Deep Dive Hydrogen Economy – A Radical Alternative

Final Report

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Introduction & Approach

Hydrogen economy – a radical alternative

What could a European hydrogen-abundant energy system look like in 2040 in the context of different global, political, economic and social constellations in and around the continent?

Climate change and the limitations of fossil fuels call for decarbonisation and the shift to alternative energy production, storage, and carrier systems. The renewable energy sector is booming, which clearly indicates that the transition is already taking place. The future success of renewables seems inevitable, with their prices being lower than those of fossil fuels. Hydrogen (H_2) technologies will play a central role when it comes to realising and finalising this transition on the scale of the whole economy.

Hydrogen technologies are not new. The principle of how a fuel cell functions was first discovered in 1801. The first fuel cell was operational in 1838. Even the term "Hydrogen Economy" was already coined in the 1970s. Hydrogen is the most abundant element in the universe. Chemically, it is the smallest and most lightweight molecule. Together with oxygen, it forms water. In this chemical reaction of H_2 and Oxygen (O_2), energy is set free in the form of heat. The process of electrolysis splits water "back" into H_2 and O_2 with the help of electric energy. A fuel cell then facilitates the opposite process of generating electricity through the reaction of H_2 and oxygen. Such a reversible and manageable reaction creates the potential to "store" energy by simply splitting water and capturing H_2. This energy is then available for later use and even transferable to different locations. Such a characteristic makes hydrogen interesting as a fuel, offering a sustainable alternative to fossil fuels. Despite today's inefficiencies in converting energy from renewables to H_2 and back to power, it could be a versatile energy carrier and a central element in storing energy to capture potential overcapacities in a fully renewable energy system. Next to its potential relevance for the energy system, hydrogen is an essential compound in the chemical industry and can play an increasing role in steel production.

However, hydrogen needs to be produced, stored and transported securely and reliably. Furthermore, the final use for a consumer or in any industrial or technical process must be safe. Different technologies are already available today for all the different stages. However, most of the infrastructure still needs to be installed, while the processes and governance of the energy system must be reconfigured. Such reconfigurations are mainly a question of the economy (investments/production), society (acceptance/cost/organisation) and policy (regulations of the transition/incentives).

Green hydrogen offers a sustainable alternative to fossil fuels, changing the world of energy supply completely – (1) geopolitically, as some countries depend on renewable energy sources for their energy supply and not on other countries; and (2) in terms of the market structure, since there will be no more dependence on a small number of all-powerful oil, carbon and gas companies.

The scenario approach

The scenario process aimed to develop positive scenarios based on the following central questions:

- What does Europe look like with a renewable energy system including hydrogen systems?
- What are the socio-economic conditions in which the energy system needs to be set up and how can the transition be a success?
- How to prepare the context for the energy transition? Which developments support and hinder the transition?
- How can and must European R&I policy support the transition?
- Where are the obstacles, drivers, and barriers?
- Are we at risk of running into lock-in effects?

The scenarios were developed in four steps using a participatory approach.

Step 1:

The first step explores the so-called scenario field. This exploration is a kind of systems analysis where key factors are identified. First, influencing factors are collected based on a search scheme (e.g., STEEP-Scheme: social, technological, economical, ecological and technological). In the next step, the most uncertain and impactful factors are selected as key factors, as they are highly relevant for the topic and in many cases have great variability in their potential future development.

Step 2:

In the second step, so-called future projections are built for each key factor. The aim is to identify up to five different future states while avoiding selecting only the most likely or most wanted alternative futures. The key factors build a morphological box with their four or five projections each.

Step 3:

In step three, the scenarios are put together. Scenarios are presentations and descriptions of possible future states. They rely on plausible and consistent combinations of projections. These combinations are based on a consistency analysis, where all combinations of projections are tested regarding their plausibility of "co-existence". Amongst millions of mathematically possible combinations, a specifically for this purpose developed software tool identifies the most consistent combinations, excluding those that are inconsistent. A scenario is then defined as a combination of one projection per key factor.

Step 4

In other words, each scenario is characterised as a set of projections. Based on that set, a brief description is drafted and then enriched up to a point where it becomes a small narrative. Depending on the purpose, these narratives can be fleshed out quite extensively, including all the information collected in the preceding steps. Furthermore, missing parts and causes can be invented in a creative process to draft a compelling and interesting-to-read story. Only the character of the scenario, built by the skeleton of projections, cannot be changed. Illustrations and representations can be elaborated to bring the scenarios to life further.

The following six key factors were identified to form the core for the H_2 -scenarios: (1) Global Power Constellations; (2) European Integration and Cohesion; (3) The Degree of Autonomy and Self-Sufficiency of Europe; (4) The Focus of European and Global Policy; (5) The Values, Preferences, and Sustainability of Lifestyles; and (6) The Organisation of the Energy Grids.

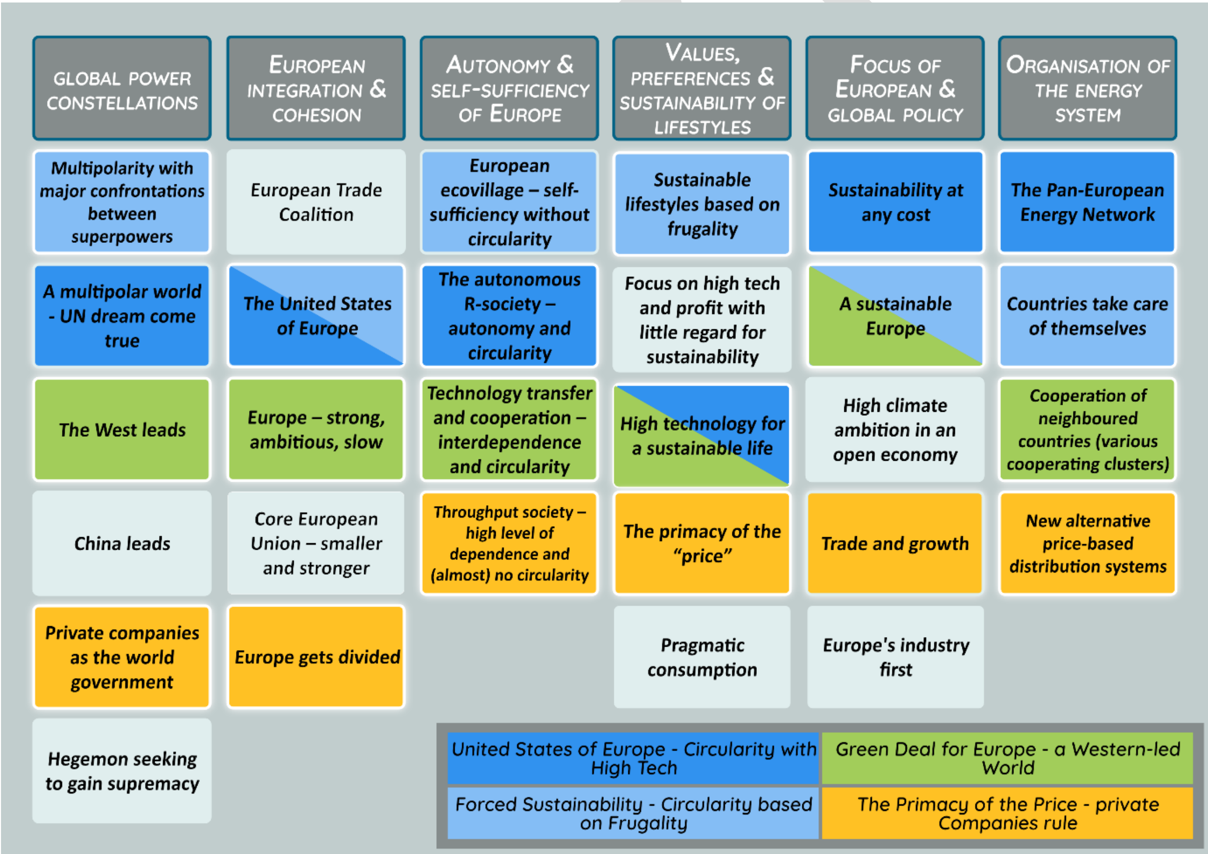
Based on this socio-economic "skeleton", the following questions were answered for the energy system in each of the scenarios:

- Where does the (primary) renewable energy come from? Is it produced within Europe? Does it come from imports? Or is it a mix of both imports and production?
- How is H_2 transported to and within Europe?
- Is H_2 produced more centrally and then transported? Or mostly decentralised? Are there differences between cities and rural areas?
- How much industrial production will be taking place in Europe, and how concentrated will it be regionally?
- What are the end uses of H_2? Furthermore, how much H_2 is needed?

The Scenarios

Overview of the resulting scenarios

The skeleton of the scenarios was built based on a morphological and consistency analysis. In the following morphological box, there is one column per key factor and its respective projections. Each scenario is marked by a pathway through the box, with one colour representing one scenario. Two scenarios contain this specific projection if a rectangle is filled with two colours.



All the developed scenarios are enabling and positive. Some of the presented future developments are more likely than others, some are already visible today, and some are preferable. In the end, this process does not aim to predict or forecast the exact future. The rationale is rather to explore various potential futures to find appropriate approaches to supporting desirable developments and to prevent those that are considered undesirable.

I United States of Europe – High-Tech Scenario

Governance

The United Nations are recognised as a world government, developing and backing international agreements and effectively overseeing their implementation and sanctioning non-compliance. The governance mechanism is based on the subsidiary principle enabling and supporting regional and local solutions. There is widespread global cooperation to face common challenges by sharing knowledge and best practices. In the European Union, a common policy is implemented and enforced in nearly all policy domains, even including the Common Foreign and Security Policy (CFSP). National governments transferred power (legislative, executive, jurisdiction) to European institutions, forming the "United States of Europe". Effectively, governance is organised along the NUTS-regions[1], enabling the application of the subsidiary principle from a very local to the global level. European integration is high.

Society and economy

The former primacy of "economic development and growth" has turned into the primacy of "sustainability and climate protection" based on the globally shared net zero vision. While policies and society took climate change seriously, some large European companies focused on heavy industrial production were too slow to transition away from the intensive use of fossil fuels. Finally, when forced to invest in needed updates for environmentally sound production, many investments were too high and they went bankrupt. This entailed the consolidation of industrial production, led by those that moved towards decarbonisation early. Markets reoriented towards digital services, recycling industries, and technological research and innovation, including research on new materials and furthering efficiency.

Europe's industry is at net zero. A lot of effort is put into the recycling industry and the reuse of materials. In total, the material turnover and consequently the use of primary raw materials has reduced significantly. In terms of materials and energy, such a reduction contributes to a mostly self-sufficient Europe. While global trade is possible, import and export rates are relatively low. Emissions trading, and carbon border adjustment mechanisms combined with other due diligence mechanisms, such as sustainable supply chain legislation, underpin the focus of environmentally friendly and climate-protective economic activities and support investments in local sourcing strategies. The focus is on high tech, digitalisation and new materials to achieve high energy and material efficiency. The pressure on the environment is relieved and the primacy of sustainability is supported.

Energy system

To reach energy and fuel autonomy, Europe has strengthened the use of its clean and renewable energy sources. Efficiency and the high degree of circularity in the economy have led to an absolute reduction in energy demand compared to 2020. Along with the emphasis on electrification aiming to decarbonise the economy and satisfy all energy uses, H_2-production was massively scaled up to complement and meet further fuel and energy demands. H_2 and its derivatives are an essential mechanism in balancing out the electricity system as well as in the climate-friendly production of steel, chemicals, and other hard-to-abate industrial products. Those industries are primarily located in regions with abundant renewable energy resources, such as the region surrounding the North and the Baltic Sea, rich in wind energy; and the Iberian Peninsula as well as South-Eastern Europe with a widespread use of photovoltaics, in particular. Some marginal imports of H_2, primarily from

[1] https://ec.europa.eu/eurostat/web/nuts/background

neighbouring countries, still occur incentivised by low H_2-production costs. This practice has been considered questionable as it undermines energy autonomy and security. Europe has become the leading continent in H_2-technology and its integration across society. These European competencies are highly demanded globally. A stronger Europe has enabled technology transfers and exports through targeted technology breakthrough RDI efforts (technology push). The internal market for H_2 is substantial in achieving economies of scale. Limited raw materials and new alternative H_2-technology paths influence technology choices. Alternative nanomaterials have substituted the import of expensive catalysts.

The EU internally produces its renewable systems, electrolysers and H_2-systems. Economic integration across Europe allows for a high level of coordination in building renewables and locating electrolysers on networks. The old electricity market structure (designed for the fossil era) was reformed to incorporate large-scale H_2-production. The focus shifted to H_2 as a means to buffering excess electricity and a way to "keep the lights on" in an increasingly electrified society. A truly pan-European H_2-market is now in place, controlled by the European Commission and regulators like ACER and CEER.

II Forced Sustainability – Circularity based on frugality

Governance

The dominance of Western countries, including the US, on the world stage, has significantly declined. Russia and China have allied but are not yet strong enough to constitute a new allied hegemon in the international system. New regional power centres have emerged around India, Brazil, and South Africa. The weakened West encourages the new power centres to strive for more global influence. As many of the states are more autocratic or even dictatorships, partly based on religious convictions, many conflicts appear in the endeavour of gaining more power and influence. Regional skirmishes show up and proxy wars multiply between the emerging and declining superpowers using, among others, cyber warfare and acts of terrorism. European countries have moved closer into a block, securing the outer borders with joined forces. In addition, a shared digital defence infrastructure is built to assure cybersecurity. Europe has established a common foreign and security policy. Furthermore, in the 2020s, after the Ukraine war and the subsequent energy crisis, the EU strengthened its neighbourhood policy by extending associated countries in the Balkans and the Black Sea Region. In addition to the common foreign and security policy, the EU Commission has extensive competence in the areas of energy, environment and sustainability policy. These were formerly in the hands of the Member States. A green transition took off, guiding Europe towards thorough ecological reforms and a degrowth pathway. This development was partly forced by the lack of international exchange and access to resources and partly driven by society's motivation to establish sustainable lifestyles. Following the idea of European ecovillages, the primacy of economic growth was replaced with social and environmental goals emphasising the self-sufficiency of local economies.

Society and economy

Overall, levels of production and consumption are significantly reduced. The global GDP has stagnated. In Europe and the US, GDP has been shrinking for years. Due to the missing global trade and exchange and the impact on trade routes and supply chains, the European economy is mainly oriented locally and based on intra-European trade. The single European market is reality: inside the borders of Europe, people and goods can freely move without any restrictions. The Global trade is not only scaled down because of the conflictive world but also due to complying with the self-sufficiency goals of the European Union. This down-scaling of trade has increased the prices of many high-tech products, making people more conscious and selective in consumption and fostering more simpler lifestyles. People focus on their local communities and value their connections with their neighbours and the surrounding nature. This shift has also been triggered by the fact that many people cannot afford the "old" high-tech-lifestyle anymore. The economy is oriented towards the local exchange of goods and services instead of (financial) growth.

Energy system

The absolute demand for energy is lower compared to the levels of 2022. Transport, heat for private houses and most parts of economic activity are based on electricity generated from renewable energy. Hydrogen is mainly a means to buffer and stabilise the renewable energy production. It is not used as fuel in transport.

Europe has built an almost self-sufficient energy system based on decentralised renewable energy installations. This was only possible because of a low demand for energy caused by a decrease in industrial production, and an increase in the efficiency and sufficiency means in society. At the community level, H_2-technology plays a role in local uses, mainly in the shape of hybrid electrolysers. There are only a few industrial production centres in areas with high renewable energy potential (mainly water power).

In urban areas, solar energy plays a central role, and the gas infrastructure is empowered to store hydrogen sufficiently to buffer the energy demands.

EU industries follow the global H_2-trends, with no particular areas of technological leadership. Focusing on regional and local H_2-developments has led to a fragmented Europe in terms of H_2 and electricity, with only a few regional coalitions led by the stronger EU Member States.

III The Primacy of the Price – private Companies rule

Governance

Large multinational technology companies (big tech) dominate the world. They even have private military services and more financial power than some nations. Due to this power, their influence on politics, regulations, and governance is quite remarkable. National governments serve more of a symbolic purpose in keeping up the appearance of democracies. Impacted by the powerful companies, most European countries have negotiated bilateral agreements to assure trade and secure peace. A European Union, as such, does not exist anymore.

Society and economy

A significant share of infrastructure and terrain has been privatised and is owned by large companies. This privatisation causes citizens, small and medium-sized enterprises (SMEs), and public administration to be highly dependent on large multinational companies. Society and the economy follow the paradigm of cost efficiency, aiming at low prices and maximising revenues. Any achievement of the social market economy gained after the Second World War is now replaced by a full free-market capitalistic economy dominated by oligopolistic or monopolistic structures. Global markets boom facilitated by agreements on the global distribution of raw materials and goods between multinational companies. The big techs recognised environmental threats, especially the climate crisis, as an opportunity for growing their business and extending their power across the economy. Demand for green products is high. Carbon trading mechanisms and "avoiding" emissions became lucrative sources of income. There is extensive trade of all kinds of goods and raw materials. Secondary raw materials play a role, as long as they make sense from an economic standpoint.

For the most parts, the public has widely trusted the corporate green agenda. Tensions arise whenever there is a case of alleged "greenwashing" in consumers' perceptions. Furthermore, financing schemes and rental arrangements created to enable access to more expensive offerings, have lured many into a debt trap. As the whole socio-economic system is purely capitalistic, the share of marginalised and impoverished people increased. Over time, a growing part of society is beginning to question the capitalistic and revenue-oriented big companies. This creates social unrest, supervised, prosecuted and even been suppressed by the big companies.

Energy system

Also, the energy system is equally fully price- and revenue-oriented. With the increasing prices of fossil fuels and due to the carbon trading mechanism, the energy system is primarily built on renewable energy, integrating H_2-solutions. The energy system and the infrastructure, are fully owned by private companies. Prices and profit maximisation are the guiding principle for the management of the energy system. Capacities and load management are perfectly optimised to avoid any shortages in energy to maintain the foundation for industrial production. Multinational companies do not consider the strategic interests of single countries, though. Paradoxically, this leads to a more integrated and optimised power grid, including imports and exports of hydrogen as a long-term buffer system. The excess electricity produced in Europe plays an important role as it is converted to H_2 for further use. Industrial production processes are optimised according to the availability of energy. H_2 is stored in pipelines as well as salt and rock caverns, ready to be re-transformed into electricity when needed. Moreover, even generator turbines can be fuelled with H_2 optimising electricity production, creating cheap electricity and keeping production constant. Long-range transport is based on hydrogen as a fuel, while local transport is exclusively using electric energy.

IV Green Deal for Europe – a Western-led World

Governance

The US and other Western countries (G7) remain the global economic and technological leaders. To counterbalance Western hegemony, China and Russia seek to cooperate with each other trying to form an alliance similar to Soviet times. Under the umbrella of this bipolarity, the world is at peace, apart from small local conflicts with no global impact. However, European trade with China and Russia is restricted, causing shortages of certain raw materials. There are partnerships with some African and mostly Latin American countries. The policy of the EU Commission is ambitious, setting far-reaching goals for various political themes, with environmental and climate policy ranking high on the agenda. Unfortunately, the administrative apparatus is large and slow in making decisions, as it is possible for single Member States to block them. However, research and innovation are advanced, especially regarding environmentally friendly products, renewable energy and hydrogen technology. The dependence on fossil- fuel- producing countries has ended, shifting global trade and money flow patterns. Emissions trading and carbon border adjustment mechanisms combined with other due diligence mechanisms underpin Europe's environmentally friendly and climate-protective economic activities.

Society and economy

As the access to raw materials in China and Russia is limited, Europe increasingly has turned to North and South America for raw materials. Europe is technologically advanced and has taken a big leap forward in implementing circular economy measures, like recycling, reusing and refurbishing techniques. Research and innovation cooperation and technology transfer push forward to decrease global levels of resource consumption. As most technology is produced and patented in Europe, technology transfer is a large pillar of European economic activity. Trade and strong economic ties with neighbouring countries outside of the EU improve cost efficiency. High tech, constant innovations, new materials and digitalisation help achieve energy and material efficiency, relieving the pressure on the environment and supporting healthy lifestyles.

Energy system

EU countries cooperate and build joined power grids and energy storage systems making Europe largely self-sufficient in terms of energy. This has meant massive investments in solar and wind power. Large production capacities in renewable energy require a storage and re-powering system based on hydrogen. On the systems' side, large-scale H_2-energy system integration emerged. Technology development led to next-generation H_2- technologies, such as regenerative fuel cells and high-temperature electrolysers (lessening the need for catalysts). Large-scale synthetic fuel schemes enable indirect H_2- storage through gas infrastructure. Energy and hydrogen are cheap and abundant.

What-if Hydrogen and Energy were superabundant?

A Preface (by Ullrich Lorenz)

An energy system based on wind and solar power does not constantly produce electricity. Windmills only produce when the wind blows. Solar panels only create electricity when the sun is shining. An energy system based purely on renewable energy infrastructure without any base-load-backup-system requires short-term, mid-term and long-term buffering systems and load management, i.e. more flexible energy consumption in production processes. In addition, the larger and better regulated the power grid, the better and easier to balance the whole system.

Nonetheless, a certain capacity of renewable energy facilities (more installed capacity than peak-demand of electricity to have a reserve and to be able to store energy when needed) and an energy storage system must be installed in case – for instance – that on a regular sunny day in winter, enough electricity is created that it covers the demand over the day plus a reserve that can be stored for the night and possibly the next cloudy day. If in such a system, all RE-facilities are producing electricity at full capacity, there is way more energy in the system than can be consumed and maybe even be stored. Such a situation results in regulating down windmills, for example. Hydrogen (electrolysis) could be an ideal means to mass-store the overproduction and revert to electricity when needed. It is likely that energy and hydrogen are temporarily available in a superabundant way in such a system. This temporary superabundance might lead to the idea of increasing the consumption of energy. The "Scenario in a box" sketches current thoughts on what abundant electricity could be used for. This scenario has not been developed in the same process as the other four scenarios.

However, such a scenario of "Superabundant Energy and Hydrogen"-uses must be seen carefully as the raw-material demand is extremely high and respectively such a superabundant scenario is not sustainable on a global scale when social and economic aspects are integrated, globally. The lower the energy demand in a system and the smarter the consumption patterns are, the smaller the renewable energy system can be. And accordingly, the faster and less resource-intensive the necessary transition to net-zero can be achieved.

The "scenario in a box"

What if H_2 and energy were superabundant?

Inspired by the work of Austin Vernon and Eli Dourado[2]

When we talk about superabundant energy, we talk about the energy readily, continuously and in sufficient quantity available to human society. This abundance can cover the energy demand of private households or keep a society's infrastructure and economy running. Such a state might be achieved if the entire European energy system was based on renewable energy with extensive overcapacities, large-scale H_2- buffer- and repower systems.

The cost of abundant energy would be irrelevant once the corresponding infrastructure is up and running. Fuels (if needed) are available at a low cost. Cheap energy decreases the cost of all energy-intensive goods and services, increasing consumption in general innovation is stimulated under these circumstances as more economic wealth allows for more research and innovation investments.

there are no incentives to save energy through sufficiency means or by increasing efficiency. On the contrary, new ways of using and spending energy will emerge, and consumption and production will be at high rates. In the next section, we will explore which kinds of innovation might take place given that energy is available abundantly.

Transportation

Transportation is directly coupled with energy consumption. It takes energy to accelerate objects and to keep them moving. In a world with superabundant energy, the number of miles travelled by people and goods transported will likely increase tremendously.

Smaller and lighter motors will change the design of planes, cars, and trucks significantly. Improvements in batteries, motors, inverters, and other power electronics allow for new vehicle designs that improve service life and reduce operating and maintenance costs.

Alongside electric cars, the future might show up with smaller electric planes for mid-distance travel. Even more convenient than electric commuter aeroplanes are vertical take-off and landing aircraft (VTOL) using distributed electric propulsion.

A hyperloop is a concept where a pod that contains passengers travels 700 miles per hour in a closed tube between stations. Such a high speed is achievable because the vehicle rides on magnetic levitation. The typical rolling resistance of wheels is eliminated, and the air resistance is reduced because air is pumped out of the tubes. The success of the hyperloop concept strongly depends on whether it is possible to develop a tunnelling technology that allows for inexpensive tubes. We might consider supersonic flights or suborbital point-to-point travel when energy availability does not play a role.

Freight transport in trucks on streets dominate. With cheap electricity available, freight transportation on trucks is more flexible and does not depend on railways. Electrification can be

[2] https://www.thecgo.org/wp-content/uploads/2022/06/Energy-Superabundance-1.pdf

achieved with super batteries or based on trolley trucks (or any combination). In remote areas, H_2 and fuel cells provide the energy for moving.

Electric and hybrid-electric cargo planes also come into play here. The bandwidth of currently proposed cargo planes ranges from fully electric or hybrid-electric aircraft (that include an engine to charge the batteries) to vertical take-off and landing (VTOL) aircraft that do not require an airport to move goods. Any mode shift to air freight dramatically increases the energy use per ton-mile. Expecting that motors and batteries get lighter and more efficient, why divert to H_2 and not stick with direct electricity use? We have to assume that we will either use H_2 to substitute fossil fuels in direct burning or use it in fuel cells. In the first case, NOx filters are needed. In the second case, the need for a H_2- tank, a fuel cell, a battery, and an electric motor would counteract efficiency, making the vehicle potentially heavier and likely more expensive, compared to direct use of electricity. Nonetheless, there are scenarios in which H_2 as a fuel source makes sense: an application can be found in freight transport or trains in rural areas, where electrification is too expensive.

Agriculture

New agricultural methods include cultures in greenhouses, allowing for controlled conditions to grow all kinds of plants and vegetables all year long. High-tech greenhouses that include supplemental lighting, heating, and water recycling systems are setting a new standard. A logical next step are vertical farms, where plants are grown in hydroponics, minimising water use and allowing operators to station facilities in sunny regions with cheap land, solar power, available labour force, and scarce water resources. Crop yields can increase if farmers optimise varieties for growing trays rather than fields. Plant genetics can be modified to produce a much higher edible mass percentage because vertical farms have controlled temperatures and neither pests nor soil. Indoor farming for the most part enables faster iteration and more growing cycles per year. In vitro meat and plant-based proteins will be the main source of (animal) proteins for human consumption. The energy consumption might be high, but the quality of the meat can be controlled. As a benefit, large areas of land previously used for livestock can be set free, which creates advantages for ecology and biodiversity. The decreasing number of livestock positively impacts the climate as well. Desalination of seawater will be a game changer, especially for countries with access to saltwater in the Mediterranean region or arid coastlines, in general. Advances in technology and material make it possible to use electrolysers with seawater. A combined approach with solar energy, desalination, H_2 storage, and power generation can be built here. If energy is superabundant, fresh water is not a limiting factor anymore for any arid country with access to seawater. Water purification and recirculation systems that demand energy will be installed to reduce water resources' pressure further.

Industry

Assuming the aim is to obtain a greenhouse gas (GHG) neutral industry, GHG-emitting industrial processes will have to be optimised to minimise those emissions assuming that energy itself is greenhouse gas free. This optimisation includes carbon capture (and usage) techniques. The chemical reduction process of steel cooking can be done with H_2 instead of carbon. Heat can be produced by burning H_2 (then NOx-filters are needed) or directly using electricity. The cement industry also produces CO_2-emissions (in the chemical process), which will also be captured (and used). Carbon chains as basic substances for the chemical industry will be synthesised using power to x-technologies. Plastics will become a valuable resource for carbon next to biomass.

Hydrogen Economy - Implications for R&I Policy

Introduction

The technologies for a hydrogen economy are already available today. However, the key question of how specifically hydrogen plays out in a modern energy system based on renewable energy remains. Hydrogen is this context not a means on its own, it is a result and a utile building block in a 100% renewable energy system.

The short answer to a long story is that hydrogen technology must and will play a key role in any modern energy system independent of fossil fuels and nuclear energy. During the discussions about a Hydrogen Economy Future in Europe, it became apparent that the challenge is not to install the technology, despite existing technical peculiarities. It is instead the socio-economic factors that determine how the transition can happen. And vice versa, the shift to a renewable energy system integrating Green Hydrogen offers new potentials for wellbeing and prosperity in Europe and globally. It will reshuffle the dependence on each other. Nonetheless, this must not occur at the cost of the environment, which underlines the importance of taking a systemic perspective and keeping an eye on trade-offs and potential synergies.

The challenges are: (1) to foster the implementation, (2) to scale and speed up the developments, (3) to prevent getting stuck in path dependencies, and (4) to consider global dependencies.

Political decisions are needed to provide orientation in the transition process. For instance, path dependencies would be created if single countries decided to re-implement nuclear energy or if individual mobility was shifted from fossil fuels to electricity in one region and to hydrogen as a fuel in another region. Infrastructure needs to be set up in a harmonised way. To achieve this set-up, regulation and (technological) standards are required, security for the consumer needs to be assured, and liability questions have to be resolved. The transition towards renewable energy and Green Hydrogen is a joint project of all European countries.

The experience with the COVID-19 pandemic and the military aggression of Russia against Ukraine show that Europe needs to reinforce its preparedness to effectively address new challenges. The rising global environmental, geopolitical, economic and social instability increases the likelihood of extreme events with disruptive effects. The **persistence of the European Energy System** in terms of stability and reliability is a critical element in the successful transformation towards resilience and provides the basis for economic prosperity and wellbeing in Europe. At the same time, the renewable energy system can contribute to relieving pressure on the ecosystems and ensuring a clean and healthy environment. A hydrogen economy can potentially turn Europe into the world's first digitally enabled, circular, climate-neutral and sustainable economy. This opens up the prospect of global technological leadership and of supporting strategic autonomy by reducing dependencies on other regions.

Currently, there are still numerous global dependencies. In the past, the globalisation of value chains posed a source of productivity gains while simultaneously creating vulnerabilities. This applies to the dependency on fossil fuels as well as raw materials. China's share in producing solar panels and electrolysers, for example, is quite large. To create a mostly self-sufficient (and autonomous) Europe, technological innovation must primarily substitute critical raw materials, enable recycling, and upscale the production of renewable energy and hydrogen technology **within** the continent. Reducing strategic dependencies in key technological areas and value chains are necessary to strengthen the resilience of the EU.

R&I policy – the big picture

The necessity to reduce EU dependency on fossil fuels implies that R&I investments and efforts must be strengthened to accelerate the development and deployment of energy-efficient and clean technologies. This will not only help to reduce the current dependency on Russia but also significantly contribute to the implementation of the European Green Deal. The current emphasis on a twin transition – "digital" and "green" – is a cornerstone. In this context, R&I policy can play a significant role in shaping the direction of innovations and choices concerning the portfolio of energy technologies. The premise will be finding solutions integrating technology and nature (nature-based solutions).

On a global scale, Europe is still in a **technological leadership** position. However, this may change quickly if the orientation of R&I is too dispersed rather than focused. Now is a good time to define boundaries for R&I in Renewable Energy and Hydrogen Technologies and to set the right course. R&I needs to determine global standards, maintain technological leadership, and enable technology transfer. As time is of the essence, the focus must be on technologies that can be part of an integrated pan-European power grid. Imbalances – also between individual countries – should be balanced out. In parallel to the upscaling of renewable energies, storage capacities need to be considered, market mechanisms revisited, and legislation across Europe be further harmonised.

Social integration is another key element to be incorporated into R&I agendas. The scenario "Primacy of the price" exaggerates the economic system's notion towards a socially unbalanced capitalism. Capitalistic tendencies and large multinational corporations are visible today, and social unrest is emerging (see also the rapid scan on "rising confrontations and their implications for transitions"). In order to support the transition, social imbalances, including energy poverty, need to be considered and buffered. As shown in some scenarios, local, decentral and partly autonomous systems – especially in rural settings – are potentially promising means for a successful transition. Here a link can be seen to the related agricultural policy.

One of the central aims of the EU is to reduce **disparities in the development of its regions**. Among the regions concerned, special attention is paid to rural areas, areas affected by industrial transition, and regions which suffer from severe and permanent natural or demographic changes. The latter especially applies to the northernmost regions with a very low population density and island, cross-border and mountain regions. The better the cooperation of the member countries, the faster and more robust the progress of the energy transition. Effort must be put into maintaining a high level of European integration and identity. This is key for setting up pan-European power-grids und to also provide access to reliable energy sources in more remote areas.

As the scenarios show, the **global context** plays a crucial role in the implementation of the energy system. One factor in all scenarios are the prevalent global power structures. Whether we live in a Western-dominated and/or peaceful world has tremendous implications. Are our societies friendly and cooperative, or are they competing or even openly hostile towards each other? Even in a fortress "Europe" surrounded by hostility, we can build up a self-sufficient energy system that includes hydrogen. Such a system looks differently, as a system that is built on global cooperation.

Undoubtedly, international relations are essential regarding **access to raw materials**. Many raw materials – classified as "critical" by the EU commission – are indispensable for the energy transition and must still be imported to Europe. Critical Raw Materials (CRMs) are those raw materials that are economically and strategically important for the European economy while carrying a high-risk associated with their supply. It is important to note, that these materials are not labelled as 'critical' because they are considered geologically scarce. The critical aspect is that they have a significant economic importance in key sectors of the European economy. Furthermore, they come with a high-supply risk due to the remarkably strong import dependence and the high level of concentration of set critical raw materials in particular countries (mostly out of Europe). Finally, there still is a lack of (viable) substitutes as the properties of these materials are very unique.

In a 100% renewable energy system that uses hydrogen as a fuel and fully abstains from fossil fuels, easily accessible carbon might become a bottleneck in **chemical production**. Carbon is the central element in organic chemistry and organic matters. Also, in technology, whether it is wind turbine materials, textiles, plastic coatings, or cars, almost everything is based on carbon. In the chemical industry, carbon has been a basic raw material from the very beginning. Most carbon sources currently in use have fossil origins, such as crude oil, natural gas, or coal, and are extracted from the ground. However, these resources are only available in limited quantities. On top of that, they release large amounts of CO_2 through combustion or decay, accelerating climate change. Assuming the energy system's and economy's independence from fossil fuels and combustion of any materials that produce greenhouse gases must be avoided, effort and research must be put into keeping carbon in a technical cycle. **Carbon capture and usage** (CCU)must still be an option, both as a bridging technology but also in a hydrogen economy.

Specific recommendations for R&I

The experts involved in the scenario process collected the following list of concrete elements for research and innovation:

- Research on integrated pan-European smart power grids and load management (AI-powered)
- Increase energy efficiency in all sectors
- Material science: electrolyser and fuel cell technology; photocatalytic H_2-production involving material (e.g., nanostructured materials) and next-generation hydrogen technologies; solid-oxide-based hydrogen production, including regenerative fuel cell technologies not requiring precious catalysts
- Technology research aiming at early-market products (niches, even in consumer markets, e.g., solar-catalytic cells or panels)
- Substitution and hydrogen blending – both as **transition and scale-up**/integration of biofuels; scenario-based research on the role of fossil-based hydrogen as a transitional energy carrier; up-scaling of H_2-production technologies, including the process of syn-fuel production (e.g., binding H_2 to C or N, yielding for methanol and ammonia)
- Carbon-capture usage for process-based CO_2-emissions
- Hydrogen as a fuel for long-range transport (e.g., ships, trains, planes)
- Research on decentralised autonomous renewable energy systems, including hydrogen
- Peculiarities of urban renewable energy systems
- Geological research on large-scale storage systems of hydrogen/large-scale hydrogen gas storage, e.g., in caverns or other natural formations
- Large-scale H_2-storage in the form of chemicals (e.g., chemical hydrides, two-reaction systems). Safe and compact hydrogen storage systems for non-professional end-user groups (such as households), including closed-loop hydrogen utilisation and associated technologies

Annex

List of activities and workshops for the elaboration of the scenarios:

- Technology scan about available hydrogen technology (forming, transport, storage, end use)
- 1. August: On-boarding workshop with the experts
- 8. – 15. August: Interviews with 6 key experts (90 min each)
- 8. September: 1st Scenario-workshop (Influencing factors, selection of key factors)
- 14. September: 2nd Scenario-workshop (building future projections)
- 26 September: 3rd Scenario-workshop: defining and characterising the resulting scenarios
- 7. October: expert meeting for the allocation of technologies to the scenarios
- 26. October: Abstracts of the scenarios available
- 18. November: 1st draft of the full scenarios

List and description of key factors for the scenarios, including projections

(1) Global power constellations

Characterisation

This factor describes the constellation and distribution of political and economic power on a global scale. For years, after the Second World War and during the Cold War, there was a clear bipolarity. With the break-up of the Soviet Union, the growth of the European Union, and the growing role of BRICS countries, the power constellations have changed. This has (had) a notable effect on global trade, access to raw materials, conflict and migration.

Possible future developments (projections)

A multipolar world – UN dream come true The world is peaceful and cooperative with a globally recognised United Nations as a sort of world government. Finding common ways to cope with climate change and other global threats helped to unify nations worldwide.	Multipolarity with major confrontations between superpowers Western dominance declined due to internal conflicts within the US. Russia and China have formed an alliance. Various centres of power emerge around India, Brazil and South Africa provoking hot wars, cyber warfare and terror, mostly on a local level. In general, the world is full of conflict.
China leads China is the global leader economically and technologically. Western countries are cooperating but China determines the rules. The US is focusing on its own territory. Trade, economic interest but also cooperation concerning tackling climate change are high on the global agenda.	Hegemon seeking to gain supremacy The world is full of conflict and tension. Russia re-formed the new Soviet Union in cooperation with China and India. Europe (27+) has no option but to tolerate this development and is loosely cooperating to avoid any armed conflicts. The US is thrown back and several placeholder conflicts are happening on the African continent.

Private companies as the world government

Google, Amazon, and Alibaba dominate the world. They have their own security and supervision installations. As they have more financial power at their disposal than single nations, they control policy.

The West leads

The US and the Western countries (G7) remain the global economic and technological leaders. China and Russia seek to corporate with one another and there are multiple agreements in place to ensure that conflicts remain few.

(2) European integration and cohesion

Characterisation

This factor reflects the status and the constitution of the European Union. A crucial indicator of that is the efficiency of European institutions and along with that, the degree to which they are acknowledged by the – rather diverse – Member States. Next to nationalistic tendencies, there might be strong disbalances in terms of economic power and wealth throughout the different countries. Which role do national governments play and how recognised is the European Commission among them?

Possible future developments (projections)

European Trade Coalition Back to the early beginnings of the cooperation of European countries. There is a clear focus and interest of European countries to (exclusively) cooperate economically. The various policy domains are subordinated to trade and economic interests. Each Member State is autonomous and politically independent.	The United States of Europe Europe cooperates politically and economically in a very integrated way. There is a common policy for all political domains, including foreign affairs and security. The European Commission carries out the role of a European government. Compared to today, there are more associated countries. Members include the Balkans and the Black Sea region.
Europe gets divided A sort of "Brexit" happened to nearly all European countries. There is no such thing as a common policy. The countries cooperate based on a series of bilateral agreements which gives more power to national governments. In most cases, decisions are more effective and efficient. Economically this has big disadvantages for most countries. Especially the receiving countries are missing support.	Core European Union – smaller and stronger It is the "party of the willing", meaning a strong coalition of selected European countries which delegate a common policy to the European Commission. After Brexit, other countries followed, leaving a small group of countries cooperating intensively in all political domains and a larger group of associated, loosely cooperating countries. Due to the decreased size, political decisions get more effective and efficient; bureaucracy is reduced.

Europe – strong, ambitious, slow

The policy of the EU Commission is ambitious. Nonetheless, the administrative apparatus is large and slow in making decisions. Single countries can block decisions. The interests of various countries vary significantly. Despite that, Europe is internationally strong and the common policy is still effective.

(3) Autonomy and self-sufficiency of Europe

Characterisation

To what extent Europe can be autonomous and self-determine its aims as well as means of implementing them, depends on its self-sufficiency, meaning its ability to provide everything it needs to sustain itself. A critical determinant in this is its access to resources, such as technology, human capital, and raw materials amongst others. While Europe is rich in resources, technology and knowledge, certain technologies critically depend on specific raw materials. Many of which are not available in Europe.

Possible future developments (projections)

European ecovillage – self-sufficiency & simplicity Europe has a strong focus on autonomy and self-sufficiency. The focus lies on available raw materials and assets in Europe. Trade is often regionalised. Global trade is minimised and life hence "simplified".	The autonomous R-society – autonomy and circularity Material cycles are mostly closed and the material turnover is strongly reduced. Following the concept of circular economy, R-strategies are applied on all levels. Consequently, the input of new raw materials is barely necessary. Europe is widely autonomous and self-sufficient. Export is therefore kept to a minimum. In recent years many raw materials, especially metals, have piled up in built infrastructures and recycling technologies have advanced significantly.
Throughput society – high level of dependence and (almost) no circularity Circularity is barely relevant. The whole economy follows the principle of efficiency and cost-effectiveness. Respectively, trade of all kinds of goods, raw materials and secondary raw materials play a major role, as long as global markets function and prices are deemed acceptable.	Technology transfer and cooperation – interdependence and circularity Europe is technologically advanced and applies recycling as well as other R-means. The economy is strongly based on research and innovation and the transfer of technology. Goods and raw materials are imported and exported. This share of labour creates high efficiency but also dependence on neighbouring countries.

(4) Values, preferences and sustainability of lifestyles

Characterisation

This factor encompasses values, attitudes, and lifestyles in Europe concerning sustainability and its different components. The discourses range from technology affinity to frugality and "back to nature". Depending on the organisation of a society, wealth and buying power will play a key role.

Possible future developments (projections)

Sustainable lifestyles based on frugality Frugal technology does not inevitably correlate with "cheap" (as in low-quality) technology and frugal technology does not automatically hinder sustainable high lifestyles. Local, appropriate and affordable technologies should be utilised to achieve high-quality sustainable lifestyles which would allow all sectors of society to improve their way of life. The emphasis is very much on the quality of life and the need to reach out to the middle class and poorer citizens. This may mean having to adapt certain habits on a societal level (e.g., travelling less, changing consumption patterns, etc.)	High technology for a sustainable life High tech, constant innovations, new materials and digitalisation help to achieve energy and material efficiency which in turn relieves the pressure on the environment and supports healthy lifestyles.
The primacy of the "price" Sustainability is not the driving force. Nonetheless, people are highly focused on cheap products and the whole economy emphasises low prices and efficiency. High tech in most cases is too costly, which leads to a focus on frugal technologies in production and consumption.	Focus on high tech and profit with little regard for sustainability The drive for high technology continues unabatedly, new products continue to be developed and consumed. There is little concern or change in attitudes and approaches to sustainable lifestyles. Consumption is status-driven and pragmatic. There is a feeling that technology will provide the answers to sustainability. Individuals see no need to change their lifestyles.

Pragmatic consumption

Consumer decisions are pragmatic and price-oriented. There is a large divergence of wealth in European society and peoples' consumption patterns are in alignment with their status, wealth and societal bubble.

(5) European and global policy

Characterisation

In general, the European and global climate policy as well as the overall orientation of industrial and sustainability policy plays a key role in how to shape the energy future of Europe.

Possible future developments (projections)

Trade and growth The premise of economic and industrial policy is growth, innovation and trade. As long as environmental and climate effects costs are not internalised, decarbonisation is only realised on optimised cost structures. In Europe though, GHG-emission reduction goals are on track to 2040, globally the targets are not necessarily binding. A sustainable Europe is surrounded by potentially less sustainability-oriented countries.	High climate ambition in an open economy Climate policy is internationally binding and countries are competing to be climate "top-runners". As an effect, there is active trade and global markets are functioning. The guiding principles for innovation are energy- and raw-material efficiency, the non-toxicity of materials and recyclability.
Europe's industry first The European market is prioritised and European policy is focused on internal trade. Energy efficiency and transitions toward more sustainability take place at a slow pace and are subject to profitability.	A sustainable Europe The Green Deal is policy-defining. The focus is on the European market and climate protection is a guiding principle. Global emissions trading and carbon border adjustment mechanisms combined with other due diligence mechanisms underpin the focus of environmentally friendly and climate-protective economic activities with a strong focus on Europe.

Sustainability at any cost

This political decision has created an extensive reconfiguration of the European economy. The former primacy of economic development and growth has now turned into the primacy of sustainability and climate protection. As a result, large companies struggled, many of which went bankrupt. This led to the consolidation and reorientation of markets.

(6) Organisation of energy systems (power-grid)

Characterisation

Not all countries have the same potential for renewable energy. There are different options for setting up an energy system for Europe based on renewable energy. One aspect is the way the (Pan) European Energy Network Grid, which provides gas and electricity, is organised and how energy is transported and distributed across Europe. While a form of energy autarky in rural areas is relatively easy to achieve in urban areas or close to industrial production sites, the provision of power is likely to be centralised and managed on a larger scale. Also, the question of how countries cooperate with each other or to what extent they rely on imports of energy, be it fuel or electricity, can make a difference.

Possible future developments (projections)

The Pan-European Energy Network

Europe is mainly autonomous, based on a renewable energy system. The electricity and gas network will be fully integrated into a bi-directional energy system, taking care of the distribution of wind, water and solar power as well as fuels. Connected energy storage systems are buffering the fluctuations. Imports are barely necessary.

Countries take care of themselves

The pan-European energy distribution does not play a big role. Countries have a focus on national energy provision systems. There is a strong orientation toward imports, storage and reserves management systems.

Cooperation of neighboured countries (various cooperating clusters)

Different neighboured countries cooperate and build joined empowered grids and energy storage systems. Energy is imported mainly as fuel, only when necessary, and as a reserve. These are managed jointly. The potential for renewable energy is largely and intelligently utilised to combine the strengths of the partner countries.

New alternative price-based distribution systems

The whole energy system is optimised for trade and exchange, including Europe's neighbouring countries. As a result, there are high fluctuations in energy prices and storage systems, and an extended energy network has been empowered. Partly non-renewable energy is cheaper and entering the market, especially from neighbouring countries.