STRATEGY ENGINEERS

Market and technology study

The future of energy

New ways to store and provide energy in a carbon-neutral way

Authors

Frank Hegenbart
Dr. Paul Fasching
Carina Schmid
Paulina Waligorski

Introduction

As the essential part of the Paris climate agreement all 196 member states of the United Nations agreed and committed to limit the global warming effect to a value considerably below 2°C above pre-industrial levels on December 12th, 2015. To achieve this ambitious goal and assuming that 2020 will be the peak of greenhouse gas emissions, first and foremost carbon dioxide (CO_2) needs to be reduced by 50% every ten years, from about 40 billion tons a year in 2020 to 20 billion tons in 2030 - to a level of maximum 5 billion tons a year in 2050. In parallel the share of CO_2-free sources of energy needs to be doubled every five to seven years from 2020 onwards.

While the renewable power industry has achieved tremendous progress in reducing the costs to produce energy from emission-free sources a critical challenge remains to be solved:

How to bridge the gap between power generation and demand?

Wind and solar power sources are volatile. Electrical energy is difficult to store and solutions for storage of electrical energy require crucial raw materials such as lithium or cobalt and have physical limits in their energy density. Thus, it is evident and necessary to think about methods of converting electrical energy produced in times of supply exceeding demand into alternative energy carriers. Power-to-X is the watchword that has become increasingly popular in recent months.

We take a close look at technologies and opportunities of the Power-to-Gas / Liquid value chain in the energy system and answer the most important questions associated with the transformation of the industry sectors both providing and consuming energy today and in future.

Converting electrical energy to chemical carriers can solve the storage and emission problem

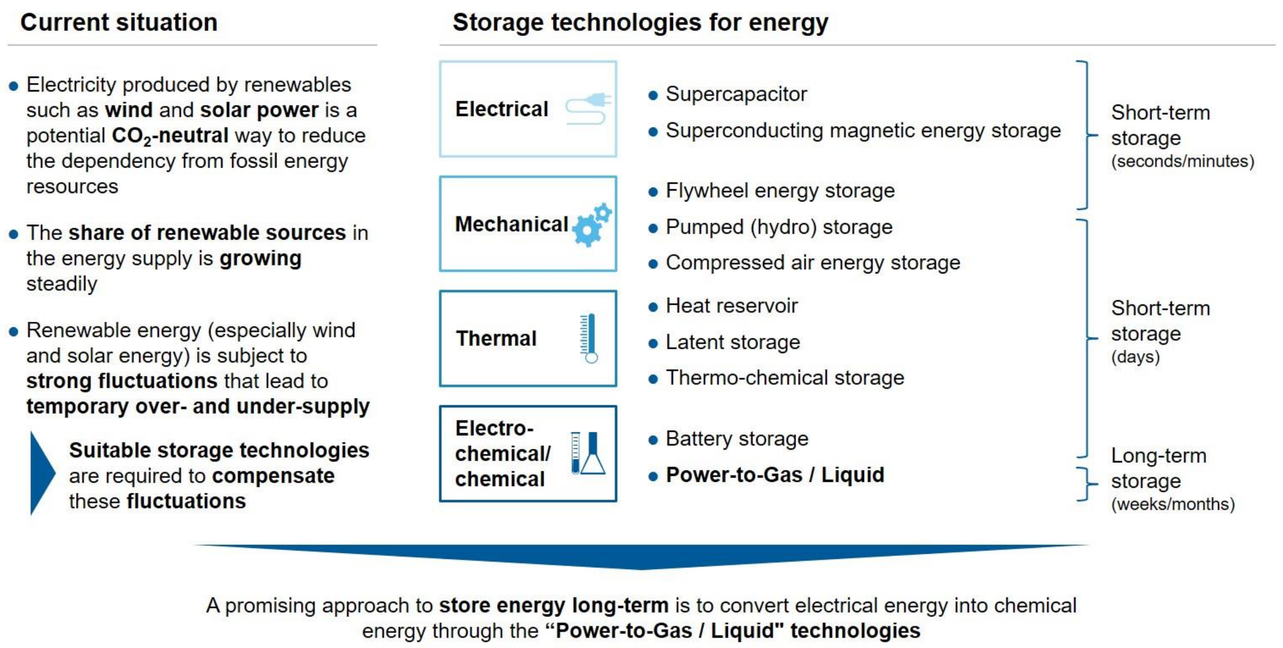
Energy storage is key to meet the emission goals

Traditional ways of producing electrical energy by converting fossil or nuclear sources are typically combined with (waste) heat. To capture or use this thermal source of energy such co-generation solutions are equipped with heat storage systems or even supply heat to a heating grid.

However, in combined heat and power plants thermal energy is a by-product. Most renewable forms of electrical power generation do not have heat as a by-product. Instead wind farms and solar parks are often able to produce more electrical energy as needed in the very moment. Storing this energy in an efficient way for use at a later point in time is inevitable to avoid a loss of valuable capacity.

Hence, the question is in which way to store this surplus energy in order to make it available for later use.

Exhibit 1 outlines the current state of renewable energy as well as four possible storage technologies for energy.



Current situation

- Electricity produced by renewables such as **wind** and **solar power** is a potential **CO_2-neutral** way to reduce the dependency from fossil energy resources
- The **share of renewable sources** in the energy supply is **growing** steadily
- Renewable energy (especially wind and solar energy) is subject to **strong fluctuations** that lead to **temporary over- and under-supply**

Suitable storage technologies are required to **compensate** these **fluctuations**

Storage technologies for energy

Electrical
- Supercapacitor
- Superconducting magnetic energy storage

Mechanical
- Flywheel energy storage
- Pumped (hydro) storage
- Compressed air energy storage

Thermal
- Heat reservoir
- Latent storage
- Thermo-chemical storage

Electro-chemical/ chemical
- Battery storage
- **Power-to-Gas / Liquid**

Short-term storage (seconds/minutes)

Short-term storage (days)

Long-term storage (weeks/months)

A promising approach to **store energy long-term** is to convert electrical energy into chemical energy through the **"Power-to-Gas / Liquid" technologies**

Exhibit 1: Four basic ways to store energy | Source: Strategy Engineers

Power-to-Gas / Liquid technologies refer to ways of producing synthetic chemical compounds by electrolytical processes and further synthesis, if required. Exhibit 2 shows the synthetic compounds that can be produced in this way. These are:

- Hydrogen (H_2)
- Methane (CH_4)
- Synthetic liquids (petrol and (clean) diesel)

Synthetic liquids as energy carriers generated from electrical energy are often referred to as 'E-fuels'.

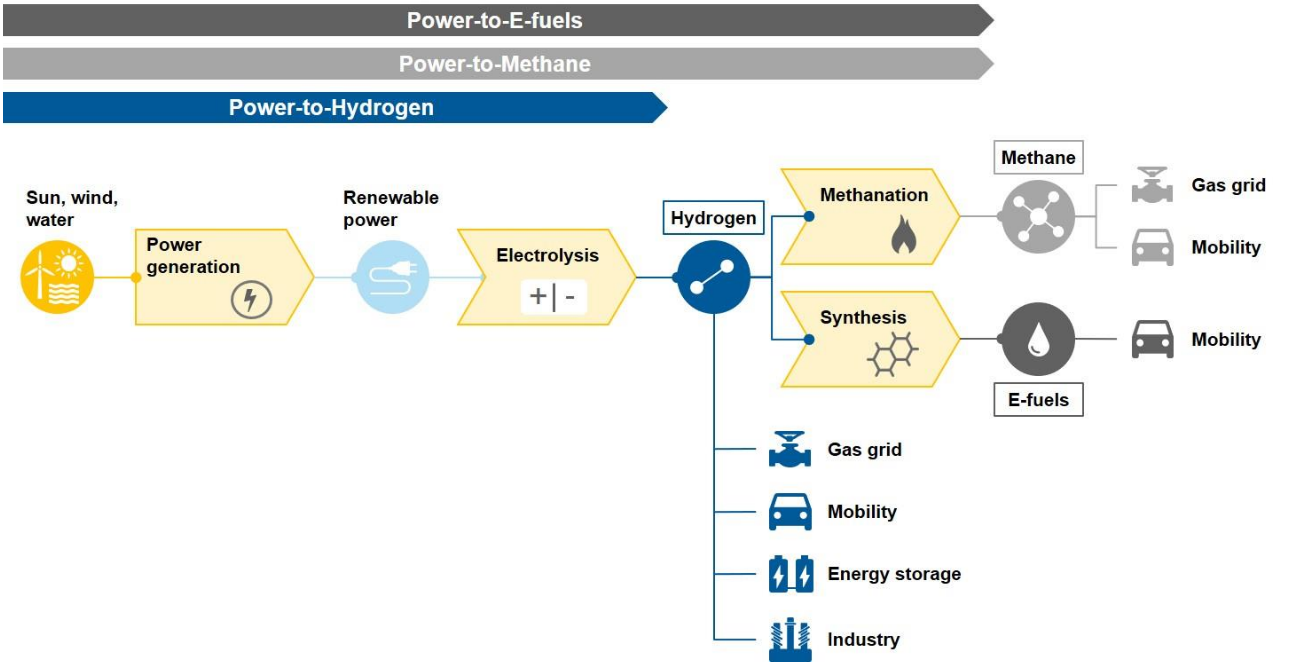


Exhibit 2: Power-to-Gas / Liquid supply chains | Source: Strategy Engineers

Especially for the generation of Methane and E-fuels, well-advanced technologies to re-use produced carbon dioxide (CO_2) or extract it form the atmosphere already exist. These technologies provide the foundation for ‘negative emissions’ and thereby close the loop for combustion-based energy conversion in a wide range of sectors such as:

- Electrical power generation, e.g. gen-sets, co-generation plants
- On-road traffic, e.g. cars, trucks, motorcycles
- Off-road vehicles and machines, e.g. tractors, construction equipment
- Water and ocean transport equipment, e.g. vessels, ferries
- Aircraft, e.g. airplanes, helicopters
- Feed-in into existing natural gas grids
- Chemical and pharmaceutical processing

And many more industrial and commercial sectors in which today fossil energy carriers like natural gas or crude oil are the primary material used.

The challenge is to industrialize the technology in a way that it can be an economically reasonable supplement to the overall energy system.

But also, the political system is faced with the important challenge to foster the right balance between these new technologies and the established ones. It is not a question of disruption, meaning one technology replacing the other completely, but a deliberate reformation and development of each country’s energy system to meet the desperately needed emission limits while keeping and enhancing quality of life on a global scale.

This Power-to-X ecosystem will consist of multiple players and must be well balanced to ensure reliable energy supply while limiting greenhouse gas emissions (see Exhibit 3).

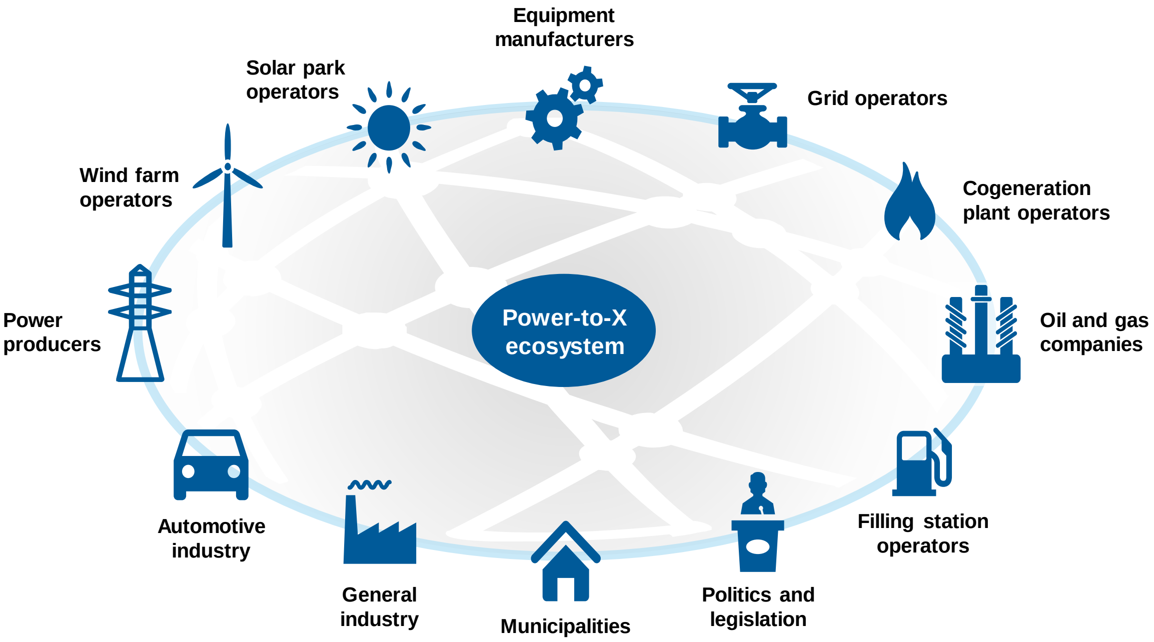


Exhibit 3: Power-to-X ecosystem | Source: Strategy Engineers

Non-feed-in electricity as a starting point

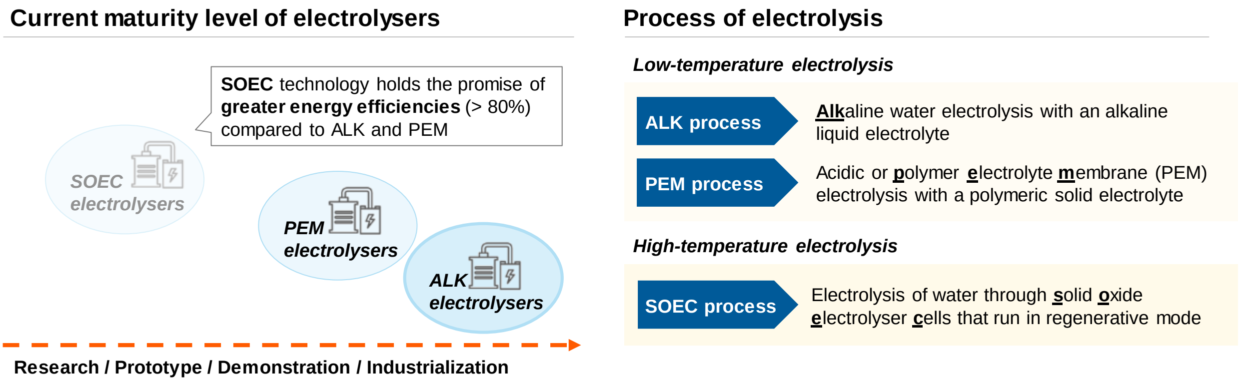
Economies with a rather high share of wind and solar energy production increasingly face the situation that electrical power could be produced - but isn't - at times of low demand. During these times, feed-in management by grid operators restricts the supply into the electrical transmission and distribution grids and energy production sites have to be stopped or put into idling or stand-by mode.

Especially large offshore wind turbines need to be in operation firstly for economic reasons and secondly for technical reasons to keep the mechanical system of the turbine intact and avoid deformation from standstill in bearings and shafts.

So instead of shutting them down, the surplus energy could be used to generate hydrogen via electrolysis. Currently there are three different types of electrolysis technologies used, named alkaline electrolysers (ALK), polymer electrolyte membrane (PEM) electrolysers and most recently solid oxide electrolyser cells (SOEC). Exhibit 4 shows the three technologies and their current maturity levels.

ALK electrolysers were developed in the 1920s, resulting in the most mature technology. Today, they are well established and dominate the market for non-energy purposes especially in the chemical industry.

In the specific use case of generating hydrogen from wind and solar energy, where a dynamic operation mode is required, the PEM electrolysers are currently the most promising technology. Advantages over ALK are that PEM electrolysers can operate more flexible and with a shorter response time. Furthermore, they are capable of short-time operation under higher capacities. Lastly, they offer a wider operating range than ALK electrolysers. The SOEC technology is still in research stage, promising a significant increase in efficiencies compared to ALK and PEM technologies. Yet, it requires a much higher operating temperature and therefore a higher energy input.



Current maturity level of electrolysers

SOEC technology holds the promise of **greater energy efficiencies** (> 80%) compared to ALK and PEM

Process of electrolysis

Low-temperature electrolysis

ALK process	**Alk**aline water electrolysis with an alkaline liquid electrolyte
PEM process	Acidic or **p**olymer **e**lectrolyte **m**embrane (PEM) electrolysis with a polymeric solid electrolyte

High-temperature electrolysis

SOEC process	Electrolysis of water through **s**olid **o**xide **e**lectrolyser **c**ells that run in regenerative mode

Exhibit 4: The most established electrolysis technologies | Source: Strategy Engineers

Spotlight: 'Unused electricity' in Germany

> In Germany, in 2017, this amount of 'unused electricity' summed up to 3,743 GWh, most of it from wind power sites in northern Germany. With the expansion of onshore and offshore wind farms such 'energy production losses' are likely to grow significantly. This amount of energy is equivalent to about 75 kilotons of hydrogen generated by electrolysis assuming a 65% efficiency factor, enough for one billion kilometres driven by fuel-cell powered heavy-duty trucks. In Germany that is enough to operate 10,000 trucks with an average annual mileage of 100,000 kilometres (assuming an average consumption of 0.08 kg H_2/km).

Given these numbers and the potential for even expanding this new form of emission-free energy supply it is unsatisfying that we do not see more fuel-cell trucks being developed and launched by truck manufacturers and that not every new wind farm commissioned in the North Sea comes with an integrated hydrogen electrolyser unit. One reason for this situation is that hydrogen is a highly explosive gas and associated with several risks and dangers during the production and storage process, thus, requiring specific precautions along the supply chain.

So, it is worth taking a closer look at the state of the art of hydrogen storage technologies.

The Power-to-Gas storage and distribution problem

Every technical innovation is an answer to a yet unsolved problem. Storing and transporting explosive and highly inflammable substances is such a problem. It is usually heavily regulated by various 'Dangerous Goods' regulations like GGV ('Gefahrgutverordnung') in Germany or Pipeline and Hazardous Materials Safety Administration (PHMSA) in the United States.

However, it is not only a question of safety but also a matter of economy and efficiency. Currently there are three options technically advanced and one in an earlier development stage to store hydrogen (see Exhibit 4)

① **Compressed gaseous H_2**
At room temperature compressed up to 700 bar

② **Cryo-compressed gaseous H2**
Cooled and compressed at 57 K (-216 °C) and
10 bar – 350 bar

③ **Liquefied H2**
Liquid H2 at 20 K (-253 °C) and up to approx.
10 bar

④ **Adsorption of H2 by a solid carrier material**
Storage capacity varies with pressure and temp.
Using activated carbons up to 8.9 weight % at
77 K (-196 °C) and 30 bar were reported in studies
Currently in pre-development stage

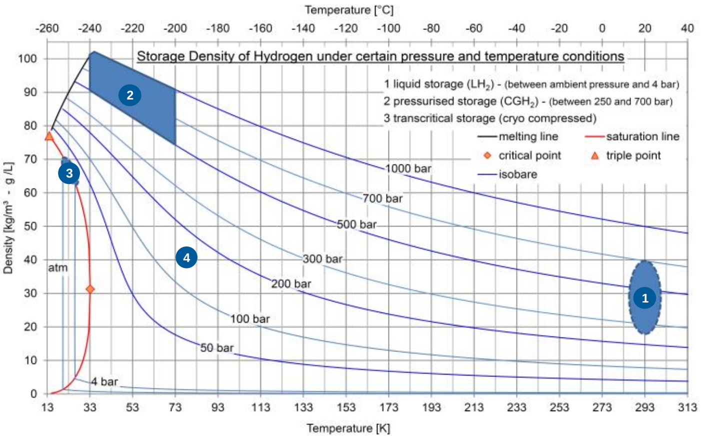


Exhibit 4: Four options for hydrogen storage | Source: BMW Group, Cryogenic cluster day, Oxford, 2012

Option 1 is obviously the most economical way to store hydrogen as many other gases as well. However, it does require space since the storage density is in a range of 20 to 40 kg/m³. Additionally, quite embracing safety precautions have to be taken especially in vehicles, aircrafts or other mobile applications to avoid explosion in case of crashes, fires or any form of physical impact.

Cryo-compressed and liquified storage as in options 2 and 3 offer higher storage densities of up to 100 kg/m³. The tanks however need to be cooled and so permanent energy supply is necessary just to keep the storage intact. This means additional costs and risks if energy supply is interrupted.

A promising approach is option 4 in which H_2-molecules are chemically bound to a solid carrier material like graphene or similar compounds. Storage density is expected to be in the range slightly above 40 kg/m³. Costs for the carrier compound material and the process of attaching and detaching the hydrogen molecules is going to be key for cost effectiveness of the solution. However, the safety concerns would be relaxed if not even eliminated.

Outlook - Are we about to enter the ‘H_2-Age’?

All things considered, or better said ‘from all we know as of now’, the answer is a clear ‘yes’. The transformation of our energy system however will be a process with break-throughs and set-backs. Energy in whatever shape or form has been key driver for economic and social development.

Because the energy system in each country is a complex ecosystem, with even more players in the years to come, broad and deliberate alignment among all players is inevitable.

Political

- **Incentivise Power-to-Gas / Liquid investments** as means to **store electrical energy** during periods of oversupply, stabilize the power grids and open up new and practical ways for effective climate protection
- Consideration of **well-to-wheel CO_2 emissions** instead of only tank-to-wheel emissions to incentivize renewable fuels in **mobility sectors**
- **Deliberate tax system evolution** to achieve a balanced transformation of the energy system in each country

Economic

- It is crucial **to utilize all possible income options** to achieve a positive business case with Power-to-Gas technology:
  - **Offering zero-emission Power-to-X products** in all possible markets
  - **Sell** the **produced oxygen (O_2)** (by-product from H_2-synthesis)
- When recognized as biofuel, the **biofuel quota** achieved with Power-to-X plants can be **sold to companies** obliged to achieve a certain share of biofuel
- **Avoid electricity transmission fees** by not using the public electricity grid in the case of **decentral hydrogen production**

Technical

- Increase **efficiency** of **electrolyzers**
- **Reduction** of **investment costs**
- **Cost reduction** through higher **production quantities** of electrolyzers and **maturing of technology**
- Increase of allowed **hydrogen share** in the **gas grids**

Exhibit 5: Political, Economic and Technological success factors for Power-to-Gas / Liquid | Source: Strategy Engineers

Aside of politico-economic conditions and regulations business development for Power-to-Gas / Liquid as an emerging business field will be crucial and will determine how quick technologies advance into the energy system. Promising business cases are created if

- Technology is in a mature state for industrialization
- Business models have coherent potential for upscaling and
- Demand is already existing and will most likely grow

If these prerequisites are met investments will be taken along the new value and supply chains (see Exhibit 5 for more details).

In the case of Power-to-Gas / Liquid already existing infrastructures can be seized, e.g. by equipping existing wind farms with electrolyser facilities. But, at the same time the distribution structure needs to be developed. Existing and new partners in various sectors will have to join forces. But it is much more a chance than it is a risk because Power-to-Gas / Liquid is one of the crucial elements of a much more diversified and climate-friendly energy system in future.

The authors

Frank Hegenbart

Frank is a Partner at Strategy Engineers with experience of more than 20 years in Consulting and Industry. His focus is on energy and high-tech industry sectors. His specific competence areas within the company are Supply Chain Innovation and Corporate Strategy.

E-mail: fhh@strategyengineers.com

Dr. Paul Fasching

Paul is a Consultant at Strategy Engineers working out of our Munich office. He studied mechanical engineering and earned his doctorate in the field of natural gas combustion engines. His primary focus is on vehicle propulsion systems and on renewable energy.

E-mail: pjf@strategyengineers.com

Carina Schmid

Carina Schmid is a Consultant at Strategy Engineers' Munich Office. She studied Technology and Management and focusses on business strategy and development, technical logistics and process management in the automotive industry and the energy sector.

E-mail: csc@strategyengineers.com

Paulina Waligorski

Paulina is a Consultant at Strategy Engineers with 2 years of combined professional and consulting experience. She studied chemical engineering and focusses on research and development, process optimisation and quality management within the automotive industry and the energy sector.

E-mail: pwa@strategyengineers.com

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www.strategyengineers.com

Strategy Engineers GmbH & Co. KG

Tel.: +49 89 4161 7235
Fax: +49 89 4161 7237
www.strategyengineers.com
info@strategyengineers.com

Munich
Seidlstraße 18
80335 München
Germany

Hamburg
Rödingsmarkt 9
20459 Hamburg
Germany

Shanghai
Room 2001, Henderson Metropolitan
No. 300 East Nanjing Road
200001 Shanghai, China

HRA 96163, Munich District Court
represented by: Strategy Engineers Verwaltungs GmbH,
Managing Director: Dr. Albert Neumann