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Sustainable hydrogen society — Vision, findings and development of a hydrogen economy using the example of Austria

*Alexander Trattner, Manfred Klell, Fabian Radner**

HyCentA Research GmbH, Inffeldgasse 15, A-8010, Graz, Austria

HIGHLIGHTS

- Sustainable hydrogen society to fight climate change and environmental pollution.
- Energy revolution and hydrogen economy as technological solutions.
- Green electricity and green hydrogen in mobility, industry, households and energy services.
- Technical, environmental, economic and social facts and recent findings.
- Implementation on a global level and in Austria.

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ABSTRACT

Based on technical, environmental, economic and social facts and recent findings, the feasibility of the transition from our current fossil age to the new green age is analyzed in detail at both global and local level. To avert the threats of health problems, environmental pollution and climate change to our quality and standard of life, a twofold radical paradigm shift is outlined: Green Energy Revolution means the complete change from fossil-based to green primary energy sources such as sun, wind, water, environmental heat, and biomass; Green Hydrogen Society means the complete change from fossil-based final energy to green electricity and green hydrogen in all areas of mobility, industries, households and energy services. Renewable energies offer a green future and are in combination with electrochemical machines such as electrolysers, batteries and fuel cells able to achieve higher efficiencies and zero emissions.

Introduction and vision

We drive the sustainable hydrogen society, the global solution to the economic, ecological, social, and health threats of climate change and environmental pollution. The sustainable hydrogen society is based entirely on emission-free primary sources and secondary energy carriers following the largely decarbonisation of our energy system by the replacement of the currently predominant fossil fuels with green electricity, green hydrogen and biomass [1]. The energy revolution to sustainable power generation and the hydrogen economy

* *Corresponding author.*
E-mail address: radner@hycenta.at (F. Radner).
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represent the next major industrial revolution, offering not only the prospect of a healthy environment worth living in for future generations, but also the economic opportunity for innovative know-how and technological leadership [2].

First and foremost, the consistent and comprehensive expansion of the regenerative energy sources sun, wind, water, environmental heat and biomass is mandatory. This expansion of mainly green electricity generation guarantees security of supply with local added value and an improvement in the quality of life through zero emissions. For buffering fluctuating power generation and as a storage medium, green hydrogen is produced by electrolysis of water ("Power to Hydrogen") from green electricity, especially during electricity peaks. Hydrogen can also be produced directly from solar power, e.g. by photo-electrolysis [3,4]. The green hydrogen is then stored and distributed in bundles, trailer, containers, large tanks, underground storage facilities or the (natural) gas network. As a carbon-free energy carrier, hydrogen enables a materially closed and emission-free cycle using the conversion with electrochemical cells [5]. Green electricity and green hydrogen can meet all final energy requirements in mobility, industry, households and energy services. Intensive efforts are being made worldwide to promote this industrial revolution and the decarbonisation of the economy [6–8].

This paper presents a path towards a sustainable hydrogen society. Chapter 2 introduces to the current situation of the global energy system. Chapter 3 gives a detailed overview of the relevant technologies for a green hydrogen age. The technology transformation as well as recommendations considering financial and organizational conditions for the implementation of the sustainable hydrogen society on a global scale and using Austria as an example are presented in Chapter 4. Finally, best-practice demonstration projects in which fossil energy carriers are replaced by green electricity and green hydrogen are outlined in chapter 5.

Current situation: fossil age

The Industrial Revolution, the process of change from an agrarian and handicraft economy to one dominated by industry and machine manufacturing began in Britain in the 18th century and from there spread to other parts of the world. The high energy density of fossil fuels led to unprecedented economic and social developments and to a tremendous increase of individual and global prosperity.

Energy system

Global energy consumption depends on the population size as well as on the locally very different per capita energy consumption. With a world population of about 7.8 billion people in 2020, annual population growth lies around 1% per year on average, with very low rates in highly industrialised countries, while parts of Africa show growth rates above 2.5% per year [9]. Energy consumption per capita also varies widely geographically, with highly industrialised countries consuming up to ten times the world average, and developing countries consuming down to below 10% of the world average [10]. The global average energy consumption per capita in 2017 was around 76 GJ, which corresponds to an average daily energy consumption of 208 MJ per capita or an average continuous power of 2400 W. The growing world population and the growing energy consumption lead to an ever increasing energy demand. So far this energy demand has been covered mainly by fossil fuels.

The global primary energy consumption in 2017 reached 585 EJ with around 81% covered by fossil fuels, nuclear around 5%, and renewables including combustible waste around 14% [10], see Fig. 1.

The dominant share of fossil fuels has remained quite constant over the years. The primary energy distribution in the EU and Austria shows a similar picture of fossil fuels dominating, Austria shows a wider share of renewables. Primary energy is converted into its final form in which the energy is used, called secondary or final energy, about 19% of which globally is electricity. The efficiency of this conversion is around 67%, so that about 1/3 of the primary energy is lost [12].

The final energy is distributed and used in nearly equal shares in the sectors mobility, industry, and households and energy services. Mobility is the fastest growing sector and it consumes about 60% of all globally produced oil. Only about half of the final energy is actually utilised as useful energy, the efficiency of the end use being only around 40–50% [1].

In addition to saving energy using a reduction of human energy consumption, there is a high potential for savings in the increase of the conversion efficiencies.

Greenhouse gases

As a result of the natural greenhouse effect, the average temperature of the earth's surface is around 15 °C instead of −18 °C. About two thirds of the natural greenhouse effect is caused by water and about one third by carbon dioxide and methane. These gases are integrated into a natural cycle. The anthropogenic (man-made) part of the greenhouse effect is caused by the emission of so-called greenhouse gases. The simulations of the Intergovernmental Panel on Climate Change (IPCC), which was awarded the Nobel Peace Prize in 2007, show that the sharp increase in greenhouse gases in the atmosphere caused by human activity is responsible for global warming [13]. Climate-relevant greenhouse gases and their global share are listed in Table 1.

About 73% of CO_2-equivalent greenhouse gas emissions originate from the energy sector, primarily from the combustion of fossil fuels. The rest originates from deforestation and land use (9%), livestock farming (6%), agriculture (6%) and industrial processes (6%) [15]. Globally, approximately 35 billion tons of CO_2 are currently emitted annually, which corresponds to an emission of approximately 13 kg CO_2 per capita per day. The CO_2-concentration in the atmosphere is constantly rising, since 2016 it has been above the value of 400 ppm all year round. In Mauna Loa in Hawaii an average value of 417 ppm was measured in July 2021, which is 48% above the pre-industrial level of 280 ppm in the reference year 1750 [16,17].

Scenarios of the IPCC to limit global warming are shown in Fig. 2. Depending on the scenario, an average global warming of 2 °C–6 °C is assumed by 2100, with the limitation to 2 °C

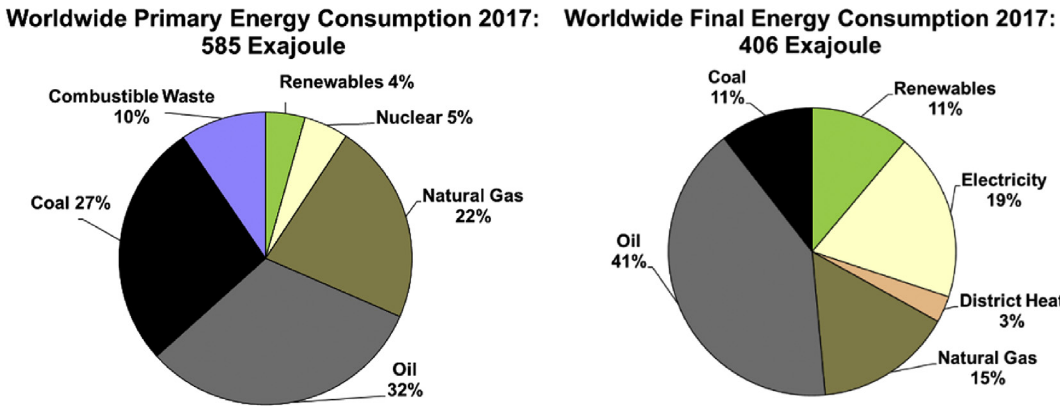

Fig. 1 – Global primary and final energy consumption 2017 [11].

Table 1 – Climate-relevant greenhouse gases with global warming potential (GWP) and their global share [14].

		Global Warming Potential	Global Share
Carbon Dioxide	CO_2	Reference Value	66%
Methane	CH_4	21	17%
Nitrous Oxide	N_2O	310	6%
Partially Halogenated Fluorocarbons		11 300	5%
Fluorocarbons		6500	2%
Sulphur Hexafluoride	SF6	23 900	(including others) 4%

being the most cost-efficient option [18]. The predicted effects of higher warming are catastrophic, ranging from a dramatic rise in sea level, millions of climate refugees, threats to food and water supplies, and extensive extinction of animal and plant species. Weather extremes such as droughts, fire, storms or heavy rain are on the increase and are already causing great damage and rampant costs [19].

To achieve this 2 °C target, an immediate and drastic reduction of CO_2 emissions is necessary, with no more CO_2 emissions by the year 2050 and even "negative" emissions thereafter, see Fig. 2. At the climate conference in Paris in December 2015 (COP 21), a follow-up agreement to the Kyoto Protocol of 1997 was adopted, according to which global average warming should be limited to "well below 2 °C" by the end of the century. The agreement was recognized by 195 states, but binding measures to achieve the 2 °C target are still lacking.

Emission, imission and health

Since the industrial revolution and with the expansion of passenger and freight traffic, emissions from the combustion of fossil fuels have increased so much that they have become a danger to the environment and health. In thermal engines the chemical energy of the fuel is first converted into heat, and only the exergy part of this heat can be transformed into useful e.g. rotational energy. Thus, the maximum theoretical efficiency of thermal engines is limited by the so-called Carnot efficiency η_C depending on the temperature of the environment T_u and the mean upper temperature of the process T_o. During the conversion around 1/3 of the energy must be released into the environment as waste heat loss.

$$\eta_C = 1 - T_u/T_o$$

The quantities of carbon dioxide formed in the ideal combustion process are considerable with high carbon content, see Table 2. In real combustion of fossil fuels a number of other pollutants are produced in addition to carbon dioxide. Incomplete combustion produces carbon, which is the basis

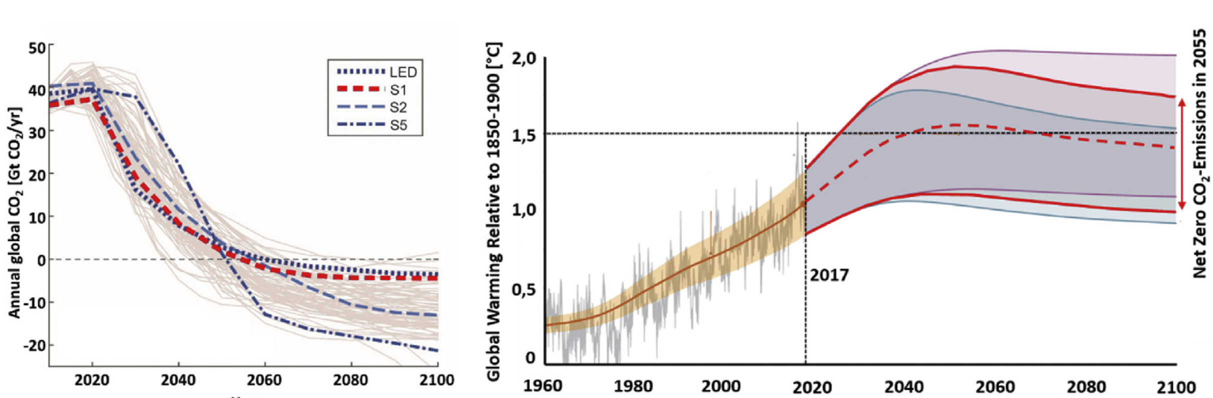

Fig. 2 – Global warming scenarios according to IPCC [20–22]: S1: sustainability oriented scenario; S2: middle-of-the-road scenario; S5: fossil-fuel intensive and high energy demand scenario; LED: scenario with particularly low energy demand.

Table 2 – Carbon dioxide formation of the ideal combustion [23].

	Coal C	Oil C:H = 1:2	Natural Gas CH_4	Hydrogen H_2
kg CO_2/kg fuel	3.67	ca. 3.2	2.75	0
Lower heating value/kg fuel	9.1 kW h	11.9 kW h	13.9 kW h	33.3 kW h
g CO_2/kWh	400	270	200	0

for the formation of soot and particulate matter. Local lack of air leads to the formation of gaseous carbon monoxide and hydrocarbons. High temperatures produce nitrogen oxides and inclusions in the fuel such as sulphur form toxic compounds [23].

The effects of pollutants on environment and health are the subject of numerous studies and publications. In the case of nitrogen oxides and particulate matter, combustion processes in industry and traffic in particular cause limit values to be exceeded worldwide, in some cases to a considerable extent, which can be hazardous to health. Although the mass of particulate matter emitted has decreased in recent years in a number of countries, the number of particles emitted has increased. This means that the size of emitted particles has decreased. Very small particles are emitted, for example, by petrol and diesel engines. Particles smaller than 1 μm can also cause damage to health in the blood and brain. According to WHO statistics, lung diseases are the third leading cause of death globally after heart disease and stroke, and even the first cause of death in low-income countries [24]. According to the OECD, 3.5 million deaths per year worldwide are due to air pollution, 50% of which are caused by traffic, mainly by exhaust gases from diesel engines [25]. 9 million premature deaths from pollution were estimated in 2015, with 90% of deaths occurring in emerging industrial countries, especially in India and China [26]. The resulting economic financial damage is estimated at trillions of Euros per year, equivalent to 5% of global economic output [27].

Outlook: green age

After many decades of the domination of fossil fuels the disadvantages of their emissions of pollutants and CO_2 and the consequences to environment and human health outweigh their benefits. In order to ensure a future worth living, a twofold radical paradigm shift is urgently recommended: Green Energy Revolution means the complete shift from fossil-based primary energy to sustainable and renewable primary energy sources. Green Hydrogen Society means the complete shift from fossil-based secondary energy to green electricity and green hydrogen and an increased application of electrochemical machines. These electrochemical machines like electrolysers, batteries, and fuel cells have the advantages of higher efficiency and zero emissions.

When analysing and evaluating different technologies, technical, ecological and economic aspects are of particular interest. In technical evaluation, efficiency usually plays the biggest role, although its importance is less for renewable energies, where sun, wind and water are available anyway, than for fossil fuels that are consumed. Ecologically, the emission of noise, pollutants and especially CO_2 is important. Economically, costs and prices play the most important role, where of course new technologies cause higher costs due to the necessary development and initially low quantities. The cost of setting up the relevant plants and machines and their recycling and disposal in a Life Cycle Analysis (LCA) is usually also included in the considerations.

In electrochemical machines the conversion between chemical energy and electric energy takes place directly, not via the heat detour. This offers a huge potential for significant efficiency improvement as compared to thermal machines. In a galvanic cell like a battery or a fuel cell, the chemical energy of the fuel is converted directly into electricity. The thermodynamic efficiency η_{th} of fuel cells or batteries is defined by the ratio of the free standard reaction enthalpy , $\Delta_R G_m^0$ which is the standard reaction enthalpy minus the thermodynamic temperature T times reaction entropy $\Delta_R S_m^0$, to the standard reaction enthalpy $\Delta_R H_m^0$.

$$\eta_{th} = \frac{\Delta_R G_m^0}{\Delta_R H_m^0} = 1 - \frac{T \Delta_R S_m^0}{\Delta_R H_m^0}$$

Values depend on the fuel used and the process applied [1]. Typical values of thermodynamic efficiencies of the most common fuel cells range between 83% and 94.5%, see Table 4.

Also, electrochemical machines largely do not have any moving parts, which offers advantages in terms of maintenance and noise emissions. When operated with green electricity and green hydrogen, electrochemical processes are completely emission-free, no pollutants are released, neither health nor environmental toxins, including carbon dioxide.

Energy revolution – green primary energy

The first step is the energy revolution, this is the consistent and comprehensive transition from fossil primary energy sources to the renewable primary energy sources sun, wind, water, geothermal energy, and biomass.

Table 3 gives an overview of the potential of globally available renewable energy sources. The theoretical potential of the renewables is abundant and far exceeds global energy needs. Most technologies for using the listed renewables are globally available and technically mature: hydroelectric power plants, wind turbines, and photovoltaics provide green electricity, biomass, and geothermal energy supply heat and electricity. The practically realisable technical potential of the renewables in Table 3 considers the current state of the art efficiency of conversion into electricity and heat as well as the technical and legal restrictions of use due to geographic location and orientation, terrain, regional planning, nature conservation, and others. This technical potential still far exceeds global energy demand. Table 3 also lists the worldwide utilisation of renewables in the year 2017, which shows that only a small portion of the technical potential has been used so far. Potentials are often specified for different boundary conditions and thus the values in the literature vary, sometimes considerably [28]. Table 3 also shows a range of production costs per kWh renewable energy, including both

Table 3 – Global primary energy potential and production costs for heat and power [11,29–34].

	Theoretical Potential	Technical Potential	Utilisation 2017	Production Costs
	[EJ/a]	[EJ/a]	[EJ/a]	[€/MWh]
Solar Energy - Electric	3 900 000	1600–50 000	1.60	>27
Solar Energy - Heat			0.01	>14
Wind Energy - Electric	6000	85–580	4.10	24–190
Hydropower - Electric	150	50	15.00	26–120
Geothermics - Electric	1400	120 - 1100	0.30	42–265
Geothermics - Heat		10–300	0.14	19–114
Biomass - Electric	1500	50–500	3.40	13–290
Biomass - Heat			3.90	14–310
Total	3 909 050	12 000	28.45	

Table 4 – Standard state values of electrolysis and fuel cell [23,39].

Process	$\Delta_R H^0_m$ [J/mol]	$\Delta_R G^0_m$ [J/mol]	E^0 [V]	η_{th} [%]
Electrolysis - liquid water	285 830	237 130	−1.23	83.0
Electrolysis - gaseous water	241 818	228 570	−1.18	94.5
Fuel cell water liquid	−285 830	−237 130	1.23	83.0
Fuel cell water gaseous	−241 818	−228 570	1.18	94.5
Gross reaction equation of hydrogen	H_2 (g) + ½ O_2 (g) ↔ H_2O (g) H_2 (g) + ½ O_2 (g) ↔ H_2O (l)			

investment costs and operating costs of the plants. Also, these numbers vary considerably according to boundary conditions, technology used, and specific local market settings and environmental conditions.

The geographic distribution of possible technical renewable energy potentials varies widely, but the potential can supply the primary energy demand in abundance [28]. On a local level, energy distribution may be necessary.

In global sustainable energy scenarios, the maximum consumption of fossil raw materials ("peak oil") is usually assumed to occur in the near future with fossils being replaced by renewables from now on, see our scenario in Fig. 3, which is based on a number of recent publications [1,11,20,35]. This scenario is compatible with the sustainability-oriented scenario S1 of the IPCC in Fig. 2, where CO_2 emissions and thus the use of fossil fuels is down to zero by 2050. The decreasing consumption of primary energy during the fossil phase-out is caused by the higher efficiency of electrochemical machines compared to thermal engines. The increase of final energy demand is assumed at up to 1.7% annual following the predictions of the IPCC middle-of-the-road scenario [20]. Even if fossil energy sources were still available, in order to achieve CO_2 emission goals, they must remain in the ground. This fact seems to be widely ignored by fossil biased energy scenarios, where the domination of fossil fuels is unrestrained extended into the next decades [36]. Carbon capture and storage or utilisation are not considered sustainable solutions on an industrial scale to the CO_2 emission problem due to their negative impact on the environment at high costs [15,37,38].

Sustainable hydrogen society – green secondary energy

The second step is the transition to a sustainable hydrogen society, based on the widespread use of green hydrogen as secondary energy carrier.

Hydrogen is by far the most abundant element in the universe and the source of all other elements. On Earth, the hydrogen molecule H_2 occurs almost exclusively in compounds, most often with oxygen in the form of water H_2O, but also in numerous organic compounds. Hydrogen is essential for all forms of life and plays an important role in many electrochemical metabolic processes of plants, animals and humans. At room temperature, hydrogen is a colourless and odourless gas with a low density and the highest specific gravimetric energy of all fuels [1].

The gross reaction equation of hydrogen and oxygen with gaseous (g) or liquid (l) water is the basis for the production of hydrogen from water through electrolysis as well as for the electrochemical "combustion" of hydrogen in a fuel cell. Table 4 shows standard state reaction enthalpy $\Delta_R H^0_m$ and free standard reaction enthalpy $\Delta_R G^0_m$, standard cell potential E^0 and maximum thermodynamic efficiencies η_{th}.

Both electricity and hydrogen are secondary energy carriers, they do not occur in their pure form in nature on an industrial scale and must therefore be produced. Electricity and hydrogen can be produced from a large range of paths by a wide variety of processes [1]. Table 5 gives an analysis of several production paths for electricity and hydrogen showing efficiencies of the production process as well as overall CO_2 emissions and costs including investments and plant operation. The figures differ considerably depending on the literature source chosen, see Refs. [40,41].

At present 95% of the production of hydrogen is based on fossil hydrocarbons, only 5% on water by electrolysis. Within the framework of this paper, only sustainable production processes are considered, i.e. production of electricity mainly from solar power and wind energy, hydrogen by water electrolysis using green electricity or by direct photo-electrolysis [3,52]. Since electrical energy from renewable sources fluctuates and does not depend on demand, large-scale energy storage is required at peak times and for seasonal energy storage of supply [53,54]. Since electrical energy cannot be stored without loss in the long term, the large-scale use of

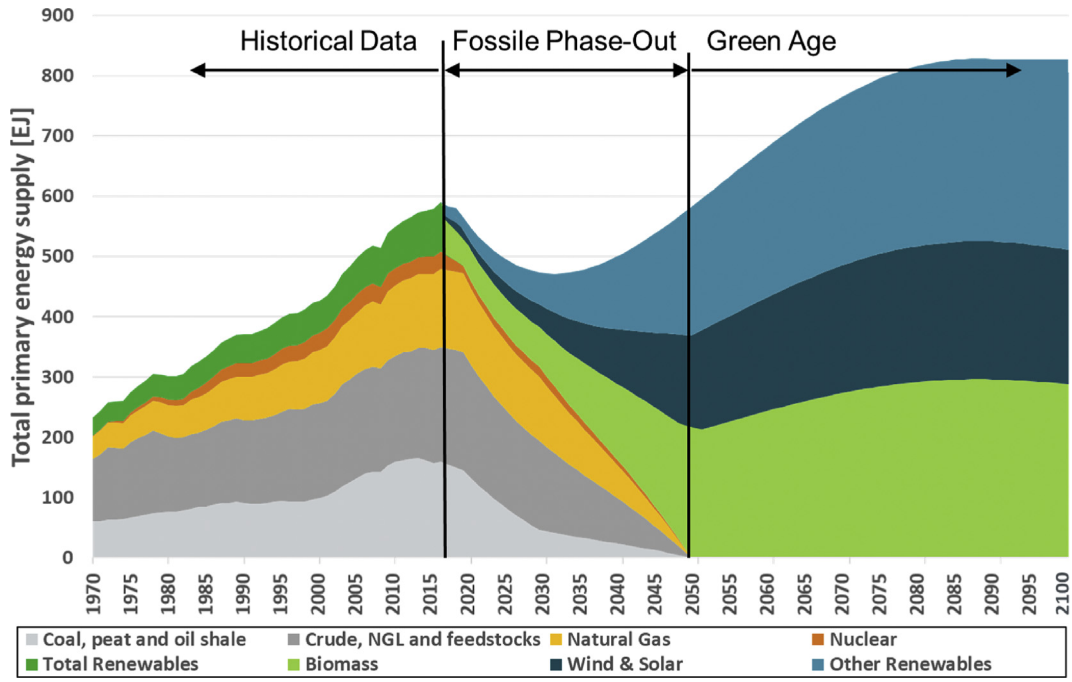

Fig. 3 – Worldwide primary energy supply [1,11,20,35].

Table 5 – Efficiency based on lower heating value [1,42–44], CO_2 emissions [45–48], costs for electricity and hydrogen production [1,33,41,49–51].

Production Path	Efficiency up to [%]	CO_2 emission [g/kWh]	Costs [€/MWh]
Electricity from coal	50%	800 - 1000	60–130
Electricity from gas (power & heat)	60%	500 (270–350)	40–60
Electricity from nuclear	30%	25–50	100–160
Electricity from solar PV	15%	50–70	25–200
Electricity from wind (onshore)	50%	15–20	25–50
Electricity from water	90%	20–40	25–95
Hydrogen from methane	80%	220	9–50
Hydrogen from biomass	55%	25–120	35–250
Hydrogen from electrolysis	70%	20–100	40–290

hydrogen as a new energy carrier offers the absolutely necessary prerequisite for the success of the energy turnaround.

In the long run, hybrid power plants using a combination of e.g. solar PV and wind energy in combination with electrolysers offer the best solution for the low-cost production on green electricity and green hydrogen. Fig. 4 gives a prospect of hydrogen production costs taking advantage of the geographical situation with combined wind and sun usage [41,50].

Big Power-to-Hydrogen [55] hybrid plants are successfully in operation, currently with capacities in the MW range. Green electricity distributed via the power grid and green hydrogen distributed via the gas grid and in containers supply electricity, heat and fuel for all applications in the sense of a regenerative sector coupling in mobility, industry, households and energy services [56]. A number of studies focus on various aspects of the implementation of the hydrogen economy [57–69].

Mobility

Mobility with a current share of fossil fuels at over 90% is the fastest growing emitter of pollutants and CO_2 globally. Electromobility with batteries and fuel cells is the emission-free alternative technology for fossil fuel-driven combustion engines. Analyses in mobility are typically divided into the conversion of primary to secondary energy form, i.e. from the source to the vehicle tank (Well-to-Tank), the conversion of secondary energy carriers to used energy (Tank-to-Wheel) and the entire chain (Well-to-Wheel).

Battery Electric Vehicles (BEV) offer high efficiencies of up to 85% from the charged battery to the road (Tank-to-Wheel) at begin of life and up to 62% Well-to-Wheel. Latest models of passenger cars reach Tank-to-Wheel efficiencies of 82% with energy consumptions of 15–28 kW h/100 km [70–72]. Batteries have low gravimetric and volumetric energy densities, see Table 6 and so are best suitable for short trips with ranges up to 200–400 km for light vehicles. In winter heating energy for

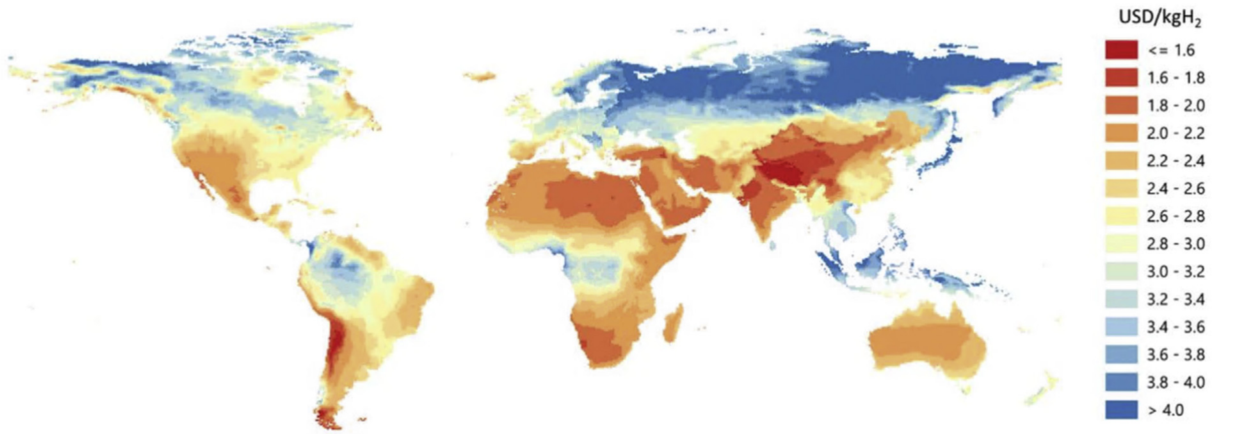

Fig. 4 – Hydrogen production costs from hybrid solar and wind plants [50]'[1].

Table 6 – Energy density, costs and CO_2 emissions of storage technologies [1,71,79–83].

Storage Option	Gravimetric Energy Density in System [kWh/kg]	Volumetric Energy Density in System [kWh/dm^3]	Costs of System Production [€/kWh]	CO_2 Emissions of Production [kg/kWh]
Hydrogen 350 bar	1.9	0.55	13	10
Hydrogen 700 bar	1.8	0.9	17	14
Hydrogen Hydride – Solid[a]	0.3–0.7	0.6–1.3	–	–
Hydrogen Hydride – Liquid[a]	0.3	0.3	–	–
Li-Ion Battery	0.1–0.25	0.1–0.3	130–250	50–125

[a] *No commercial systems available for vehicles.*

the vehicle interior is provided by the battery and can diminish range by 30% or more [70]. Recharging still represents a challenge due to a number of limitations regarding charging infrastructure and technology, impact of ambient conditions, battery cell chemistry or charging time. Depending on the vehicle and charging power, charging stations allow for fast charging of 80% within 20 min. In addition, the charging efficiency with values of 70–95% is dependent on the charging power and battery temperature [70,72–74] and is often unacceptably neglected in well-to-wheel considerations. Since electricity cannot be stored locally without additional energy storage, both charging energy and charging power must be provided directly, which places a heavy burden on the electrical infrastructure.

Fuel Cell Electric Vehicles (FCEV) offer Tank-to-Wheel efficiencies up to 60% [56,75] in the foreseeable future, current models reach Well-to-Tank efficiencies up to 50% with real world energy consumptions of 30–35 kW h/100 km [76,77]. Well-to-Wheel efficiencies can reach up to 40%. Fuel cell technology seems to be more complicated at first sight, the fuel hydrogen is stored in a hydrogen storage system at high pressure, in the cell it is oxidized with oxygen from the air and supplies electricity. In PEM fuel cells at an operating temperature of about 80 °C, the only exhaust gas is pure water. The separation of energy storage and energy converter allows significantly higher energy densities and thus vehicle ranges compared to batteries. Fuel cell driven cars allow for ranges of over 650 km [78] and hence are suitable for longer trips and higher loads, see Table 6.

Even at low temperatures, the functionality of the fuel cell is fully maintained. As with conventional fuels, refuelling is carried out by overflowing from a reservoir at the filling station. This enables significantly higher refuelling performance: if 5 kg of hydrogen are filled up at a refuelling station in 3–5 min, as it is currently usual for passenger cars according to SAE J260 [84], an energy of 167 kW h is transferred in 0.05 h, which corresponds to a refuelling performance of 3.3 MW. The high flow fuelling nozzle TK16 for 350 bar hydrogen fuelling of truck and buses delivers 100–120 g hydrogen per second, thus allowing for a refuelling performance of over 14 MW [85]. By stocking the hydrogen at the filling station, several fuel dispensers can be operated in parallel. Such charging capacities are very hard to reach for batteries, and it is also challenging to provide the required electrical energy at the same time and place to this extent. As far as the infrastructure requirements for charging stations and hydrogen filling stations is concerned, analyses show that for large fleets of 20 million cars, the investment for a hydrogen refuelling infrastructure is lower than for a battery charging infrastructure; however, the specific costs per driven kilometer are comparable [70].

Due to their comparable electric drivetrain, the technological development of both BEV and FCEV could be synergetic [56]. Also, a diversification of technologies reduces the risk of

[1] Source: IEA (2019), [The Future of Hydrogen], [www.iea.org]. *This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.*

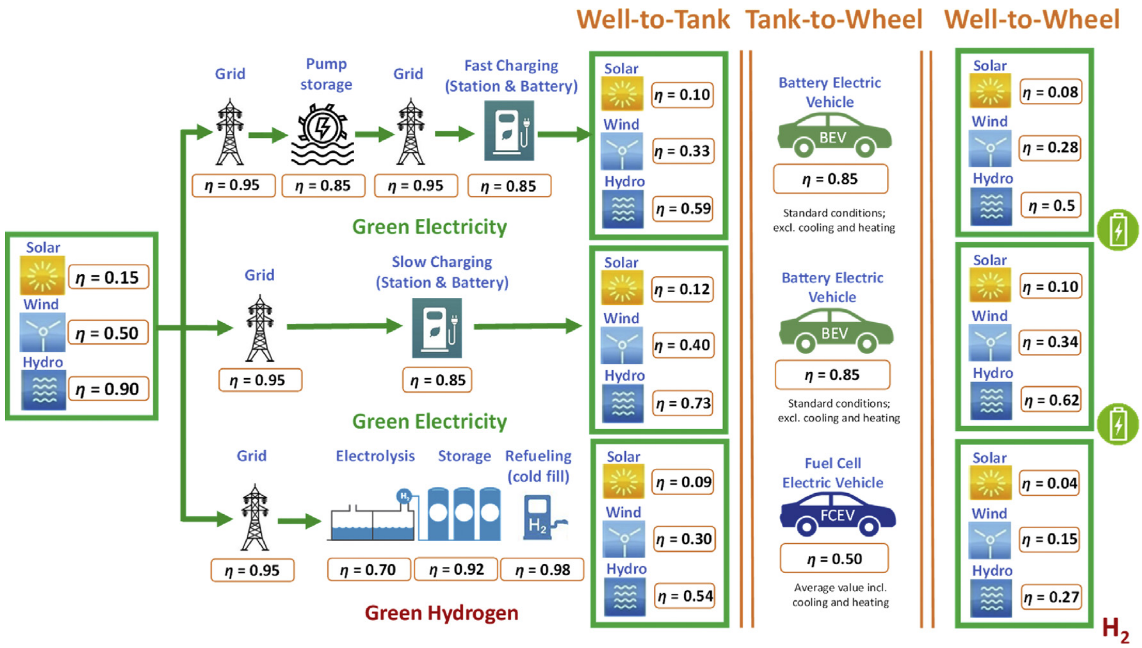

Fig. 5 – Well-to-Tank, Tank-to-Wheel, and Well-to-Wheel efficiencies of fuel cell and battery electric vehicles.

raw material shortages [70]. In a future mobility sector, the technologies must be chosen according to their strengths. The optimal technology for a certain application can be selected by its operational requirements as range, refuelling time or necessary energy density [86]. While BEV tend to be ideal for short distances at low loads, FCEV are suitable for the "Heavy Duty Electromobility", with short refuelling times and long ranges, as heavy cars, trucks, buses and ships and trains without overhead lines.

Biogenic and synthetic "CO_2-neutral" energy carriers could be used in heat engines in fields of application where batteries and fuel cells are not yet competitive, like in ships or planes. However, their claimed CO_2 neutrality must always be critically examined in terms of time and place. The disadvantages of the low efficiency and local emissions of the combustion process remain in any case.

To assess the quality of different mobility options in terms of resource usage, environmental sustainability and cost-effectiveness, the efficiencies, CO_2 emissions and costs have to be considered, with life cycle analyses also taking into account production and disposal. Greenhouse Gas Emissions of live cycle analyses for battery electric and fuel cell electric vehicles show that small BEV with a battery capacity of 45 kW h and a consequent driving range below 250 km have the smallest CO_2 emissions over the vehicle lifetime. With higher driving ranges and higher loads, FCEV have advantages over big BEV vehicles [46,56,80]. Based on shown above data, Fig. 5 gives an overview of achievable efficiencies in mobility. The Well-to-Tank efficiencies and accordingly the Well-to-Wheel efficiencies depend very significantly on the selected primary energy. However, in energy considerations and energy flow diagrams, the generation efficiency of renewable electricity and, correspondingly, of renewable hydrogen is usually neglected [47,87,88].

Industry

Globally industry accounts for a third of final energy consumption and a quarter of CO_2 emissions. Currently 95% of the 50 million tons of hydrogen produced globally and of the 10 million tons of hydrogen produced in the European Union are used in industrial processes [51].

Most of the hydrogen is used in refinery processes for the processing of crude oil, especially for hydrofining and hydrocracking, as well as in the Haber-Bosch process for the production of ammonia, which serves as a starting material for the production of nitrogen fertilizer. Hydrogen and carbon monoxide (synthesis gas) are also the starting materials for the production of liquid fuels from gas, biomass or coal using the Fischer-Tropsch process and for the production of methanol. Hydrogen is also used in the semiconductor industry, analytical chemistry, food chemistry, water treatment and metallurgy.

In many industrial applications, green hydrogen can replace fossil energy carriers, greatly reducing the resulting CO_2 footprint. Hydrogen can replace natural gas as an energy carrier, but changes to the combustion chamber and the burner are needed. The replacement of fossil fuels in industry must be considered depending on the process.

Two-thirds of all energy is consumed by only a few industrial branches (chemicals, petrochemicals and refining, aluminium, cement, iron and steel, pulp and paper), all of which require large quantities of high grade heat above 400 °C to run equipment such as boilers, steam generators, and furnaces [56]. Boilers and industrial furnaces are used in numerous applications for different purposes and processes. In steam generators, thermal energy is used to convert water into steam. The steam often drives a turbine to produce electricity in a power generator. Heat is currently generated by burning fossil or biogenic fuels. Efficiency can be improved through insulation, additional heat exchangers and enhanced burners. For decarbonisation, fossil energy carriers can be completely substituted by green hydrogen and biogenic energy carriers.

For medium- and low-grade heat, from under 100–400 °C, hydrogen can complement electrification and heat pumps.

In the steel industry hydrogen can replace natural gas as fuel in the furnaces and carbon as a reducing agent, first pilot plants are in operation [89].

Stationary motors are used to drive compressed air systems, fans, pumps, refrigeration plants, conveyor systems and other industrial applications. The majority of the drives are electric motors representing the largest electrical consumer of the entire industrial sector. Efficiency can be improved by optimization of the driven units and improvements in the field of electric motors (adapted dimensioning, optimized load and speed control). In the small segment of internal combustion engine drives green hydrogen can completely replace fossil fuels.

Households and energy services

In households and energy services, electrical appliances and machines are widely in use for a variety of purposes and processes.

Room heating and air conditioning in buildings consume around 1/3 of the final energy demand. Efficiency in buildings is largely determined by thermal insulation and the resulting energy efficiency standards as well as individual behavior. A thermal renovation of the current building stock and the implementation of the lowest energy and passive house standard in new buildings can reduce energy demand by half [90]. In addition to the savings in consumption, the further replacement of fossil fuels by green hydrogen, green electricity and green district and ambient heat will result in major savings in greenhouse gas emissions. Heating in cold environments is currently fuelled by natural gas in most countries. Low concentrations of green hydrogen could initially be blended into public natural gas networks, before entire cities could be converted to pure hydrogen heating [56]. Recommended combinations for heating include electric energy for heat pumps with air and soil, heating networks from waste heat utilisation, solar panels and fuel cells [91]. Direct electrical heating should be avoided as its exergetic efficiency is low [53].

For local energy and heat supply, units combining renewable power generation, electrolysis, hydrogen storage and fuel cells for re-generation of electricity are on the market. Gas-condensing boilers, gas-heat pumps, CHP/cogeneration units combining heat and power, and recovery of waste heat increase efficiency. Communities have three main options to decarbonize building heating: waste-heat recovery (e.g., in district heating networks where sustainable sources of waste heat are available), electrification (e.g., installing electrical heat pumps), or transitioning from natural gas to clean hydrogen.

Lighting and electronic data processing (EDP) are important consumers of electrical energy in all sectors [92]. In the lighting sector, huge savings can be made by changing lamp technology (e.g. LEDs) and by modernising lighting and control technology (demand-oriented use).

Implementation tools and costs

Technically, hydrogen applications and electrochemical machines are well developed, they function reliably and are ready for the market. Their so far higher costs have to be reduced by mass production and further specific research.

Overall costs for the green energy revolution are estimated globally at 270 to 410 billion € per year to reach the 1.5 °C and 2 °C climate targets respectively [93]. This seems to be an enormous amount, but in the view of the ongoing health and environmental damage, it is not a question if we can afford this shift, but if we can afford not to engage in it now. Analyses show, that the longer we wait for the implementation, the higher the costs will be [94,95]. On the other hand, using hydrogen at the proposed scale would create a revenue potential of more than 2 trillion € per year. Half of this revenue would come from hydrogen sales, the other half from sales of vehicles, trains, heaters, machinery, industrial equipment, and components. This would create about 30 million new jobs [56,86].

The implementation of measures to reduce CO_2 emissions is proving difficult internationally. Those measures have to implement 3 main strategies to tackle the climate crisis: The shift to renewable primary energy sources, increasing the efficiency of the energy supply chain by a technology shift and a change of the consumption behavior and sufficiency measures to reduce energy demand. Many of the measures are associated with perceived restrictions for people and are therefore unpopular. They are usually expensive and only pay off in the long term. It is up to the resolute intervention of government authorities to conduct this shift.

So far, the political will to shift funds from the fossil economy to the hydrogen economy or to effectively tax CO_2 ("tax steers"!) is flourishing tentatively, often high fossil subsidies are still granted and the time points for implementation are way too late.

Considering this, it is not understandable that the fields of research and climate change had to face budgetary cutbacks in the commission proposal for the EU long-term budget 2021–2027 [96].

In order to implement the changeover from the fossil age to the green age in an efficient way, the following measures have to be taken and imposed by legislation, including the fixing of a definitive date for their completion in order to give long-term planning security to industry and to allow for the ramp-up of alternative energy generation:

- Green primary energy only by the year 2050. Fossil sources have to be replaced completely by solar, wind, water, geothermal and biogenic power.
- Green secondary energy only by the year 2050. Fossil sources have to be replaced completely by green electricity and green hydrogen.

In order to implement this complete decarbonisation, the following tools are indispensable:

- Immediate termination of direct and indirect subsidies for fossil energy

- Immediate implementation of efficient carbon taxing
- Immediate implementation of sectorial driving bans and travel restrictions for fossil driven vehicles
- Immediate termination of the installation of fossil heating systems
- Immediate termination of the installation of fossil power generation

Implementation paths for Austria

Using Austria as an example, it will be shown how the implementation of a hydrogen economy with complete decarbonisation is practically feasible. Despite specific Austrian characteristics, such as a high share of hydropower in electricity generation, an analogous consideration to exit the fossil energy industry can be implemented in any other country. The current situation of the Austrian energy system is shown in Fig. 6.

The primary energy demand in Austria is currently covered by 68% fossil energy carriers, only a third by renewable sources. About 95% of the fossil energy sources are imported. Numerous studies have analyzed the technical thermal and electric potentials of renewable energy sources in Austria [95,97–100], as well as the local distribution of useful exergy demand and exergy potential in Austria [53,54]. The average of these studies shows that the total energy generation in Austria can be covered completely by renewable energies if the technical potential is fully exploited and end energy technologies are adapted. For the Austrian implementation path shown in Fig. 7, the technology transition and energy demand reduction measures according to chapter 3 were applied. No sufficiency measures were considered. Table 7 gives an overview of the applied scenario for Austria's renewable energy system.

The conversion to a green energy system in Austria means the full replacement of fossil fuels in the final energy sectors by 55 TW h of green electricity and 53 TW h of green hydrogen, see Fig. 7.

The substitution of fossil feedstocks or energy carriers in industry must be considered separately depending on the process. For example, in the steel industry hydrogen can replace carbon as a reducing agent. For this purpose, an additional 20 TW h of green hydrogen were considered, resulting in a total of 73 TW h of hydrogen for the entire energy system. To calculate the total energy demand, hydrogen is assumed to be produced by electrolysis with an average efficiency of 70% with green electricity. In total, to produce 73 TW h of hydrogen through electrolysis 104 TW h of green electricity are required, resulting in a total green electricity demand of 162 TW h. In this way, all primary and final energy sources in Austria could become renewable and sustainable. The sustainable energy flow chart of this future Austrian renewable energy system with the described gains in efficiency and equal final energy output is shown in Fig. 8.

Costs of energy transition in Austria

Non-action in climate policy and its economic consequences for Austria are being analyzed in numerous ongoing and completed research projects. The Covid 19 crisis creates a unique opportunity for government policies to promote sustainable and healthy structures at lower financial, social and political costs than would otherwise have been possible: Fossil energy prices at the lowest possible level facilitate the reduction of environmentally harmful subsidies and an earlier introduction of the planned CO_2 pricing. Failure to act in climate policy is already a burden on our society in Austria today (2020): Fossil imports cause value added losses of around 8 billion € annually, environmentally harmful subsidies cost the public budget around 4 billion € annually, the public sector spends around 1 billion € annually on climate change adaptation, and weather and climate-related damage currently averages at least 2 billion € annually. The latter is expected to be in the range of at least 3 billion to 6 billion € around 2030 [94,101–104].

Renewable power generation technologies generally have high investment and low operating costs. Electricity generation from water, wind and sun does not generate any fuel costs as is the case with fossil fuels. Running costs include personnel, maintenance, plant renewal and insurance. The

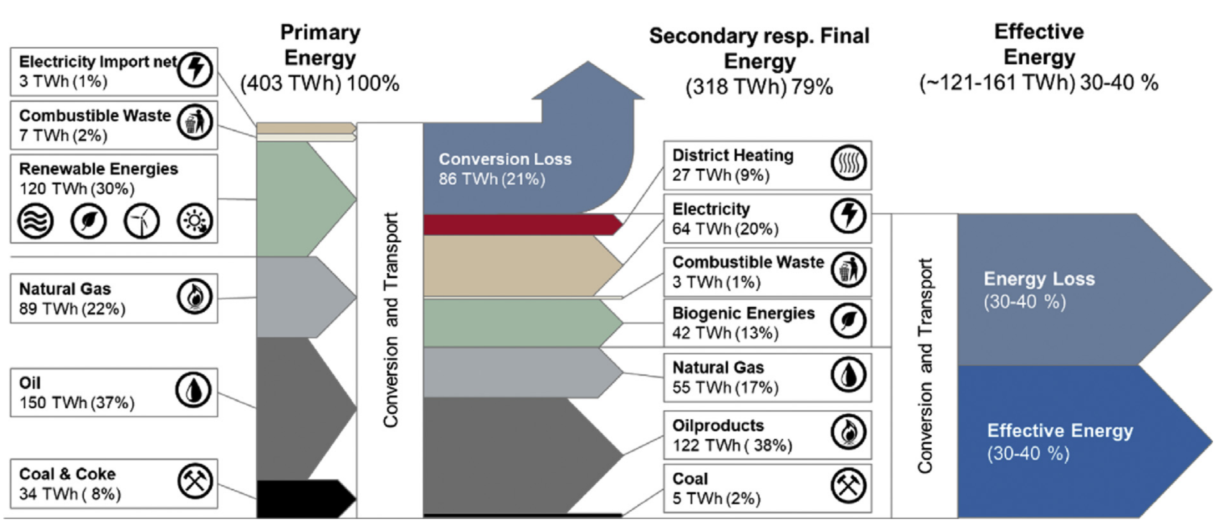

Fig. 6 – Energy flow chart of the 2019 energy system in Austria based on fossil fuels [92].

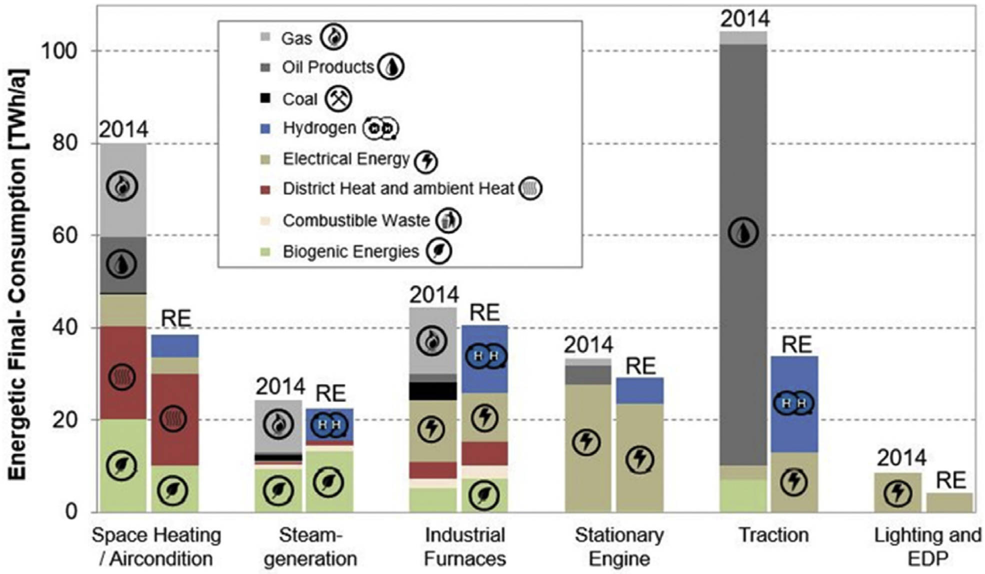

Fig. 7 – Savings in final energy demand by sectors – Comparison of renewable energy system (RE) and energy consumption 2014 in Austria [1,87,92].

Table 7 – Applied scenario for the reduction of Austrias primary energy demand based on chapter 3 [1].

Sector	Adaptions
Space Heating & Airconditioning	Reduction of heating demand by 50% through thermal refurbishment and replacement of fossil fuels with green electricity, hydrogen and ambient heat.
Steam Generation	Reduction of energy demand by 15% through insulation, additional heat exchangers and enhanced burners and substitution of methane by green hydrogen.
Industrial Furnaces	Reduction of energy demand by 10% through improvement measures, such as minimising heat losses through insulation and the use of improved burners. Substitution of fossil fuels by green electricity, green hydrogen and biofuels.
Stationary Engines	Reduction of electric motor energy demand by 15% through optimized operating mode and power adjustments. Fossil fuel combustion processes are replaced by hydrogen combustion.
Traction	Reduction of energy demand by transition of the vehicle fleet to electric vehicles with share of 50% battery electric vehicles and 50% fuel cell electric vehicles under the assumption of unchanged traffic behavior.
Lighting and EDP	Reduction of energy demand by 50% through modernization of lighting and control technology (demand-oriented use).

fixed and variable costs result in the electricity production costs. Electricity generation costs are shown in Table 3. The costs for the necessary expansion of renewable energy production of 118.7 billion € are obtained by multiplying the investment costs for the full extension of electricity from hydropower, wind energy and photovoltaics with the required annual energy requirement according to Table 8.

Imports of fossil energy sources cause annual cost of approximately 9.2 billion € in Austria, resulting in costs of 25 million € per day [92]. This sum is ultimately available in the decarbonisation of the Austrian energy system for the transition from the fossil-based to the regenerative-based energy system.

In addition to the production costs of the various energy sources, taxes and levies have a major influence on the price for end customers. This leads to significant price differences between households and industry. For the conversion of the energy system controlling measures in the energy policy are urgently necessary, e.g. by a consideration of the climatic damages and a functioning emission trade can cause environmental-promoting shifts in the price structure.

The implementation of energy system transformation and hydrogen economy in Austria is technically and economically possible, with corresponding will of politics and economy and with corresponding involvement of the population this vision can be implemented in the next decade. In addition to the complete freedom from emissions of the entire energy system, we achieve domestic and local value creation, energy self-sufficiency, security of supply, import independence and international know-how leadership as additional advantages.

Best practice examples

An excellent way for research, industry and the civil society to experience the benefits of the energy system transformation

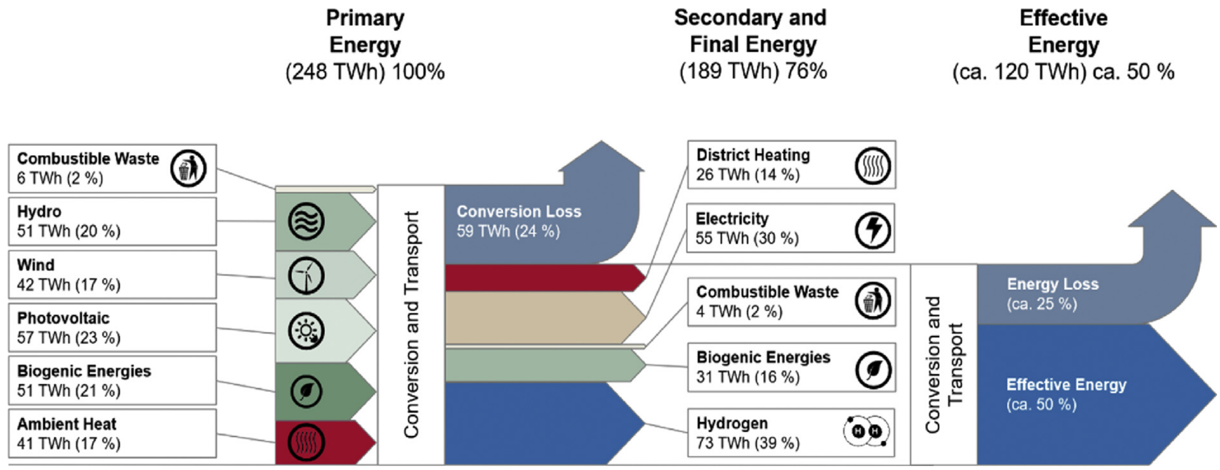

Fig. 8 – Energy flow chart of the future Austrian renewable energy system by 2050 [1].

Table 8 – Costs of setup of the renewable energy system [1].

	Existing (in TWh/a)	Required (in TWh/a)	Expenses (in billion €)	Investment Cost (in €/kWp)
Hydropower	39.9	51	13.3	5000–7000
Wind Power	3.0	42	20.8	1500–1700
Photovoltaics	0.6	57	84.6	900 - 1800

and the hydrogen economy is to carry out demonstration projects in which fossil energy carriers are replaced by green electricity and green hydrogen.

On a European level, the recently launched European Clean Hydrogen Alliance serves as a springboard for kick-starting the industrialization of hydrogen technologies fostering knowledge and pushing for fact-based policy making ensuring that the European regulatory framework enables the role of hydrogen in our society. Hydrogen Europe is the European association representing the interests of the hydrogen and fuel cell industry and its stakeholders promoting hydrogen as the enabler of a zero-emission society. With more than 160 companies, 83 research organizations and 23 national associations as members, Hydrogen Europe encompasses the entire value chain of the European hydrogen and fuel cell ecosystem collaborating in the Fuel Cell Hydrogen Joint Undertaking [105].

A wide range of best practice examples in Austria is supported by the Climate and Energy Fund in all three sectors of mobility, industry and households and energy services [106]. One of the most comprehensive projects supported is the WIVA P&G, Hydrogen Initiative Energy Model Region Austria – Power and Gas, of which HyCentA Research is a founding member [107,108]. In WIVA P&G leading Austrian industrial companies and research institutions are demonstrating the feasibility and practical operation of all mentioned components of the energy system transformation and hydrogen economy to the public in networked projects distributed all over Austria in the fields of green mobility, green industry and green energy, see Fig. 9. From the large number of green hydrogen projects underway, this publication highlights just a few illustrative examples [109].

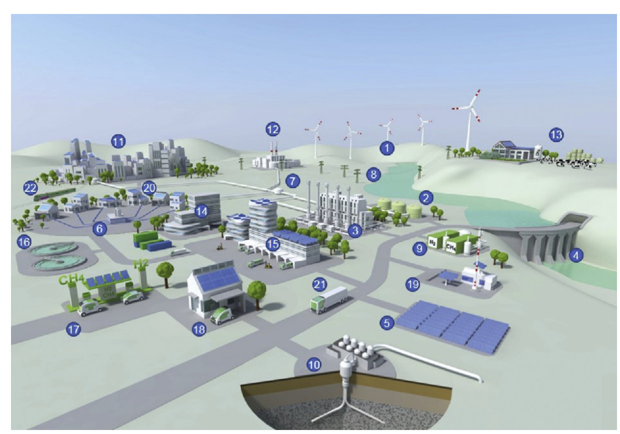

Fig. 9 – Future energy system - WIVA P&G [108]. Energy supply: 1 Wind power plant, 2 Biogas plant, 3 Gas power plant, 4 Hydro power plant, 5 PV power plant; Energy distribution and storage: 6 Regional gas grid with municipal storage, 7 Supra-regional gas grid, 8 Electricity grid, 9 Central electrolysis/methanisation plant, 10 Hydrogen/natural gas storage; Energy use: 11 Smart City and zero-emission public transport, 12 Green industrial processes, 13 Energy-autonomous agriculture and small businesses, 14 Smart buildings, 15 Green intralogistics, 16 Sewage treatment plants, 17 Hydrogen/gas/electric filling station, 18 Energy-autonomous single-family house, 19 Energy-autonomous remote station, 20 Smart village, 21 Zero-emission heavy traffic, 22 Zero-emission rail traffic.

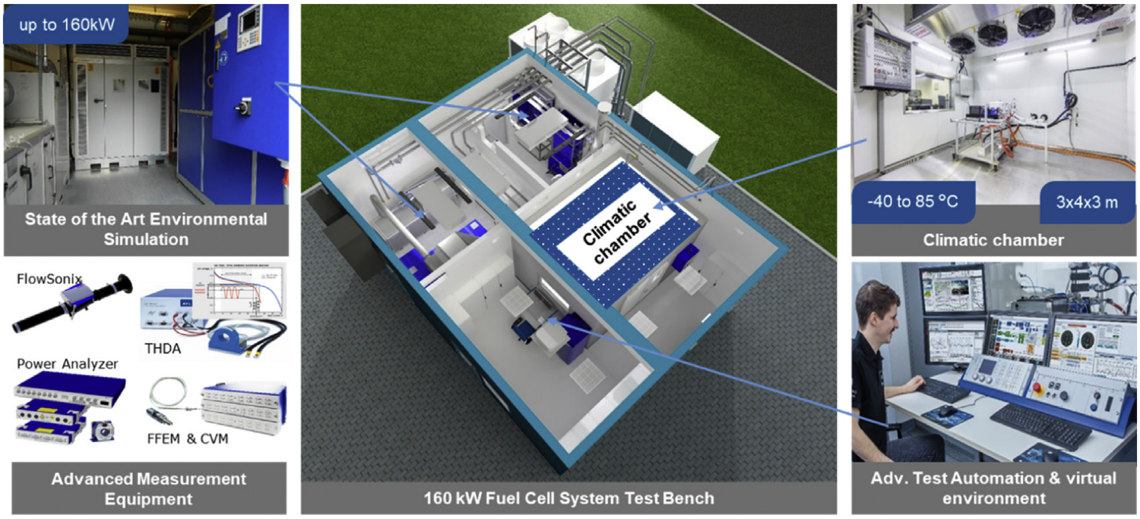

Fig. 10 – Project HIFAI-RSA

Mobility

Due to its high visibility and emotional significance mobility is a main field for early applications of green electricity and green hydrogen in electromobility. The development of fuel cells and batteries, their adaption for different applications and their integration into a specific vehicle is a demanding task that relies on highly complex infrastructures as well as the know-how of experienced researchers. Several excellent hydrogen research institutions offer their support in this respect to vehicle manufacturers.

Testing infrastructure HIFAI RSA[2]

An example for a test infrastructure for PEM fuel cells is the HIFAI-RSA (Highly Integrated Fuel Cell Analysis Infrastructure – Research Studio Austria) test-stand of HyCentA [110,111], see Fig. 10.

In this project, for the first time in Austria and Europe, the project partners HyCentA and AVL have set up a highly integrated test infrastructure in which fuel cell systems are integrated as hardware in the loop (HiL) in a virtual overall system and in which the vehicle, driver and driving cycle are simulated by software in real time. This allows fuel cell systems to be dynamically operated, analyzed and optimized under real load and environmental conditions from $-40\ ^\circ C$ to $+85\ ^\circ C$ for stationary and mobile applications. The application-oriented research topics that can be carried out with the test bench range from energy to thermal management and vehicle integration to the investigation of the dynamic behavior, cold start behavior and aging behavior of fuel cell systems [112,113].

Fig. 11 – KEYTECH4EV [106,123].

Example: hydrogen snowmobile HySnow[3]

Decarbonisation in winter tourism is demonstrated in the highly innovative and holistic flagship project HySnow funded by the climate and energy funds, see Fig. 12 [114–116].

Fig. 12 – HySnow fuel cell snowmobile and infrastructure.

[2] Project partners: HyCentA Research GmbH, AVL List GmbH; Funded by: bmwfw - Bundesministerium für Wissenschaft, Forschung und Wirtschaft, FFG - Österreichische Forschungsförderungsgesellschaft mbH.

[3] Project leader: BRP-Rotax GmbH & Co KG, project partners: HyCentA, TU Graz, Fronius, Elring Klinger, ECUSOL, Hinterstoder/Wurzeralm Bergbahnen. Funded by: Climate and Energy Fund.

Fig. 13 – Move2zero - Bus testing and refuelling at HyCentA [129].

A 30 kW peak photovoltaic plant has been set up to produce green electricity at around 1600 m above sea level. This plant is directly coupled to the electrolyser producing green hydrogen. The on-site hydrogen production is integrated in the on-site refuelling station with 350 bar. Two prototype snowmobiles were developed, including operation strategies and improved stack design of the fuel cell system for low temperature and high-performance targets and the integration of the powertrain into the vehicle [117]. The results of this project show that PEM fuel cell drives can be used for the highest performance requirements, integrated into small installation spaces and successfully used under the most challenging conditions such as permanent negative temperatures, high sea altitude and high vibrations. Since 2020, the whole chain of the emission-free application in winter tourism is demonstrated under real-life operating conditions in an Austrian top winter tourism area. The concept of decarbonisation in this winter tourism sector has been adopted by others for snow groomers.

Example: hydrogen cars KEYTECH4EV[4]

The highly innovative approach of the KEYTECH4EV project is to combine PEM fuel cell and battery technologies into a dedicated hybridized powertrain architecture following the strategy of a mid-size concept (around 60 KW fuel cell and battery size around 10 kW h). This mid-size concept reduces overall powertrain costs in comparison to FC dominant powertrain concepts and pure BEVs. The developed key technologies comprise the stack, fuel cell system, injector/ejector anode system, hydrogen-tanks, thermal management, energy management, and controls. Moreover, a completely integrated diagnosis functionality was integrated into the fuel cell system, which enables diagnosis-based system control. Finally, a C-segment fuel cell hybrid demonstrator vehicle shows the functionality of the technological solutions developed. By this, KEYTECH4EV and comparable projects significantly contribute to the reduction of the main barrier of electromobility, i.e. range anxiety, drivability, durability and high vehicle cost, see Fig. 11 [118–122].

Example: hydrogen busses and project Move2zero[5]

Considering the high energy density of hydrogen and the advantages of FCEV powertrains, FCEVs will be especially important in decarbonizing buses, heavy-duty transportation, and non-electrified trains. Fuel cells busses have thoroughly been tested since years and several hundred busses are in operation world-wide. In Europe around 100 fuel cells busses are in operation and more than 11 million km have been driven up to August 2020 [124].

Move2zero is developing a concept for the gradual decarbonisation of the entire public transport bus fleet in Graz, see Fig. 13. Based on the results and facts of the several years lasting demo of 4 battery and 4 fuel cell busses, the best mix of zero-emission bus technology and the corresponding renewable supply infrastructure is developed. Hence, move2zero will pave the way for an efficient and effective stepwise conversion of urban bus fleets towards an emission-free future [125–128].

Example: hydrogen trains and project HyTrain[6]

Due to their advantages in heavy-duty applications, fuel cells are a suitable drive for trains, especially when lines are not electrified. The installation of overhead contact lines is cost-intensive, uneconomical on sections of line with low-capacity utilization, and often undesirable in scenic and tourist areas.

A pioneer in the field is Alstom group with its Coradia iLint – the world's 1st hydrogen powered train, in operation first in Germany, now also approved in Austria, see Fig. 14 [131,132]. The train has a range of 600–800 km with the stored 180 kg of hydrogen and the installed fuel cell power of 400 kW enables a top speed of 140 km/h.

The lighthouse project HyTrain will use Austrian know-how to bring the hydrogen-powered (narrow-gauge) trains to market maturity. This includes the development of the hydrogen drive train and the facility for refuelling the train with green hydrogen [133–135]. The project is supporting the implementation phase on the H2Zillertal Railway.

The hydrogen-electric train system is to be designed for heavy-duty train applications (suburban train operation with high acceleration capacity), simulated on the HyCentA test bench and tested on a train platform of the Zillertal Railway. The project focuses on the development of fuel cells systems for heavy duty applications. Subsequent extensive tests on the narrow-gauge track in the Zillertal will provide insights into the robustness, durability, reliability, service life, cold start characteristics etc. of the system in order to be able to further optimize the overall powertrain.

Industry, households and energy services

Infrastructure projects and industrial processes form focal points in the supply and application of green electricity and

[4] Project leader: AVL List GmbH, project partners: Elring Klinger AG, Magna Steyr Engineering AG, HOERBIGER Ventilwerke GmbH, HyCentA Research GmbH, IMM – TU Vienna, CEET – TU Graz, IESTA - Institute for Advanced Energy Systems & Transport Applications. Funded by: Climate and Energy Fund.

[5] Project leader: Holding Graz – Kommunale Dienstleistungen AG, 13 project partners from industry and research including HyCentA Research GmbH. Funded by: Climate and Energy Fund.

[6] Project leader: FEN Sustain Systems GmbH, project partners: Zillertaler Verkehrsbetriebe AG, HyCentA Research GmbH, Molinari Rail Austria GmbH, WIVA P&G – Wasserstoffinitiative Vorzeigeregion Power & Gas. Funded by: Climate and Energy Fund.

Fig. 14 – Fuel cell train Coradia iLint by Alstom [130].

green hydrogen in the industrial and household sectors. In the energy sector, hydrogen plays a vital role to enable blackout-proof and reliable electrical energy supply based on renewable energy.

Example: power to power plant in Hy2Power[7]
Within the project Hy2Power an overall technology concept which can compensate the increasing fluctuations in the electricity grid by supplying power control reserve was developed. For this purpose, suitable technologies for energy storage, hydrogen production and power generation were combined, see Fig. 15. The technology concept stores surplus electricity by electrolysis in the form of hydrogen or with battery storage systems and feeds it back into the power grid when needed.

Using the highly sophisticated simulation tool HYDRA (hydrogen infrastructure simulation and optimization tool [136–138]) the plant topology and operation strategy taking into account real market data and future forecasts were designed. The best fitting plant concepts from a technical point of view were additionally subjected to an economic analysis. This allowed the identification of an optimal topology of the plant for the specific application as well as a desired operating regime.

The designed Power-to-Power plant was optimized for a total capacity of up to 15 MW. The demonstration of the designed hybrid reconversion module takes place at the LEC high-tech full engine test bench [139].

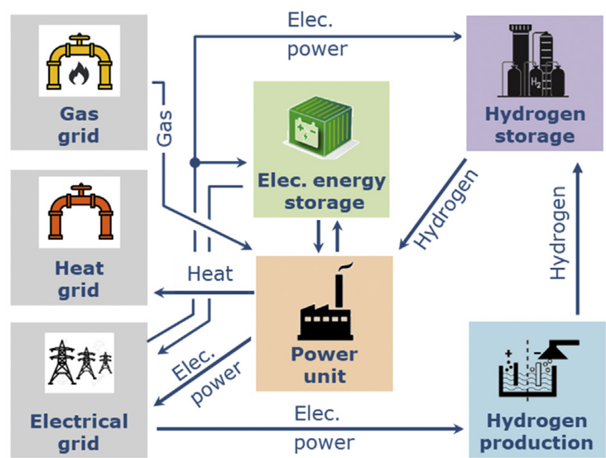

Fig. 15 – Power-to-Power plant layout of project Hy2Power [139].

Example: power to hydrogen plant Wind2Hydrogen[8]
The Wind2Hydrogen research project was primarily aimed at gaining new insights into the storage of hydrogen in the natural gas grid. For this purpose, a power-to-gas pilot plant in the order of 100 kW – the first of its kind and size worldwide – was realized at the site of the OMV gas station Auersthal in Lower Austria in 2017, where wind energy was converted into hydrogen by electrolysis see Fig. 16 [140–142].

As requirement for a power to gas-overall solution for Austria, a pilot plant was realized in this project. This included the development of a new, module interconnected high-pressure PEM electrolyzer at 200 bar, which produces hydrogen flexibly with the aid of renewable wind electricity [143]. The produced hydrogen can be stored and transported without any mechanical compression, or it can be fed into the natural gas grid. In the process, important experience was gained on control technology and quality control, but also on planning and operation, as well as on economic and ecological questions. In addition, business models for possible further plants were run through and designed.

Example: hydrogen filling stations UpHy[9]
The aim of the project UpHy – Upscaling of green hydrogen for industry and mobility – is the production of green hydrogen on an industrial scale with a world-scale electrolysis and its use for industry and mobility. On the one hand, it will be used as fuel for public bus lines in the Vienna area and on the other hand, it will be used for industrial applications in the hydrogen hub of the refinery, e.g. for the hydrogenation of CO_2

[7] Project leader: LEC GmbH. Project partners: INNIO Jenbacher GmbH & Co OG, VERBUND Thermal Power GmbH & Co KG, Graz University of Technology - Institute of Internal Combustion Engines and Thermodynamics, HyCentA Research GmbH, AIT Austrian Institute of Technology GmbH. Hy2Power is a project in the COMET Centre LEC EvoLET, Funded within the COMET – Programme by BMK, BMDW and the Provinces of Styria, Tyrol and Vienna. The COMET Programme is managed by FFG.

[8] Project leader: OMV Gas & Power, project partners: Fronius, EVN AG, HyCentA Research GmbH, Energieinstitut at JKU Linz. Funded by: Climate and Energy Fund.

[9] Project leader: OMV Downstream GmbH, project partners: WIVA P&G, Verbund Energy4Business GmbH, Energieinstitut at JKU Linz, VF Analysen-und Messtechnik GmbH, HyCentA Research GmbH. Funded by: Climate and Energy Fund.

Fig. 16 – Project Wind2Hydrogen.

from exhaust gas streams to produce sustainable fuels [144,145].

Within the project, the construction of an electrolysis plant of up to 10 MW is planned. This is a unique size for Austria, which, in addition to lower manufacturing costs, will demonstrate for the first time both the service life and the highest availability for commercial use in industry and mobility. In addition to the electrolysis, the development of the entire value chain with hydrogen purification, hydrogen trailer loading, trailer logistics with 300 bar trailers used for the first time in Austria as well as a highly available, energy-optimized bus filling station is planned.

Examples: hydrogen industrial processes

Other Austrian WIVA P & G projects using hydrogen in industrial processes include H2Pioneer and H2Future.

In H2Pionieer[10], a demonstration plant for the production of high-purity hydrogen from renewable electricity sources is implemented at Infineon in Villach, and the recyclability of hydrogen used in the semiconductor industry is analyzed [146,147]. As part of the EU-funded H2Future[11]project, partners are researching into the industrial production of green hydrogen as a means of replacing fossil fuels in steel production over the long term [148,149]. What is currently the world's largest pilot plant for the CO_2-neutral production of hydrogen has successfully commenced operation at the voestalpine site in Linz in 2019, simultaneously setting an international milestone in the advancement of new energy supply options.

Example: renewable gasfield[12]

The Renewable Gasfield research project takes a comprehensive Power-to-Gas approach, generating green hydrogen from renewable electricity by electrolysis and combining a catalytic methanation on a large scale for sustainable energy supply in the sectors heating, mobility and industry.

Based on green electricity from photovoltaics, a PEM electrolysis will produce up to 168 000 kg of hydrogen annually. Some of the hydrogen will be processed in the methanation plant with CO_2-containing waste gases from an existing biogas plant to produce green natural gas. Green hydrogen and green natural gas will be used in a local heat network for heating purposes, green hydrogen will be used in mobility and industrial processes, green natural gas will be fed into the natural gas infrastructure [150–152].

Conclusion

The green energy revolution and the sustainable hydrogen society described in this paper are definite solutions for the complex problems of climate change and emissions: Fossil fuels like coal, oil, and gas must be abandoned entirely and have to be replaced by renewable primary energy sources from water, wind, and solar energy supported by the secondary energy carrier hydrogen, see Fig. 17.

These solutions are not only theoretical approaches, but it was shown in general, that the technical, organizational, and financial conditions for the implementation of the energy revolution and the hydrogen economy can be met with some effort given the willingness to change.

These solutions have been voiced and advocated by a large number of prospective thinkers and responsible scientists for decades already [2,5,6]. So, it is the responsibility of politicians and public authorities in cooperation with industry to lead through this transition by issuing necessary legal and fiscal regulations. In the long run, security of supply, security of employment and affordability can only be guaranteed by a shift to a sustainable economy. The threats to economy and health by climate change and pollution far

[10] Project leader: Verbund Energy4Business GmbH, project partners: Infineon Technologies Austria AG, HyCentA Research GmbH, Energieinstitut at JKU Linz, WIVA P&G. Funded by: Climate and Energy Fund, FFG.

[11] Project partners: voestalpine, Verbund, Siemens, Austrian Power Grid, K1-MET and TNO.

[12] Project leader: Energie Steiermark, project partners: Montanuniversität Leoben, HyCentA Research GmbH, Energieinstitut at JKU Linz, WIVA P&G, Energienetze Steiermark, Energie Agentur Steiermark gemeinnützige GmbH, Amt der Steiermärkischen Landesregierung, Verbund Energy4Business GmbH. Funded by: Climate and Energy Fund.

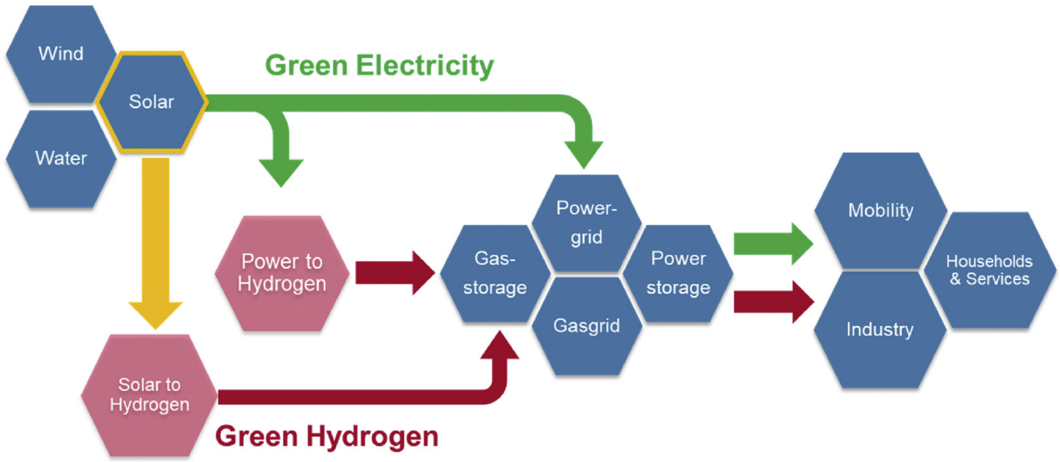

Fig. 17 – Vision of a sustainable hydrogen society.

outweighs any consequences that we have seen in recent crises.

Energy turnaround and hydrogen economy represent the next step in technological evolution towards an emission-free and sustainable energy system. The measures for their implementation require a courageous reorientation of society, economy and politics. In the light of growing unrest by scientists and especially young people with the hesitancy regarding the necessary transition steps in our economy [153–155], it remains to be hoped that this path of energy transition is recognized quickly as the chance that it poses for the health and liveable environment of future generations.

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Author credit

Alexander Trattner: Conceptualisation, Writing - Original Draft - Review & Editing, Supervision.

Manfred Klell: Conceptualisation, Writing - Original Draft, Review & Editing.

Fabian Radner: Investigation, Writing - Original Draft, Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations in general

BEV	Battery Electric Vehicle
EDP	Electronic Data Processing
EU	European Union
COP 21	United Nations Framework Convention on Climate Change, 21st Conference of the Parties
FCEV	Fuel Cell Electric Vehicle
IPCC	Intergovernmental Panel on Climate Change
OECD	Organisation for Economic Co-operation and Development
CHP	Combined Heat and Power

Symbols used in equations

η_C	Carnot efficiency
η_{th}	Thermodynamic efficiency
T_U	Lower process temperature or ambient temperature
T_O	Highest process temperature
T	Thermodynamic temperature
$\Delta_R G_m^0$	Free standard reaction enthalpy
$\Delta_R S_m^0$	Standard reaction entropy
$\Delta_R H_m^0$	Standard reaction enthalpy
E^0	Standard cell potential

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