament, EPRS.

Sector coupling involves:

- Using the electrical grid to electrify transportation, industry, and homes,
- Gas production from renewable energy sources, such as hydrogen (H2) and methane (CH4),
- Energy storage in the form of pumped hydro, batteries, and gases (H2 and CH4),
- Renewable gas supply to end-use sectors, and
- Fuel cells and thermal power plants generate electricity from hydrogen and gas.

Cross-vector integration, often known as 'power-to-X,' entails using electricity to generate heat, gaseous, or liquid energy carriers for usage in end-use industries. The utilization of electricity to generate heat, hydrogen, and other gaseous and liquid fuels is part of this strategy. Electrolysers, fuel cells, hydrogen storage, transportation, and conversion of end uses, such as steel production, to utilize hydrogen instead of fossil fuels would all result in increased expenses. However, using the current gas transportation and storage infrastructure would require less extra funding. End-use sector coupling would need less investment in electricity production capacity, transmission, and storage. The present gas grid might be converted to hydrogen, either by mixing hydrogen with natural gas or by totally replacing it. In a few EU countries, hydrogen can currently be mixed with natural gas (Belgium, Denmark, Germany, the Netherlands, and the UK). The conversion of gas transportation and storage infrastructure will take a significant investment. Experts believe that each of these techniques will play an essential and complementary role in a future low-carbon economy, but there is a dispute on how best to combine them.

Transport.

The transport sector in the EU is still heavily reliant on fossil fuels, which have a high energy density and are easy to move and store. Transportation electrification (using low-carbon electricity) is one way to reduce emissions in this sector. This can be accomplished by switching to already electrified forms of transportation (such as trains) and electrifying vehicles. Heavy-duty vehicles (trucks and buses) are more difficult to electrify than light-duty vehicles (cars and vans) due to the weight and volume of the batteries. Another option is to use renewable hydrogen in conjunction with an electric engine powered by a fuel cell. This would also work for non-electrified train lines and heavy-duty transport. Other gases or liquid fuels derived from renewable sources (e.g., methane, methanol) may also be useful. In addition to reducing greenhouse gas emissions by combining biofuels with internal combustion engines, biofuels remain an issue in terms of their sustainability (the Renewable Energy Directive specifies sustainability criteria for biofuels in terms of GHG reductions against fossil fuels, and measures are taken to ensure the environmental sustainability of biofuel production). Liquid jet fuel derived from renewable sources is currently preferred for aviation because batteries are too heavy for planes. Batteries are being employed for short travels (e.g. ferries) in the maritime industry, while renewable gas appears to be better suitable for longer distances.

Heating and Cooling

While most cooling in the EU is done using electricity, the majority of heating is done with fossil fuels (primarily gas, with heating oil and coal playing a decreasing role) or biomass (mostly wood). Heat pumps are a cost-effective technique for electrifying the heating industry. They capture heat from the outdoor air or groundwater to attain great efficiency. When power is available and cheap, heat pumps and electric water heaters can be used to store energy in thermal form for later consumption. Converting renewable electricity into gas for heating allows for indirect electrification of the heating sector. This method requires minimal power system expansion, and the energy may be stored for extended durations in existing gas storage facilities. This would close the gap between the summer months, when solar electricity is available, and the winter months, when heating energy demand is highest.

5.3 Logistics

5.3.1 Pipeline / Storage Infrastructure

Hydrogen is now primarily a regional industry. Around 85% of hydrogen gas is produced and consumed on-site rather than purchased and sold on the open market (IEA, 2019a). Even where hydrogen is marketed, logistical challenges and high prices prevent it from being delivered across long distances.

Hydrogen could become a globally traded commodity in the future. The green variety adds to the ability to "ship sunlight," or transfer solar and other renewables across national borders. The cost of electricity is the single most expensive component of producing green hydrogen (IRENA, 2020a). The price of hydrogen will vary significantly depending on the levelized cost of renewables in each region. In areas with the most favourable ratio of abundant renewable resources, available land, water, and the capacity to transmit and export energy to important demand centres, green hydrogen will be produced most affordably.

Pipelines and ships are the two main techniques of delivering hydrogen across borders. The cheapest option is determined by distance and volume [see Fig. 20 page 48]. Pipelines, for example, could be less expensive than ships for short distances below 1500 km (e.g., 0.3 million tonnes of hydrogen per year). A newly built hydrogen pipeline would be most cost-effective for transporting large volumes (e.g. 1.5 million tonnes of hydrogen per year) over distances up to 4,000 km. When repurposed natural gas pipelines are used, the cost-effective range can be extended to 8 000 kilometres. To put some of these distances in context, a pipeline between Windhoek, Namibia, and Johannesburg, South Africa, would be around 1500 kilometres long. A pipeline of around 4000 kilometres would be required to connect Toronto, Canada, with Mexico City, Mexico. The distance between Chile and Japan is nearly 17,000 kilometres.

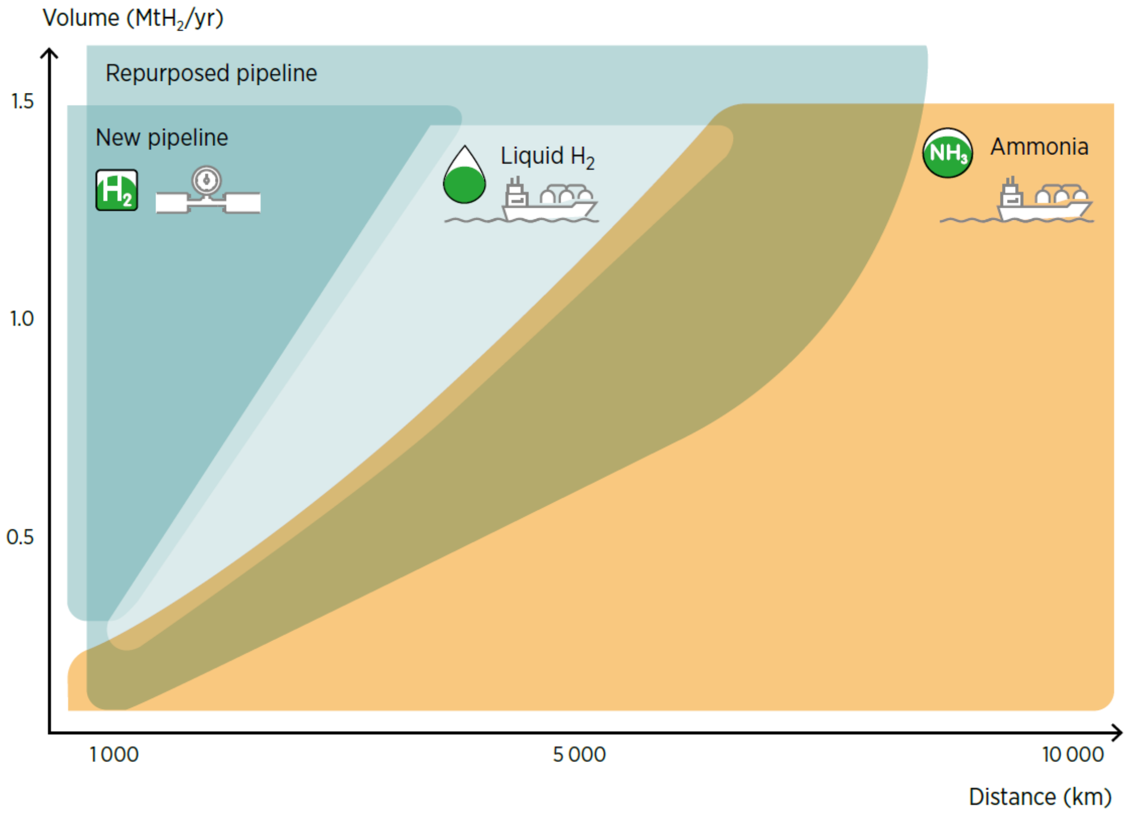


Figure 20: Cost efficiency of transport options when considering volume and distance.

Source: IRENA (forthcoming-a)

In north-western Europe, the Russian Federation, and the United States of America, there are approximately 4 600 km of specialized hydrogen transmission pipelines in operation. Trunk pipeline systems termed the "hydrogen backbone," are being developed throughout Europe (Gas for Climate, 2021a). It's also possible to send renewable electricity via wires and convert it to hydrogen at the other end. Several factors influence whether a pipeline or a cable is the best option, including the end product, terrain topography, and distance.

For longer distances where pipelines are not a possibility, hydrogen delivery by ship is technically viable. Gaseous hydrogen is typically transformed into a more energy-dense liquid before being put on board a ship due to its low energy density by volume. There are various options for shipping hydrogen, but ammonia is the most promising. It is already a globally traded commodity, with 18 million tonnes traded in 2020 (about 10 percent of global production) (Atchison, 2021).

Hydrogen transportation costs are currently expensive, but because of economies of scale, lower project risks, and technological advancements, they are expected to fall. Because blue hydrogen has fewer production costs and can use existing gas infrastructure, it might be scaled up much faster than green hydrogen. Green hydrogen trade is predicted to expand by 2030 as economies of scale improve and enabling legislation is implemented, lowering manufacturing costs.

According to IRENA, by 2050, roughly a third of green hydrogen will be transferred across borders (IRENA, forthcoming-a). This percentage is slightly higher than the current global share of natural gas traded (24%). In 2050, pipelines will likely carry around half of the hydrogen trade, including repurposed natural gas pipes that already exist. The remaining half would be carried as ammonia by long-haul ships. This position is similar to that of natural gas, which is divided between regional pipeline-based commerce (which will account for 48% of total trade in 2020) and global LNG trade (52%) (BP, 2021). Countries are already in the process of forming bilateral agreements that could set the way for new hydrogen trade relationships [see Fig. 21 page 49].

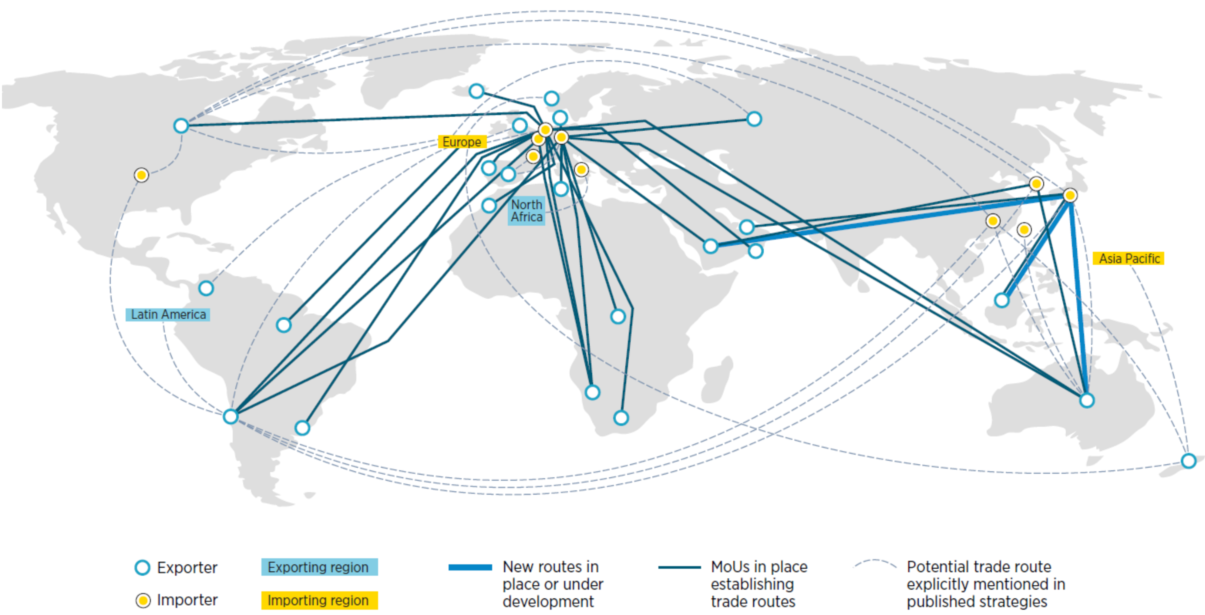


Figure 21: An expanding network of hydrogen trade routes, plans and agreements.

Source: IRENA (forthcoming-a). Map source: Natural Earth, 2021

Energy relations are likely to become regionalized, resulting in a shift in the geopolitical landscape. Renewable energy could be provided in every country, with renewable electricity being exported via transmission connections to neighbouring countries. Clean hydrogen could also make it easier to transport renewable energy across vast distances via pipelines and shipping, potentially uncovering previously untapped renewable resources in some far places. However, transportation costs are expected to create a dual market for hydrogen: a regional market for ammonia, methanol, and other liquid fuels, and a global market for ammonia, methanol, and other liquid fuels. To put it another way, hydrogen could wind up in a market that is more diversified and regionalized than the oil and gas markets.

Hydrogen is currently used mostly in industrial coastal zones, which are home to many of the world's refineries and chemical plants. These ports are perfect springboards for accelerating clean hydrogen scale-up. They may eventually grow into import or export centres, as well as bunkering fuel storage facilities for the maritime sector. These ports, as well as other regions with concentrated industries throughout the hydrogen value chain (known as "hydrogen valleys"), may eventually be connected by hydrogen transportation lines. The ports might also serve as hubs for a network of hydrogen recharging stations that stretches along major freight routes.

Some current natural gas transmission pipelines could be reused to carry hydrogen (with technological adjustments). The diagram of the current natural gas transmission networks, even with green hydrogen [see Fig. 22 page 51] indicates where possible cross-border links may remain. Natural gas pipelines clearly do not reach all parts of the world equally. The dense pipeline networks in East Asia, Eurasia, and North America contrast sharply with the sparse networks on other continents, and the near-complete absence of pipeline infrastructure in Sub-Saharan Africa. Africa's tremendous renewable potential, on the other hand, uncovers possibilities for the continent's transition to a net-zero world.

No energy infrastructure choice should be made without taking into account the likelihood that the geography of infrastructure in a decarbonized economy will be considerably different from what it is now. On the supply side, for instance, it is conceivable that locations other than the current oil and gas resources will produce renewable hydrogen (Muttitt et al., 2021). Significant electrification of end-uses, on the other hand, will change demand in terms of size and scope. Because every new investment decision has a long lifespan, permanent pipeline infrastructure should be evaluated using a logic that is future-proof. Any gas pipeline infrastructure created today, for example, should be able to be "repurposed" to carry clean gases like hydrogen and biomethane. Technical obstacles and economic expenses accompany such repurposing, all of which must be considered into investment planning.

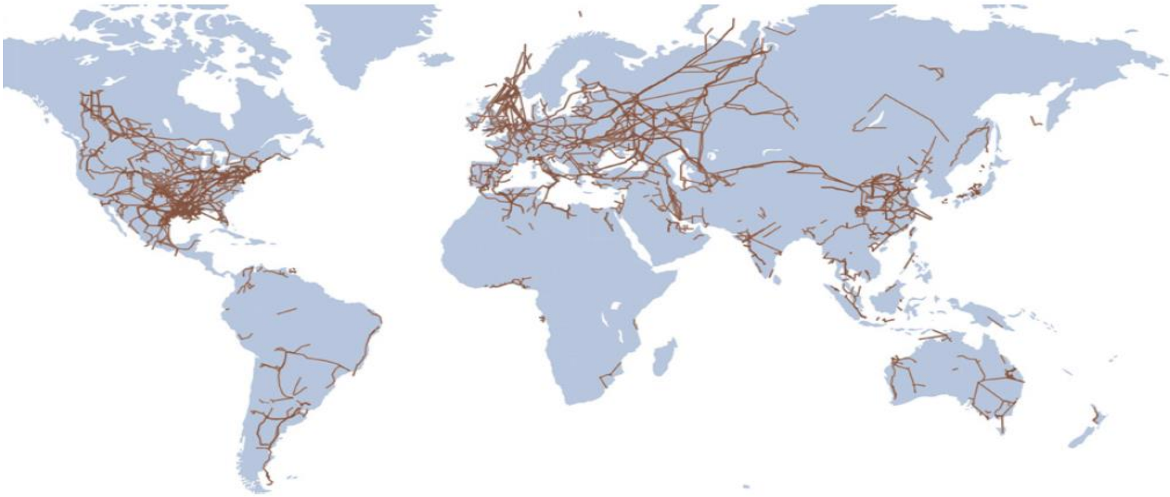


Figure 22: Global map of natural gas transmission pipelines.

Source: GreenInfo Network and Global Energy Monitor (2021). Map source: Natural Earth, 2021.

Hydrogen trade opens up new regional and cross-regional collaboration options. Regional hydrogen trade could be facilitated between Europe and North Africa (van Wijk and Wouters, 2021), Australia and the Indo-Pacific (Bowen, 2021), or even across the African continent.

Hydrogen may also influence future maritime trade routes. International value chains and shipping routes are already being planned by some corporations and governments. In December 2019, a tanker carrying hydrogen produced in Brunei and transformed into methylcyclohexane set sail towards the Japanese port of Kawasaki City, marking the world's first transoceanic shipment of hydrogen. The "Suiso Frontier," the first dedicated hydrogen tanker for testing shipments of liquid hydrogen from Australia to Japan, was launched in the same month by Kawasaki Industries. The first shipment of "blue ammonia," created from hydrogen, was sent from Saudi Arabia to Japan in September 2020, where it was utilized to generate power. These pilots and demonstration projects point to the start of a new era in the energy industry.

5.3.2 Transport

With oil products providing 90% of the necessary energy, the transportation sector is responsible for almost 20% of global GHG emissions and 25% of total energy consumption. To date, hydrogen has been used rarely in the sector, accounting for less than 0.01 percent of total energy consumption. Nonetheless, hydrogen and hydrogen-based fuels have the potential to reduce emissions, particularly in hard-to-electrify transportation segments (e.g. long-haul, heavy-duty trucking, shipping, and aviation).

In the Announced Pledges Scenario, hydrogen and hydrogen-based fuel use in transportation will reach 520 PJ in 2030, accounting for 0.4 percent of total transportation energy demand. As the stock of fuel cell vehicles grows to over 6 million, over 60% of this demand is for road vehicles. Shipping accounts for over a fifth of total demand, with hydrogen and ammonia accounting for 1% of total shipping fuel usage in 2030. Similarly, about 1% of rail energy usage is accounted for by hydrogen and synthetic fuels. In aviation, the utilization of hydrogen-based synthetic fuel remains limited, accounting for less than 1% of total consumption. Requirement for hydrogen and hydrogen-based fuels across all transportation end-uses is expected to be almost 15 times higher by 2050 than it was in 2030, supplying 6% of the sector's energy demand.

The deployment of hydrogen and hydrogen-based fuels is increased in the Net-zero Emissions Scenario, and demand reaches 2.7 EJ in 2030, accounting for 2.6 % of transportation energy consumption. As in the Announced Pledges Scenario, road cars account for the majority of demand (almost 45%). In 2030, hydrogen will account for about 2% of total fuel use in shipping, while ammonia will account for nearly 8%. In the Net-zero Emissions Scenario, synthetic fuels account for 1.6 % of aviation fuel use in 2030. In this scenario, hydrogen and hydrogen-based fuels will meet more than a quarter of overall transportation energy demand by 2050.

Heavy-duty vehicles (HDV) are ideal candidates for fuel cell applications because their electric motors produce more torque while using significantly more power than passenger vehicles. Fuel cell heavy-duty trucks have only lately begun to be used globally. China will demonstrate 500 FC trucks soon, while procurements in the United States have reached 800 trucks, with plans to increase the fleet. Toyota has completed a prototype hydrogen fuel cell truck using Mirai technology and is now working on the next generation. In Europe, the FCH 2 JU project REVIVE is procuring a fleet of 15 waste collection trucks, while the EU project H2-Share (co-funded by Interreg North-West Europe) aims to deploy a heavy-duty truck and mobile HRS at six locations in four European countries. In 2018, the number of heavy-duty trucks in Europe is likely to rise even further.

Using a truck for transportation has a lot of advantages: predictable scheduling, cost-effective for short distances, superior for perishable commodities that can be easily stored, just-in-time delivery, door-to-door service, and still a lot of room for efficiency gains.

As a result, businesses such as BYD in China have produced multiple electric truck types. Volvo, Renault, Tata, Hyundai, and Kia have all sold many electric trucks. Mitsubishi Fuso, MAN, and Mercedes-Benz all have fully developed electric types of their traditional trucks.

A trolley truck version of some types is also available. This lowers expenses and eliminates the need for large batteries with extended charge times. Experts believe that the battery for Tesla's semi-truck, due out in 2023, will weigh up to six tons or more, lowering efficiency and payload dramatically.

Battery-powered trucks are significantly more suitable for stop-and-go traffic in cities than lengthy routes. They can use smaller batteries because of energy recovery through recuperation. Several smaller businesses have created innovative and effective last-mile delivery models.

United Parcel Service started testing a hydrogen-fuelled delivery van in 2017. Class 8 hydrogen fuel cell trucks will also be tested by US Hybrid, Toyota, and Kenworth. Hyundai started commercial manufacturing of its Xcient fuel cell trucks last year and has already delivered ten to Switzerland. In 2022, the company wants to offer them in other countries, including the United States. And this is just the start.

A growing number of parties have indicated that they want to join this initiative and work together on hydrogen-powered freight transport after the launch of HyTrucks in the spring of 2020 and the announcement of a goal to operate at least 1000 hydrogen-powered trucks in the Netherlands, Belgium, and West Germany by 2025.

The collaboration between Air Liquide and the Port of Rotterdam has grown to include over 60 partners from three countries. It is carried out in close collaboration between Rotterdam, Antwerp, and Duisburg ports.

Suppliers of hydrogen, truck manufacturers, filling station operators, transporters, and shippers are among these. There are still interested parties. Clean hydrogen, in addition to electrification and other available options, is required in the energy mix to ensure emission-free heavy road transport.

With advancements in both truck and network technology, it will be ready to travel larger distances in a hydrogen-powered truck. This makes achieving European climate goals and establishing and maintaining zero-emission areas in cities a possibility.

HyTrucks is one of Europe's most ambitious projects for the establishment of hydrogen-powered trucks and infrastructure. The goal of the initiative is to enhance air quality and decrease CO2 emissions by 100,000 tonnes, or 110 million truck kilometres in equivalent.

Hydrogen refuelling is not a new concept. Buses and passenger cars, taxis, and even some hydrogen-powered trucks are now running in the Netherlands from various places. The speed with which a big volume of hydrogen can be refuelled is critical for trucks. A truck consumes significantly more fuel than a passenger automobile, and truck drivers must meet strict delivery timetables. Furthermore, because trucks do not travel defined routes from a central point, they cannot consistently refuel at the same location. For the aforementioned parties, a good and reliable hydrogen network is required to make hydrogen utilization in heavy road transport a success.

HyTrucks has also made numerous important efforts to put hydrogen on the map in this area, including the establishment of twenty-five hydrogen filling stations along major transportation corridors connecting the Netherlands, Belgium, and Germany's Ruhr region.

As a result, hydrogen is a viable and viable option for transporters. The European standardization process, as well as collaboration with other international truck projects, will allow this to be implemented on a large scale, rather than just in the Netherlands, Belgium, and Germany.

This is a one-of-a-kind alliance that should lead to rapid and efficient scaling. Europe welcomes and promotes such alliances to accomplish climate goals. All the ingredients are in place to reach the grandiose aim. The first 1,000 trucks are expected to save 37 million litres of diesel each year. If all 6.1 million trucks switched to hydrogen instead of diesel, Europe's annual diesel usage would be reduced by 227 billion litres.

Despite this, hydrogen mobility is still at an extremely low level. While the fuel cells are costly due to the necessity for rare platinum, the technology exists. Deutz, a German firm, recently unveiled a hydrogen direct combustion engine. Other companies will shortly do so as well.

Alstom introduced the first commercial service of a hydrogen fuel cell passenger train on a 100-kilometer road in Germany in 2018. Hydrogen and fuel cell technology have been shown in rail applications such as mining locomotives, switchers, and trams since the early 2000s. Since then, two Alstom trains have travelled over 180 000 kilometres in Germany, and other countries are testing and adopting fuel cell trains.

A hydrogen train commenced regular passenger service in Austria in 2020, and experiments in the United Kingdom and the Netherlands have begun. France, Italy, and the UK are among the European nations that have bought hydrogen fuel cell trains, with Germany's enormous fleet of 27 hydrogen trains set to enter regular service in 2022.

Also showing interest in hydrogen fuel cell trains are nations including China, Korea, Japan, Canada, and the United States. Hydrogen trams, line-haul, and switching locomotives, in addition to passenger trains, are at various phases of research and deployment. Fuel cell rail applications can assist decarbonize the industry where direct electrification of lines is problematic or too expensive.

Transportation of cryogenic liquid hydrogen by truck or rail could be important in the early stages of hydrogen infrastructure development. The technique of liquefying molecular hydrogen uses up to 40% of the energy content of the weight delivered, and it could be a promising technology development opportunity. If that could be reduced to a 20% loss through some form of breakthrough, there may be a $0.20/kg cost reduction compared to today's liquefaction expenses.

Research into lowering the cost of liquefaction for hydrogen could benefit not only its cost of transportation by truck, ship, or rail, but also its storage at plant sites to avoid unforeseen shutdowns. Because this method of transportation may predominate in the early phases of the deployment of fuel cell vehicles, this study is better suited for near-term funding.

Since the early 2000s, hydrogen fuel cells have been tested on several coastal and short-distance vessels. Fuel cell ferries were planned to commence commercial service in the United States and Norway in 2021. Passenger ships, ferries, roll-on/roll-off ships, and tugboats are the most common hydrogen-fuelled vessels now being demonstrated or planned for deployment in the coming years, with fuel cell power ratings ranging from 600 kW to 3 MW. In addition, a recent EU partnership plans to create a hydrogen ferry with a fuel cell power output of 23 MW.

Both gaseous and liquid onboard hydrogen storage schemes have been completed or are in the works. Because of hydrogen's low volumetric density (whether in gaseous or liquid form), it will be limited to short- and medium-range vessels, particularly those with high power demands that cannot be satisfied through battery electrification.

Hydrogen-based fuels are also gaining popularity as marine fuel for large oceangoing ships. For instance, ships' internal combustion engines can emit less CO2 when using green ammonia. Major industry players have stated that 100% ammonia-fuelled maritime engines will be available as early as 2023, with ammonia retrofit packages for existing boats starting in 2025.

Methanol, which is more mature than hydrogen and ammonia, has also been proved as a fuel for the maritime sector. Methanol may be a short-term solution for reducing shipping emissions because of its compatibility with existing maritime engines, but ammonia has a longer-term decarbonization potential.

The 12th Clean Energy Ministerial (1 June 2021) saw the formation of the CEM Global Ports Hydrogen Coalition, which seeks to enhance cooperation between port officials and government authorities to increase the use of low-carbon hydrogen.

The transition of companies in these clusters from fossil-based to low-carbon hydrogen would increase hydrogen fuel consumption by ships and trucks serving the ports, as well as surrounding industrial sites (e.g., steel factories), lowering costs.

The Coalition broadens the discussion on hydrogen's potential for port operations by bringing together various ports and stakeholders, such as the International Association of Ports and Harbours, the World Ports Climate Action Program, and regional associations (e.g., the European Sea Ports Organisation). Along with other industry players, the Hydrogen Council, the world's largest industry initiative, will take part in Coalition activities.

5.4 Qualitative Analysis/Interviews

To add some qualitative analysis, the interviews were conducted with Mr. Dominik Matheisl, a hydrogen officer at Linz AG and Dipl. Ing. Dominik Kreil, Project Manager for Hydrogen in the Climate Office at Magistrate Linz. Here are the questions and answers listed below:

1) Is Hydrogen going to be one of the critical technologies in solving climate change? If yes, then why?

Dominik Matheisl: One of the critical technologies – Yes. It will not solve all our problems on its own. However, hydrogen will play a key role in decarbonizing hard-to-avoid sectors like high-temperature processes in the industry or special mobility applications like aviation or shipping. It will also help stabilize the whole energy system.

Dominik Kreil: As you may know, hydrogen is an energy carrier, not an energy source. Therefore, it is essential to extend renewable energy sources like photovoltaic or wind power. With this backbone, hydrogen will help us to decarbonize particular fields in industry and mobility and will be a crucial technology for sessional energy storage.

2) Where do You think the Austrian energy system is headed until 2030?

Dominik Matheisl: I am an optimist. We should reach our goals to increase renewable energy production and decrease greenhouse gas emissions. In terms of the national hydrogen strategy, we can also reach the goal to replace at least 80 % of the already used gray hydrogen with green hydrogen, or in other words, to install electrolysis with a total power of 1 GW. I see an atmosphere of departure in the industry and the Austrian energy sector, more and more companies start their hydrogen activities, which will lead to their hydrogen projects. The biggest obstacles are the length of approval procedures and, even more, the shortage of specialists.

Dominik Kreil: As you may know, hydrogen is an energy carrier, not an energy source. Therefore, extending renewable energy sources like photovoltaic or wind power is essential. With this backbone, hydrogen will help us to decarbonize particular fields in industry and mobility and will be a crucial technology for sessional energy storage.

3) How would you recommend or implement changes to the Austrian energy system?

Dominik Matheisl: The Austrian government should intervene if federal provinces like upper Austria or the western provinces of Austria will not allow renewable energy projects like wind parks or solar parks.

Dominik Kreil: We must be more ambitious in implementing renewable energy sources. This needs more investments and better laws to accelerate this development. In order to stabilize the electricity and energy grid, we must invest in long-time-storage applications. Thermal energy storage, as well as chemical ones like hydrogen and derivate, will help us to do the job.

4) What influence will the implementation of hydrogen have on Your company or organization/Town?

Dominik Matheisl: Potentially significant influences on the whole company – we are a fully integrated public utility company, so that the influence could reach above the energy business, including utilities like wastewater treatment, the river port at the Danube, logistics, and public transport. However, at the moment, it is not quite sure which sectors of hydrogen will have the most significant impact, so all the mentioned influences are somewhat hypothetical. We will see what the future brings.

Dominik Kreil: The city of Linz plans to be climate neutral until 2040. Therefore, hydrogen will be a crucial part of this transformation. Linz was and still is an industrial city with a lot of creative and innovative potential. The implementation of hydrogen technologies and competence centres, as well as the settlement of new companies in the hydrogen sector, will ensure jobs and wealth.

5) Would there be a slow transition to hydrogen technologies, or will it be a hyped movement?

Dominik Matheisl: There will be a hype wave initially, with high expectations, followed by disillusionment when the first projects hit technical, administrative, and regulatory obstacles. Nevertheless, these obstacles will be solved, and we will reach an excellent steady increase in hydrogen productivity. In other words, hydrogen will follow the typical path of the „Gartner Hype Cycle. "

Dominik Kreil: I think both will happen! As for every new technology, which carries many potentials, there will be quick jumps in development. It is astonishing how companies and governments dedicate themselves to climate neutrality and hydrogen technologies. With this commitment, a long-scale and sustainable revolution are possible.

6) When do You think hydrogen will be one of the primary and irreplaceable technology to use and store energy?

Dominik Kreil: As a chemical compound, hydrogen has been used for almost a century. Therefore, we already know how to treat this molecule on a grand scale. What we have to do now is to build extensive facilities to produce green hydrogen, which is planned not only in Austria but also worldwide. We will see essential steps in the next few years, maybe already in 2025!

7) The Austrian government targets an electrolyser capacity of 1 Gigawatt by 2030. It will thus contribute around 1% to the EU's target of producing ten megatons of hydrogen per year within the bloc, as per industry calculations. Do You think there will be any setbacks in reaching this goal?

Dominik Matheisl: As stated before, yes, I think there will be obstacles and setbacks – still, in my opinion, we can solve these problems and come close to reaching the goal.

Dominik Kreil: A new electrolyser with 300MW power is planned in Burgenland, which is almost a third of the targeted capacity. To reach the 1GW in time, we have to start projects like this; otherwise, the time to build such a facility will be too long to finish on time.

The main setback will be the price of green hydrogen; right now, it is not competitive with grey hydrogen or natural gas. To overcome this inequality, new laws and a price for carbon dioxide have to be implemented and set high enough.

8) How do You see the growth of blue and green hydrogen in Austria?

Dominik Matheisl: I concluded that temporary solutions represent a delay rather than a solution for decarbonizing our energy system. Therefore, we should focus on green hydrogen and work on import routes for green hydrogen to Austria to fully decarbonize the Austrian industry and energy system, as we will not be able to produce enough green hydrogen on our own.

Dominik Kreil: It is planned to transform 80% of the used hydrogen to be climate neutral until 2030. This is a very ambitious goal to reach. However, the impacts of climate change are heavy, and it is crucial to reduce the emission of CO2 drastically. The production of blue hydrogen with proper carbon capturing and storage (CCS) and utilization (CCU) of complex and valuable chemicals will be essential to the transformation process.

9) Which part of the value chain of hydrogen technology needs development the most?

Dominik Matheisl: The part of applications of green hydrogen – industry and enterprises should get supported to transform their production processes from fossil fuels to renewable fuels, including green hydrogen. The production, import, and distribution of green hydrogen will develop along. A second part of the value chain that needs additional development is the long-term storage of green hydrogen in order to shift the additional available energy from the summer to the winter.

Dominik Kreil: The most potential lies in hydrogen technologies. The know-how in production is there, but have to be cheaper to compete with natural gas, and we know how to build infrastructure for gases like pipelines and other cargo systems. The fields where we can implement hydrogen to reduce emissions are much more diversified, starting from the steel industry to CCU and ending in mobility topics.

10) Is there any idea that You would finally share with me?

Dominik Kreil: As already mentioned, hydrogen is not an energy source but a carrier. This is one of the most important messages we have to share with people. Behind hydrogen technologies, there is the need for an energy transformation to renewable sources. Hydrogen will be a crucial ingredient for a clean future, but it will help us at most 25% down the road to climate neutrality.

In Austria, we have some excellent opportunities for hydrogen technologies. First, we have a lot of innovative power and a diverse field of companies and know-how. Second, a big part of our electricity system is powered by renewable hydropower. Furthermore, third, the geological circumstances are ideal for storing gases for long periods, and this will be curtailed to become one of the key players in this new field of energy systems.

6. Scenario Analysis

6.1 Selection of software

Starting with the literature review, the plan was to collect all different software that might be suitable for the idea and then compare them with each other to work with the best one. The scientific article Sola A, Corchero C, Salom J, Sanmarti M, Multi-domain Urban-Scale Energy Modelling tools: a Review, Sustainable Cities and Society (2019), which included a number of different modelling tools with table comparisons of each in terms of availability, time scale, demand modeling approach, and many more, provided the best information about various types of software.

After trying them and getting to know their functionality, the last choice was City Energy Analyst CEA software. Out of all the simulation tools discovered, the user interface and self-explanatory settings of the City Energy Analyst were the most helpful in comprehending and utilizing the tool in the short term, even though it has problems and faults. Other options like Energy+, Modelon, or Python models were too complicated and too manual for short-term research. One of the earliest open-source initiatives of computing tools for planning low-carbon and highly effective cities is CEA, a platform for urban building simulation.

The CEA combines urban planning and energy systems engineering knowledge in an integrated simulation platform. This makes it possible to examine the impacts, compromises, and synergies of various urban design concepts and energy infrastructure ideas. The only negative side of this software is that it is new and needs much improvement since there are a lot of bugs and issues along the way of creating a project. The data is coming from ETH Zurich and Google GIS.

6.2 Modelling

The process of the setup was in steps described below:

- Creation of the Project
- Creation of the Scenario
- Application of the scripts to generate the input database
- Application of the scripts to generate the output database

We will go through each of them in detail.

1) The Project.

The project will be needed to compare different scenarios and develop the best scenario at the end. It is also essential to save it in ample memory storage because the software is heavy, and input/output data is pervasive. There is nothing, in particular, to define at this stage, only the storage place and name for the project.

2) The Scenario.

In this step, the critical point is to choose the proper database for the input files. Since the software is developed jointly in Switzerland and Singapore, there are two databases to pick from each country. In this case, the Swiss database would be more fitting due to the country's geographical position to Austria. We turn on all the data management tools like terrain and weather to have information about elevations and irradiance in the future.

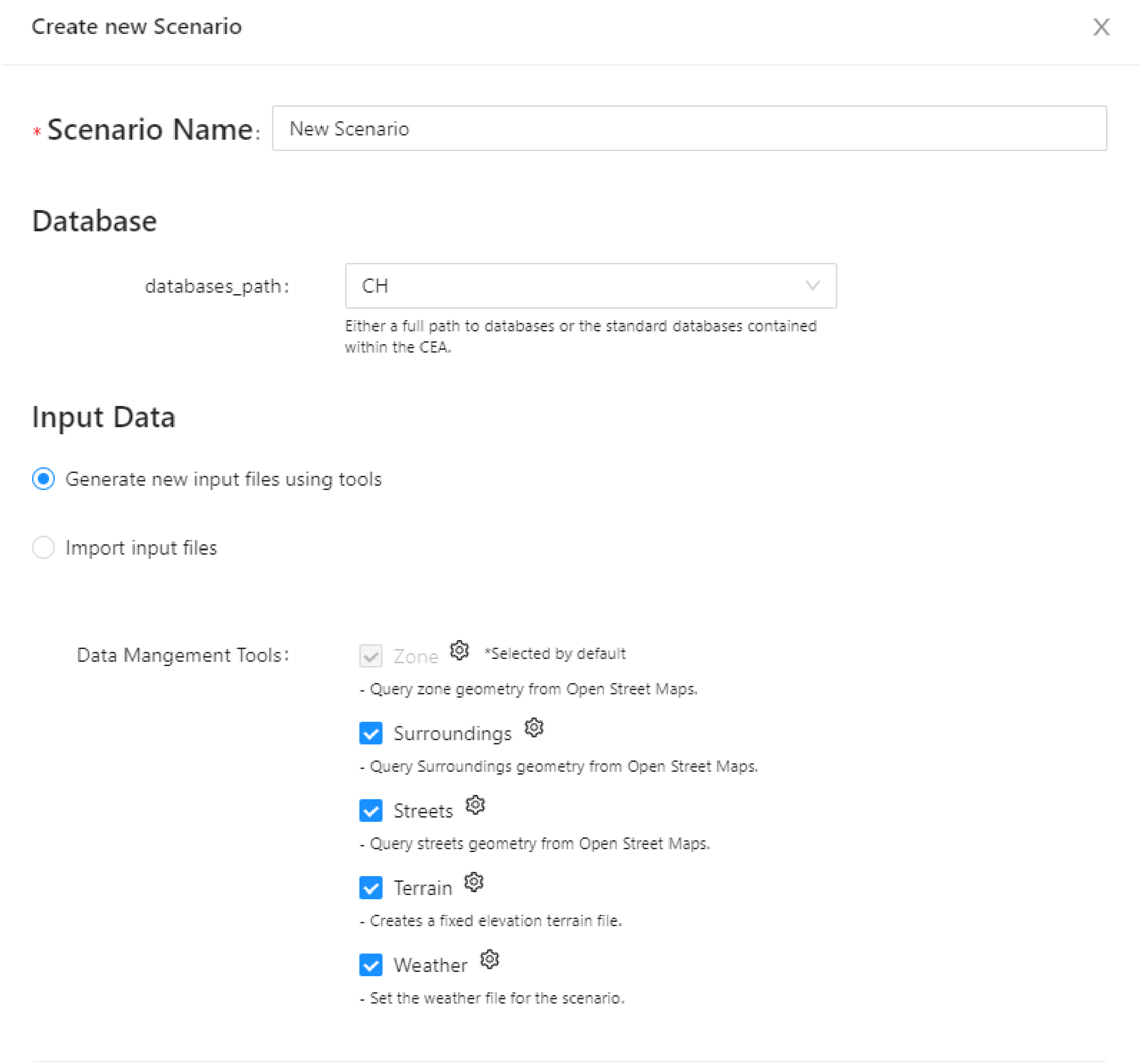


Figure 23: Setting the scenario

Lastly, in this section, the definition of the borders of the desired region must be done. With red dots, the official territory of Innere Stadt Linz was defined. The selected area was 2.46 km2. Minor imprecisions may be caused due to curved lines of the territory, which is hard to get with straight lines between red dots on the software.

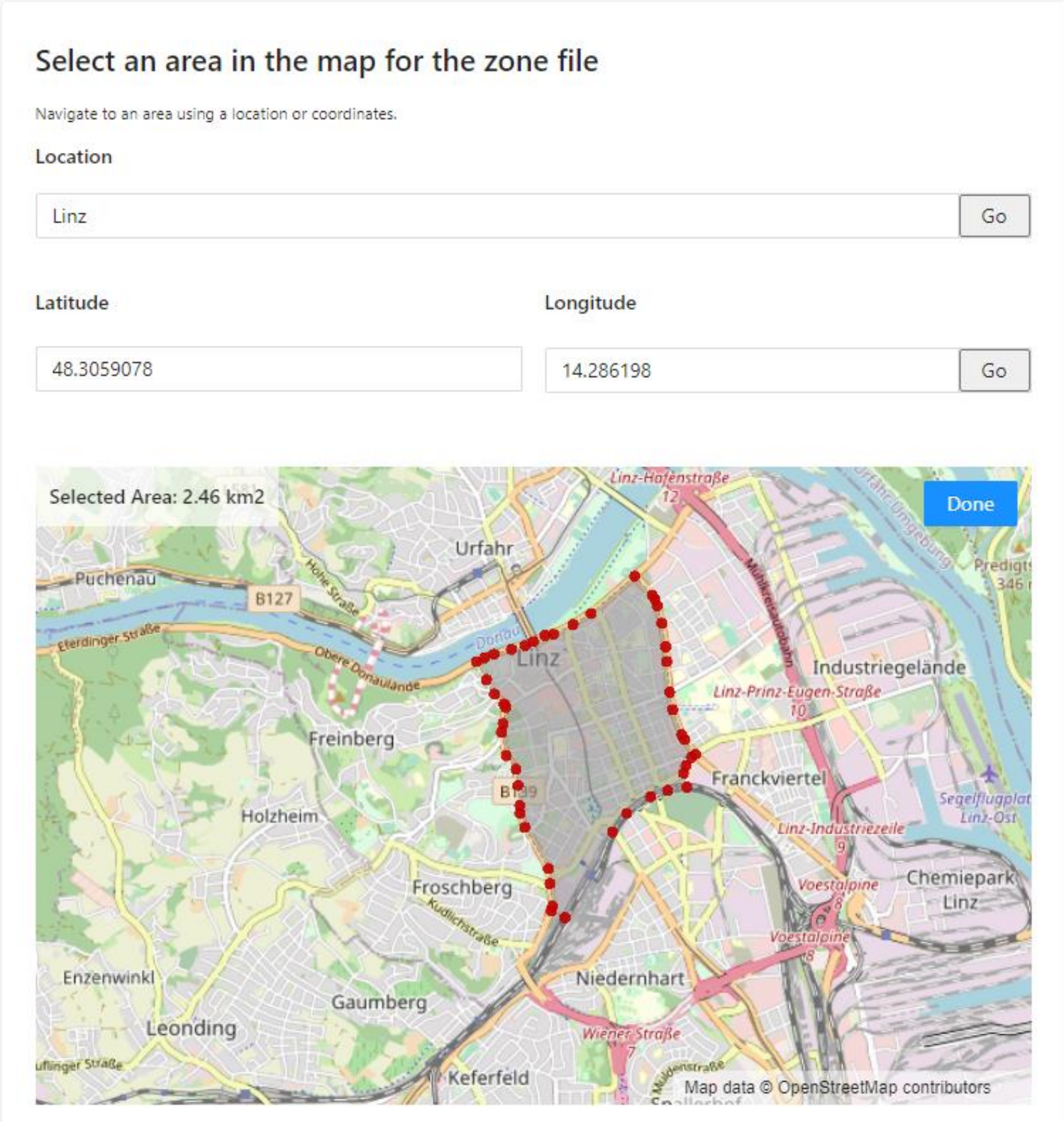


Figure 24: Definition of project boarders

3) The Scripts.

All the scripts are organized in script groups, and there are basic and additional ones for different purposes.

The ones that were used are:

- Archetypes mapper

To assign building properties and systems from the archetypes database. Each building will have its archetype to get more precise data on its energy consumption. For example, in the picture below, we can observe the dormitory that I live in right now, and CEA categorizes it as a dormitory to get more precise estimated calculations.

Figure 25: Characteristics of every building

- Weather - helper

We define our weather file for implementing the weather conditions in the selected region for one specific year with a time step of 1 hour. Is it possible to upload a weather file from external sources for more precise and up-to-date data, but the used one was given by the software because there were some bugs in inputting the external data. However, the function is there, and soon the bugs will be resolved, and the software will be even better with the weather information. In the picture below, the list of databases is illustrated. The selected data was Zuerich-SMA_2016 because it was the most recent from the available ones.

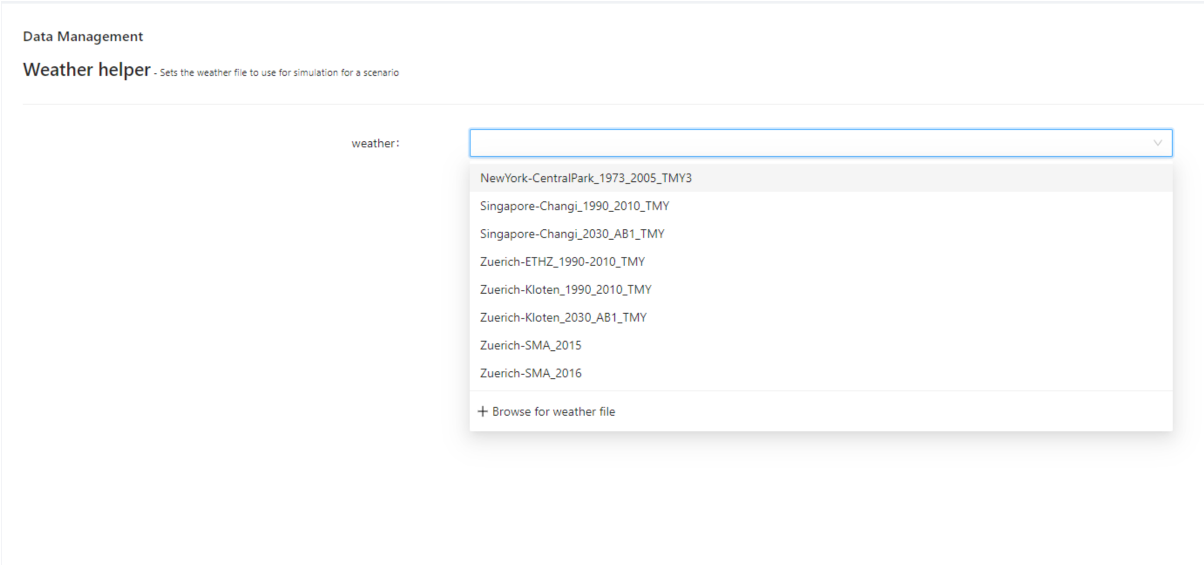


Figure 26: List of weather databases in CEA

- Building solar radiation

With the help of Daysim binaries, which can run more significant sites faster, the script calculates the solar radiation on all the buildings' surfaces. That is the most extended script to run and usually takes around 20 hours to finish on a 16 GB RAM computer. There are a lot of additional advanced settings like albedo and consideration of intersecting walls between the buildings. However, implementing them would increase the time of running by five times. Therefore, the radiation script was in a default setting with 0.2 albedo.

Also, radiation data is considered an output, so it is the first output information that CEA produces. It creates two CSV files for each building, one is for the geometry, and the second one is for the radiation data. The last CSV file is the sum of all these CSV files. The geometry file shows the types of walls and their size in each direction. The radiation file has hourly information about the amount of radiation received by each side and roof of the building.

- Building schedules

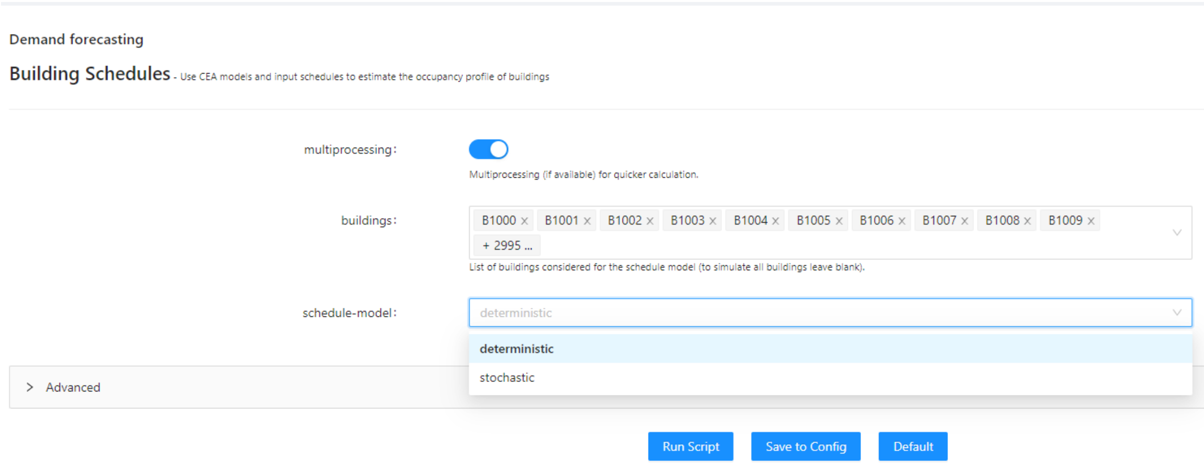


Figure 27: Schedule script setting in CEA

To estimate the occupancy profile for each building, the script "Building schedules" is used. As shown in the image above, there are two schedule models to choose from: stochastic and deterministic. Stochastic models are the reverse of deterministic models in that they display data and forecast outcomes that take into account varying degrees of randomness or irrationality, as opposed to deterministic models that consistently deliver the same outputs for a given set of inputs. The logic behind choosing the deterministic model was to replicate the lifestyle of regular statistical people, who will go to work and come back five days a week. This information will be helpful to calculate the energy demand script more precisely since it will also consider internal energy gains and not constant usage of electricity, for example.

- Building solar demand

Through many calculations, the script calculates the overall total energy demand by considering many parameters. For each building, this script calculates many outputs. Almost 50 relevant output measurements about the energy requirements, refrigeration systems, hot water consumption, and use of electricity for appliances are one of many that can be estimated using the energy demand script.

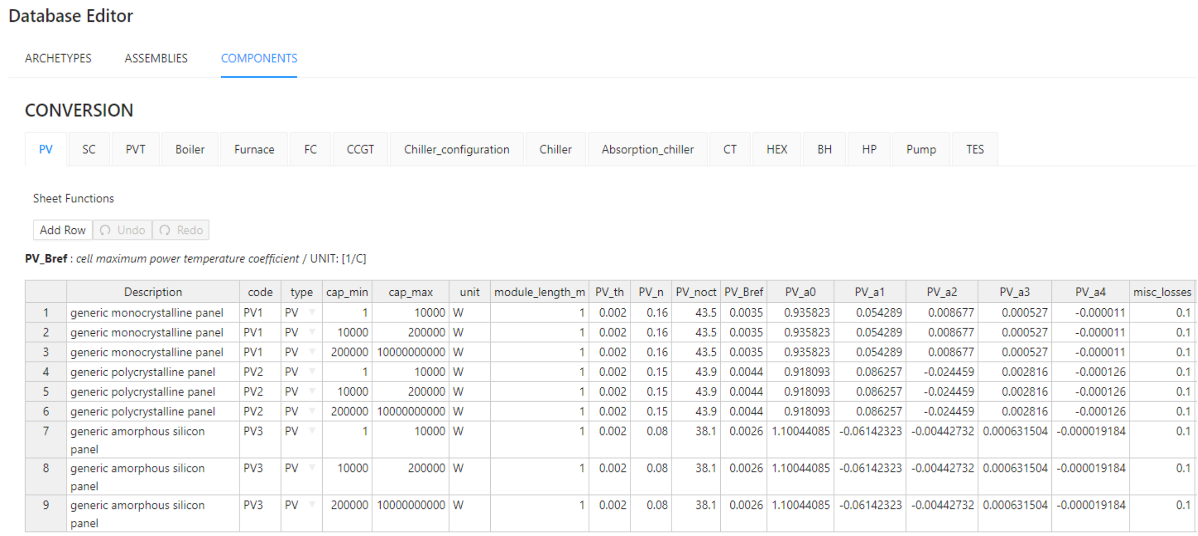
DATE	Name	people	x_int	PV_kWh	GRID_kWh	GRID_a_kWh	GRID_l_kWh
01/01/2016 00:00	B1000	611	5.369	0	24.545	18.343	6.191
01/01/2016 01:00	B1000	611	5.899	0	24.54	18.343	6.191
01/01/2016 02:00	B1000	611	6.278	0	24.535	18.343	6.191
01/01/2016 03:00	B1000	611	6.584	0	24.535	18.343	6.191
01/01/2016 04:00	B1000	611	6.792	0	24.537	18.343	6.191
01/01/2016 05:00	B1000	611	6.957	0	44.215	33.018	11.143
01/01/2016 06:00	B1000	367	6.817	0	163.398	121.065	40.859
01/01/2016 07:00	B1000	244	6.592	0	45.608	33.018	11.143
01/01/2016 08:00	B1000	0	6.163	0	25.961	18.343	6.191
01/01/2016 09:00	B1000	0	5.839	0	25.939	18.343	6.191
01/01/2016 10:00	B1000	0	5.557	0	25.93	18.343	6.191
01/01/2016 11:00	B1000	0	5.376	0	25.926	18.343	6.191
01/01/2016 12:00	B1000	489	5.691	0	163.346	121.065	40.859
01/01/2016 13:00	B1000	244	5.741	0	45.573	33.018	11.143
01/01/2016 14:00	B1000	0	5.503	0	25.912	18.343	6.191
01/01/2016 15:00	B1000	0	5.302	0	25.906	18.343	6.191
01/01/2016 16:00	B1000	0	5.122	0	25.912	18.343	6.191
01/01/2016 17:00	B1000	244	5.209	0	45.573	33.018	11.143
01/01/2016 18:00	B1000	489	5.495	0	163.369	121.065	40.859
01/01/2016 19:00	B1000	489	5.696	0	202.625	150.414	50.765
01/01/2016 20:00	B1000	489	5.851	0	45.582	33.018	11.143

Table 5: Data output sample for B1000 building

For example, in the above screenshot of the table for building labeled as B1000, we can see how the number of people changes with time during the day and how the energy consumption also reflects that change.

- Photovoltaic panels

Photovoltaic panels script calculates the electricity production from solar photovoltaic technologies by using the output of the "Radiation" script. One of the essential parts to define in the script set is the panel type and the tilt angle of the panels. The picture below shows the selection of PV modules and their properties.



Database Editor

ARCHETYPES ASSEMBLIES COMPONENTS

CONVERSION

PV SC PVT Boiler Furnace FC CCGT Chiller_configuration Chiller Absorption_chiller CT HEX BH HP Pump TES

Sheet Functions

Add Row Undo Redo

PV_Bref : *cell maximum power temperature coefficient* / UNIT: [1/C]

	Description	code	type	cap_min	cap_max	unit	module_length_m	PV_th	PV_n	PV_noct	PV_Bref	PV_a0	PV_a1	PV_a2	PV_a3	PV_a4	misc_losses
1	generic monocrystalline panel	PV1	PV	1	10000	W	1	0.002	0.16	43.5	0.0035	0.935823	0.054289	0.008677	0.000527	-0.000011	0.1
2	generic monocrystalline panel	PV1	PV	10000	200000	W	1	0.002	0.16	43.5	0.0035	0.935823	0.054289	0.008677	0.000527	-0.000011	0.1
3	generic monocrystalline panel	PV1	PV	200000	10000000000	W	1	0.002	0.16	43.5	0.0035	0.935823	0.054289	0.008677	0.000527	-0.000011	0.1
4	generic polycrystalline panel	PV2	PV	1	10000	W	1	0.002	0.15	43.9	0.0044	0.918093	0.086257	-0.024459	0.002816	-0.000126	0.1
5	generic polycrystalline panel	PV2	PV	10000	200000	W	1	0.002	0.15	43.9	0.0044	0.918093	0.086257	-0.024459	0.002816	-0.000126	0.1
6	generic polycrystalline panel	PV2	PV	200000	10000000000	W	1	0.002	0.15	43.9	0.0044	0.918093	0.086257	-0.024459	0.002816	-0.000126	0.1
7	generic amorphous silicon panel	PV3	PV	1	10000	W	1	0.002	0.08	38.1	0.0026	1.10044085	-0.06142323	-0.00442732	0.000631504	-0.000019184	0.1
8	generic amorphous silicon panel	PV3	PV	10000	200000	W	1	0.002	0.08	38.1	0.0026	1.10044085	-0.06142323	-0.00442732	0.000631504	-0.000019184	0.1
9	generic amorphous silicon panel	PV3	PV	200000	10000000000	W	1	0.002	0.08	38.1	0.0026	1.10044085	-0.06142323	-0.00442732	0.000631504	-0.000019184	0.1

Figure 28: Database editor for selection of photovoltaic panel in CEA

The choice fell on the generic monocrystalline panel type to make the case more realistic because it is higher in efficiency, and the performance decreases only if the temperature goes up. However, the average temperature in Linz in the hottest months barely reaches 26 degrees Celsius. Realistically, it will be simpler to obtain monocrystalline solar panels as they are the most often used residential solar panels due to their power capacity and efficiency. Regarding the angle, standard 30-degree tilt in the South direction was defined.

6.3 Results (Energy demand)

After getting the output data with a script running, it is crucial to open the dashboard in the software because CEA will save all the graphical output in the dashboard section. There are multiple ways to graph the data. For example, we can compare different scenarios to see which is more optimized for energy demand or CO2 production. Additionally, we can get the comfort chart for each building to see what the comfort levels throughout the year in this building for potential implementation of improvements are. In the image below, we can observe the comfort chart for the same building labeled B1000.

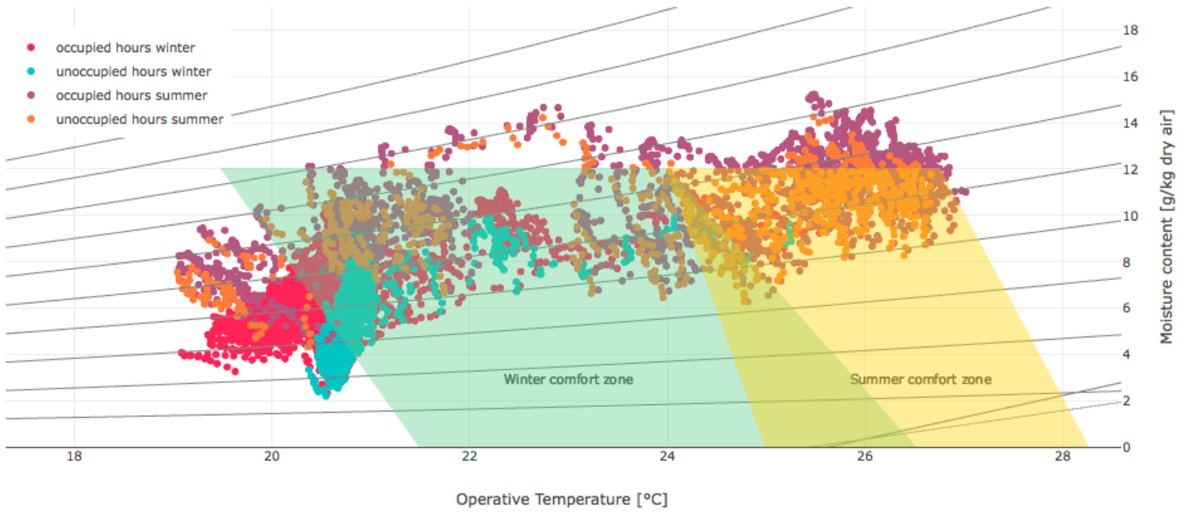


Figure 29: Comfort chart for B1000 building

However, our primary goal is to get information on energy demand. Therefore, we get the load curve of all the buildings with specified information on the percentage of energy usage that goes to lighting, space heating, hot water, and other auxiliary energy expenditures.

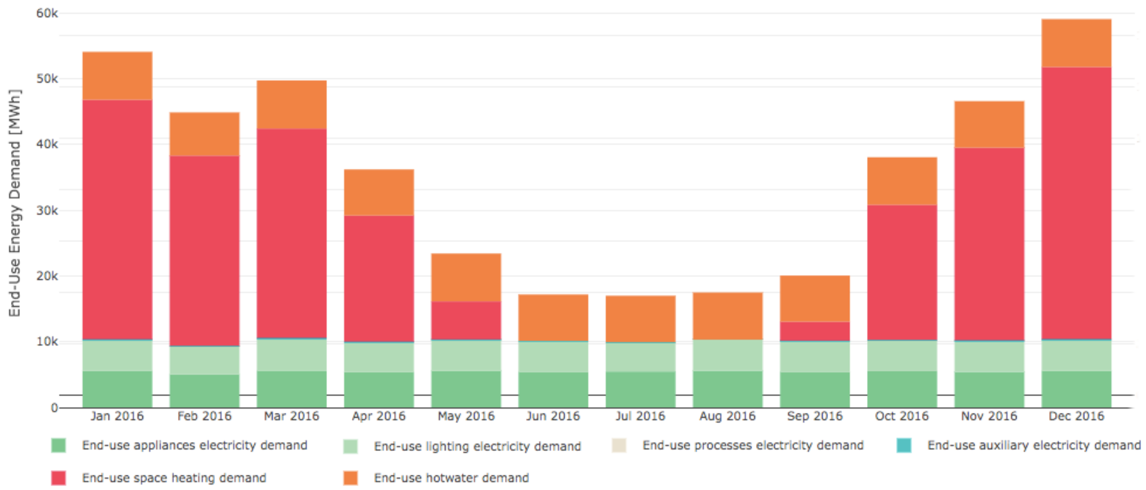


Figure 30: Energy demand graph for all buildings in selected area

In the graph above, it is visible that most of the energy demand comes from space heating. 51% of all the energy demand to be precise. 216.35 GWh annually. Also, it is shown that we have very regular usage of hot water, lighting, and electricity demands each month, and not as much variance as compared to space heating demand.

Additionally, the software generated the solar radiation data for all the buildings to have a general knowledge about the amount of solar energy annually. In the image below, the solar potential graph is presented.

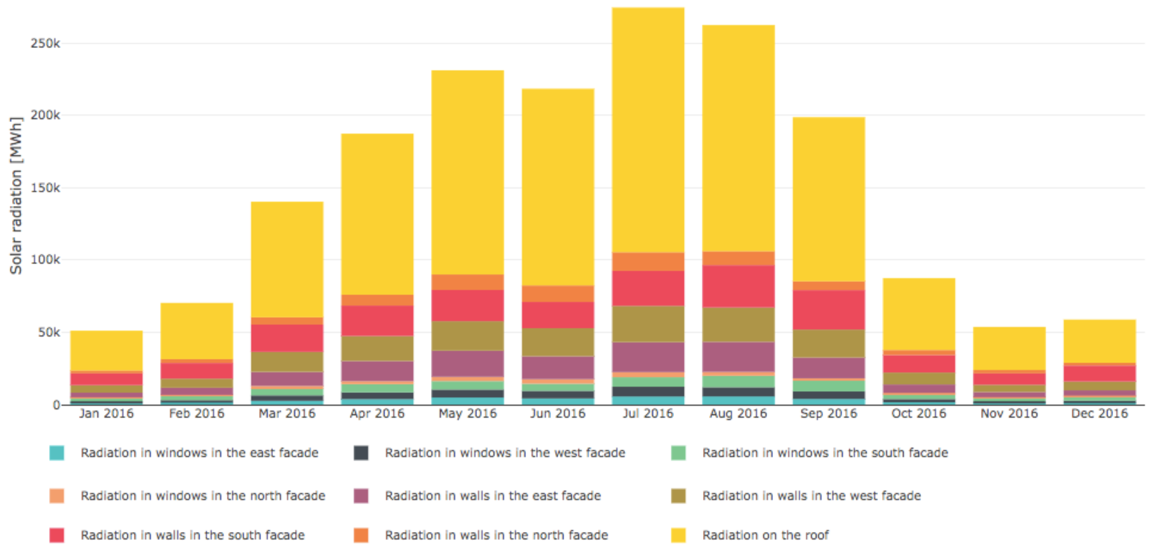


Figure 31: Solar Radiation graph for all the buildings in selected area

All the solar radiation is absorbed by all four sides of the building and rooftop, and solar radiation on the roof is much higher than on all facades. Therefore, calculating the potential energy production from photovoltaic panels would be the next logical idea. Since we consider the extensive usage of hydrogen technology, it might be convenient to have some information about the renewable energy potential to make hydrogen as green as possible.

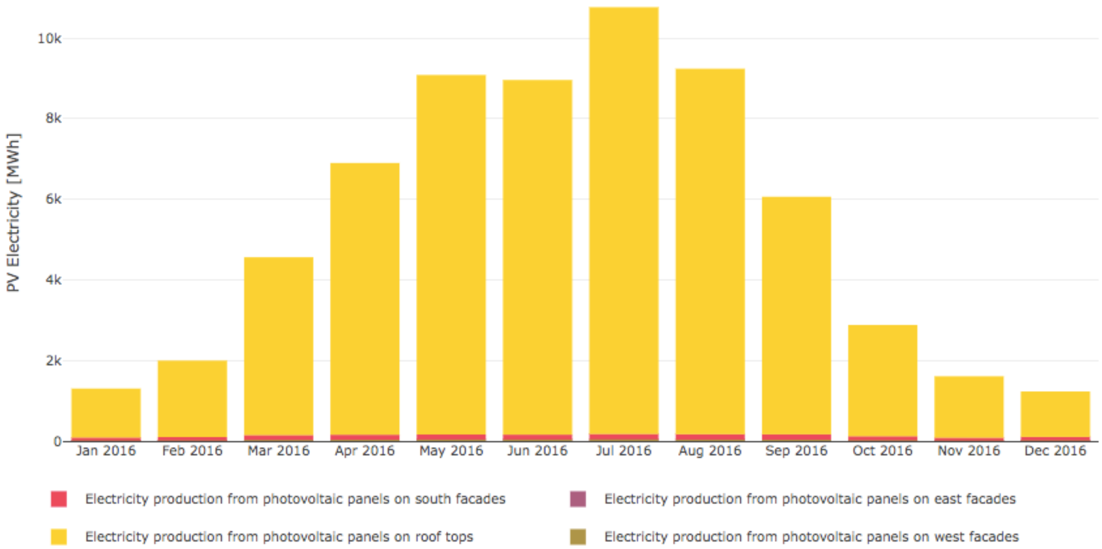


Figure 32: Solar Photovoltaic potential of all buildings in selected region

As shown in the image above, the graph demonstrates the photovoltaic potential on all four facades of the buildings and rooftop. It makes sense to consider only photovoltaic potential from the rooftops due to the extreme difference between solar roof potential and any solar facade potential. The total yearly potential generation from roofs of all the buildings considered in the region of Innere Stadt in Linz with 30-degree tilt angle and South facing panels generates approximately 63 GWh annually.

These results will give the overall image of energy storage capacity and the amount of energy needed to generate for Innere Stadt. Based on these results, we will estimate every other aspect of sector coupling.

7. Calculation of hydrogen substitution

7.1 Energy losses during the whole process from creation to usage of Hydrogen

To calculate the amount of hydrogen needed to replace all the fossil fuel boilers in the district heating system, we should consider the adequate amount of losses throughout the whole hydrogen production chain, from electrolyser loss to fuel cell energy losses. At the beginning of green hydrogen production, there is a 20-30% energy loss. During electrolysis, gas bubbles are formed, causing some energy loss since the surface area of water touching the cathode and anode decreases because of the bubbles. (Lisa Zyga, 2013) After that, there is a 10% energy loss due to the compression and storage of hydrogen. And we are lastly, converting hydrogen back into electricity wastes another 30% of the initial energy. (Andrew Lerma, 2021)

Fuel Cell losses:

There are three types of losses in the fuel cell. (Deepakkumar Yadav, 2022)

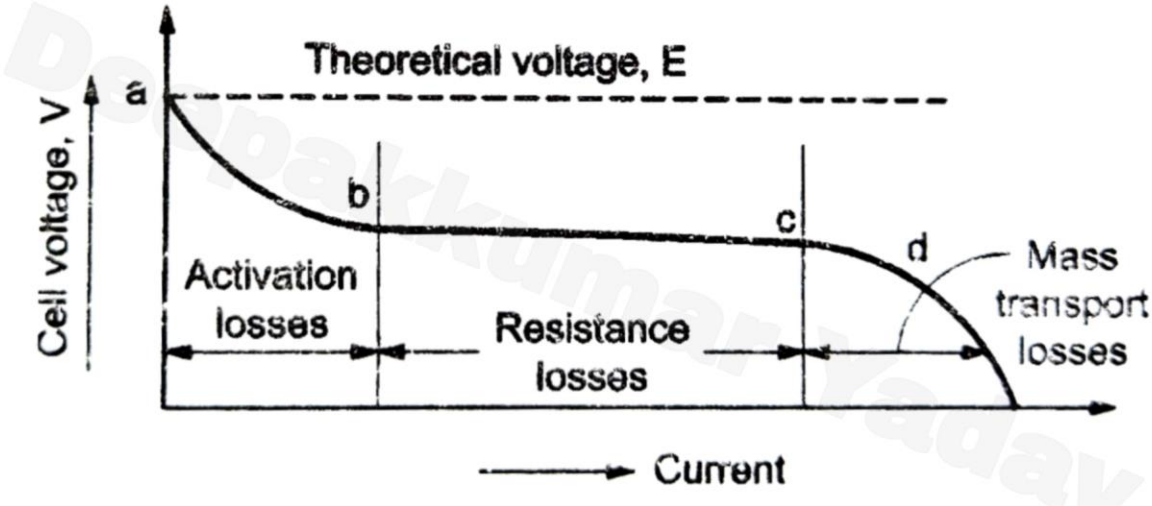


Figure 33: Voltage-Current Characteristics of Fuel Cell

Source: Deepakkumar Yadav (2022) Losses in Fuel Cell

- Activation losses

Activation losses are the voltage required to overcome the activation energy of the electrochemical reaction on the catalytic surface. This polarization determines losses at low current densities and assesses the catalyst's efficiency at a particular temperature.

This voltage loss at no load is called activation loss (E – Vb), as shown in Figure 33 by curve (a - b). The ability of the cell to dissociate and generate the chemical reaction at low temperatures is related to these losses.

- Resistance losses

The graph illustrates how the voltage of the cell continues to decrease as load causes current to flow from the cell (b - c). These losses are ohmic or resistance losses brought on by the cell's electrical resistance to the current. These losses (Vc-Vb) are called resistance losses.

- Mass transport losses.

Mass transport losses in fuel cells are reduced by utilizing complex flow architectures with several narrow flow channels. The flow structure serves two primary purposes. Prior to harvesting the fuel cell's electrical current, it feeds the reactant gases and eliminates the reaction by-products. (O'Hayre, R., Cha, S.-W., Colella, W. and Prinz, F.B. 2016)

In the end, we are left with a round trip efficiency of hydrogen energy of around 47%. We will need this efficiency to calculate the energy required to produce enough hydrogen to replace fossil-burning boilers.

7.2 Calculation of Energy substitution in District heating by Hydrogen technology

In terms of substitution, it is not obligatory to substitute space heating demand in the Innere Stadt, but since, in our case, it is half of the annual overall energy demand, we will choose space heating. The output data from CEA software shows that the yearly space heating demand is 216.35 GWh. Because of the round-trip efficiency of hydrogen, if we want to cover all of the energy expenditures on space heating demand, we need to divide the energy demand by that efficiency. It makes 460.32 GWh of energy that must be produced and put into all the production, storage, and utilization chain, with its energy losses ending with 216.35 GWh yearly.

After the interview with Mr. Matheisl, a hydrogen officer at the Linz AG, he forwarded my questions to his colleague at Linz-Mitte, who answered my questions about the district heating system in Linz. The number of connected households and the amount of CO2 released per kWh. It is important to remember that only fossil CO2 is considered, not biogenic CO2. First, the number of connected households is around 85000, representing 66% of the whole Linz. Therefore, we can assume that the 3000 buildings are included in this 66% for more straightforward calculations. Second, the amount of fossil CO2 per kWh is 270 grams. Consequently, the amount of fossil CO2 released in 1 year just for space heating demand with 216.35 GWh is 58414 tonnes.

Also, we should mention the critical assumption. Since fuel cells produce heat and electricity, we consider everything as total output energy because Linz-Mitte produces electricity and heat. However, it is easier to visualize the case if we consider covering only one energy demand: space heating. Additionally, Linz-Mitte produces 3-4 times more thermal and electrical energy annually, which both generate fossil CO2 from natural gas boilers. Therefore, to simplify the case, we will consider only the total energetic output of fuel cells.

Therefore, by covering the district heating system for the Innere Stadt Linz, this project will save 58414 tonnes of CO2 annually.

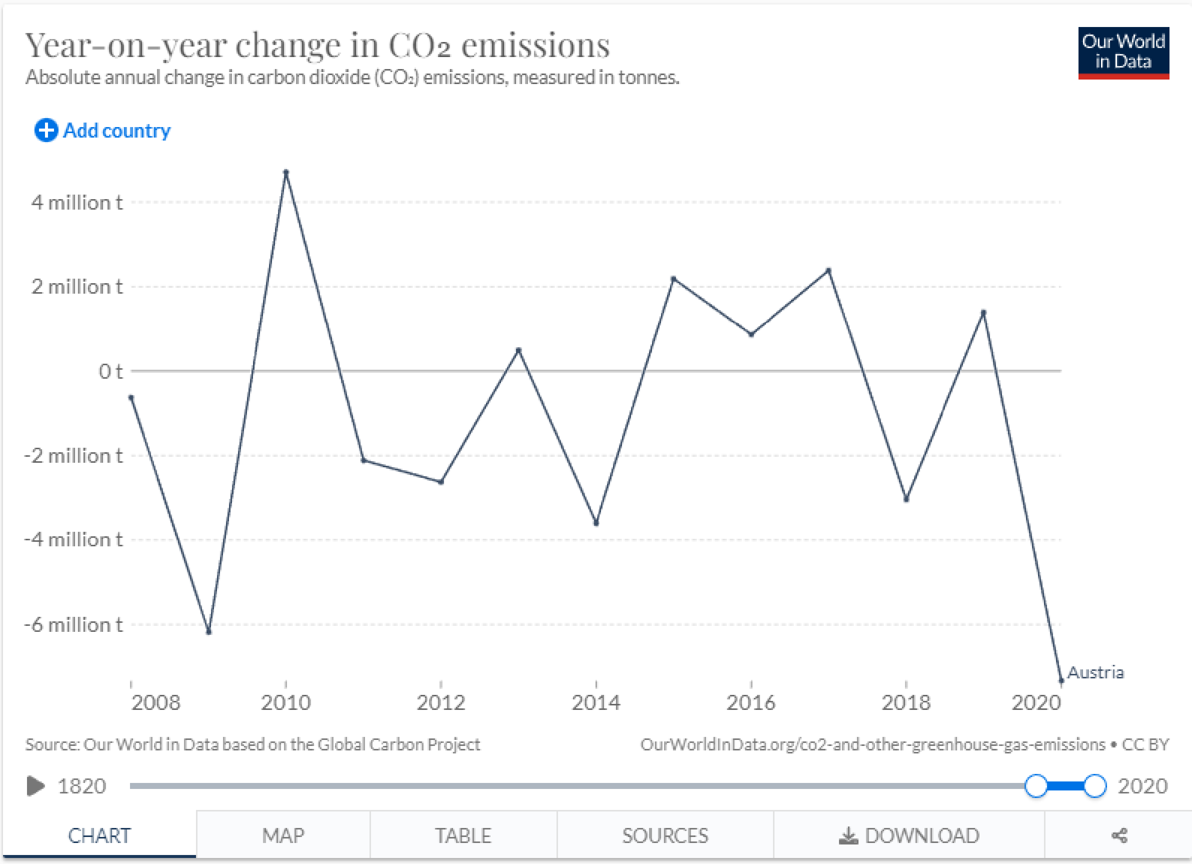


Figure 34: Year-on-year change in CO2 emissions in Austria

Source: Our World in Data based on the Global Carbon Project

How significant are 58414 tonnes of CO2 reduction? If we look at the annual change in CO2 in Austria, we can see a maximum decrease of around 3 million tonnes. We are not considering the decline from 2019 because of the pandemic and its significant effects on greenhouse gases. So, if we compare our reduction to the general reduction of CO2 for Austria in 1 year, it is around 2% which is very significant for a small district in the center of the city, being only 3rd biggest in the country and having eight times less population than in the capital.

7.3 Calculation of Storage requirement for a hydrogen sector coupling

For the total sector coupling, we need to consider all the energy demand of 3000 buildings in Innere Stadt and assume generation with python code. The code can be found in the Appendix section.

The idea is simple: find the difference between consumption and generation and plot the graph of the difference, which will specify the amount of energy stored. It is also essential to guess the initial energy stored on the 1st of January to have a point from which we can start the calculations. In this case, it will be 60GWh. Also, the baseline generation is assumed to be 13 GWh per month and fluctuates from season to season, peaking with an additional 10GWh. I entered space heating consumption from the outputs CEA software gave for a realistic estimation, particularly for this case.

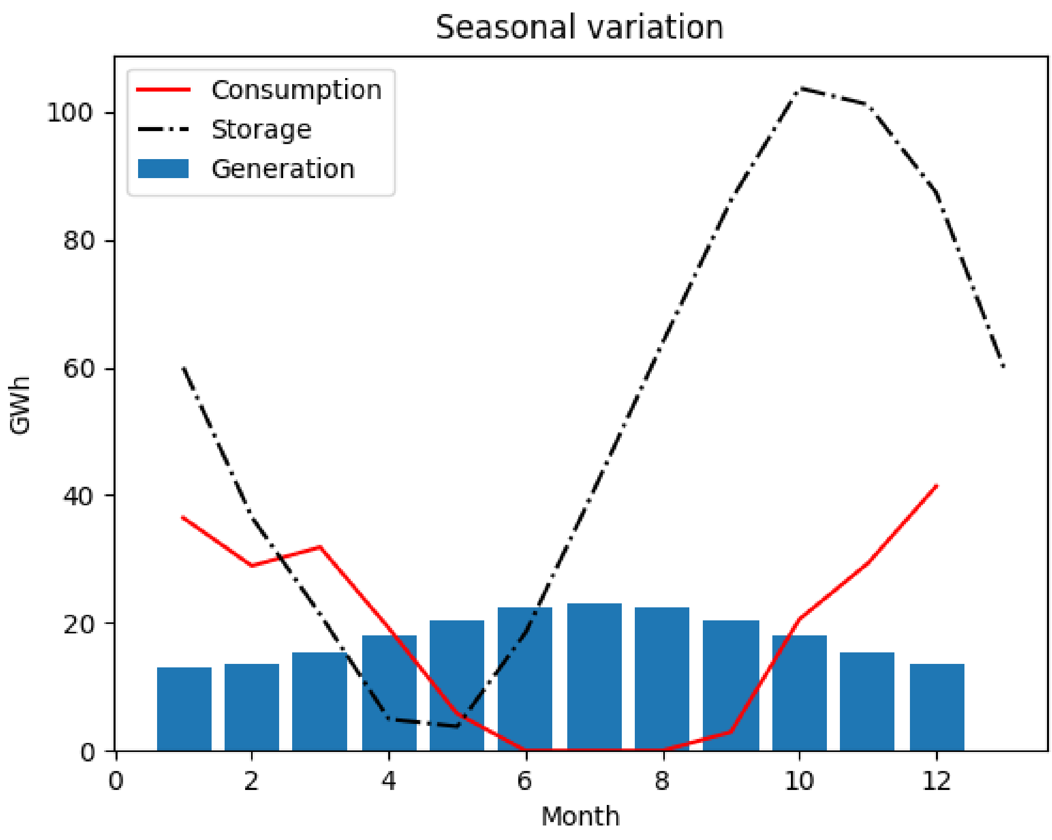


Figure 35: Graph of Storage, Consumption and Generation from Python code

Here is the graph of storage capacity in a dashed line which shows the amount of energy available. And the maximum capacity during the year will be 100-105 GWh.

Depending on the storage system, the volume will differ for this storage. However, since there are not as many underground salt caverns in Austria, alternative, underground depleted natural gas reservoirs can solve the issue. Hydrogen's energy density at 50°C and 100 bar is 237 kWh/m³ (Gas Infrastructure Europe, 2021) which is around 422000 cubic meters for a 100 GWh of storage capacity.

Above the storage, the electrolysers must be built on the ground. We need to take the month with the highest generation and lowest consumption to determine the electrolyser capacity. This way, we get the maximum possible amount of excess energy that can be directed into electrolysis. As we can see from the graph above, the month with the highest generation and lowest consumption is July. The difference s 23GWh, and if it is translated into the electrolysis, then we should divide 23GWh by 31 because of the days in a month and then by 12 hours because we will count sunny hours during the day. So, in the end, we get approximately 64 MW capacity for our electrolyser, which will produce around 26.2 tonnes of hydrogen daily.

7.4 Solar photovoltaic potential with implementation of Hydrogen technology

In this part, we will consider the final target situation—the usage of hydrogen technology with full implementation of renewable energy generation at maximum capacity. Of course, having solar photovoltaic modules on every roof in the region will not cover all the demand and decarbonize the city. Additional renewable energy power plants are expected to be built. However, the implementation of solar energy generation from PV panels can significantly reduce the demand for heat and electricity. How significant? We can calculate that as well with the output data. Since we need 216.35 GWh annually for space heating, and if we consider 47% of the round-trip efficiency of hydrogen technology, 460.319 GWh per annum must be input into electrolysers. However, let's take a case where all the rooftops are covered with monocrystalline photovoltaic panels with a 30-degree tilt angle and facing the South direction. We found out that we can produce an additional 63 GWh, reducing our demand by ~13.7%. Considering that Innere Stadt is in the city center and the ratio between rooftop area to the building size is smaller than in the other regions, 13.7% is a substantial reduction in energy demand which is significant enough to consider the idea. Also, it is assumed that by 2030-2040 the energy will be completely renewable, and most of the demand will be covered with green hydrogen produced from new renewable power plants. Installing photovoltaic modules will only decrease the overall energy demand and not influence greenhouse gases much.

Additionally, with the help of CEA software, we can calculate the solar-thermal gains from the rooftops, not only photovoltaic generation. The perfect combination between photovoltaic and solar thermal construction on the rooftops is yet to be found. Nevertheless, the idea of trying new compositions to generate as much renewable energy as possible through software is essential.

8. Conclusion

This paper reviews the general state of the art of hydrogen technology and estimates the parameters for hydrogen sector coupling of Innere Stadt Linz. The reviewed model consisted of 3000 buildings with solar photovoltaic modules on their roofs, and the panels are South-facing with 30 degree of tilt angle. Via the City Energy Analyst (CEA) software, the demand and other estimations were collected and used to calculate CO2 reductions and storage requirements. The final results of this project are the reduction of CO2 by 58414 tonnes with a need of 422000 cubic meters of storage at 50 degrees Celsius temperature and 100 bar pressure. This reduction of 58414 tonnes of CO2 for a small district in Linz is around 2% of Austria's average yearly CO2 reduction. Additionally, the solar photovoltaic panels on the roof of every building reduce the demand for space heating energy by 13.7%, further pushing the idea of generating renewable energy on every building.

Additionally, in future development, it would be useful to experiment with different configurations of buildings and the ratio of solar PV and thermal installations, as well as the project sizes because the initial idea was to simulate all the buildings in Linz, which are 45000. However, the hardware available for that wasn't powerful enough to do it in an adequate amount of time.

Although this paper shows the massive potential of the current the landscape of modelling tools for modern city energy systems, there are still some challenges related to the availability and quality of these resources. The available ones and good quality usually don't have an easy user interface or vice versa. This work contributes to the general modelling of future smart cities with fully decarbonized energy systems, which is a worthwhile topic to be studied.

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10. Appendix

Python Code:

```
"""
Created on Wed Sep 14 16:14:29 2022
```

```python
@author: ReichelErwinWIVAP&G
"""
import matplotlib.pyplot as plt
import numpy as np

f, a = plt.subplots()
mon = np.linspace(0, 11, 12)

# Generation
ebase = 13  # GWh per Month baseline
epeak = 10  # Seasonal variation
esaison = ebase + epeak * 0.5 * (1 - np.cos(mon / 12 * 2 * np.pi))
#esaison = [36.4,28.9,31.8,19.2,5.8,0,0,0,2.9,20.6,29.3,41.4] for the pv
generation

# Consumption
vbase = 35  # GWh per Month baseline
vpeak = (sum(esaison) - 12 * vbase) / 6  # Seasonal variation

vsaison =
[36.434,28.934,31.848,19.191,5.793,0,0,0,2.899,20.558,29.304,41.387] #Space
heating

#vsaison =
[54.085,44.87,49.735,36.2,23.4,17.175,16.987,17.484,20.056,38.054,46.586,59
.064] #Total demand
#vsaison = vbase + vpeak * 0.5 * (1 + np.cos(mon / 12 * 2 * np.pi))

a.bar(mon + 1, esaison)
a.plot(mon + 1, vsaison, 'r')

stor = [60]  # Storage level January 1st

t = [0]
for m in mon:
    stor.append(stor[-1] + esaison[t[-1]] - vsaison[t[-1]])
    t.append(t[-1] + 1)

a.plot(np.array(t) + 1, stor, 'k-.')

plt.title('Seasonal variation')
plt.legend(['Consumption', 'Storage', 'Generation'])
plt.xlabel('Month')
plt.ylabel('GWh')

mstor = max(esaison - vsaison)
# print("Maximale Speicherleistung: {} TWh/Monat bzw {:2.3g}
GW".format(mstor,mstor*1000/(30*24)))
# print("{:2.3g} TWh in Batteriespeicher a 100 kWh: {:3.3g}
Millionen".format(max(stor),max(stor)*1e12/(Ctesla)/1e6))

figtext = """Maximum storage capacity: XX GWh/Month or YY GW
Necessary storage capacity: 50 GWh
"""
#max(np.array(esaison)-np.array(vsaison))

print(figtext)

plt.savefig("LinzEnergyStorage.png")
```