Handbook Energy Storage

SCCER Heat and Electricity Storage

Storage
Swiss Competence Center
for Energy Research

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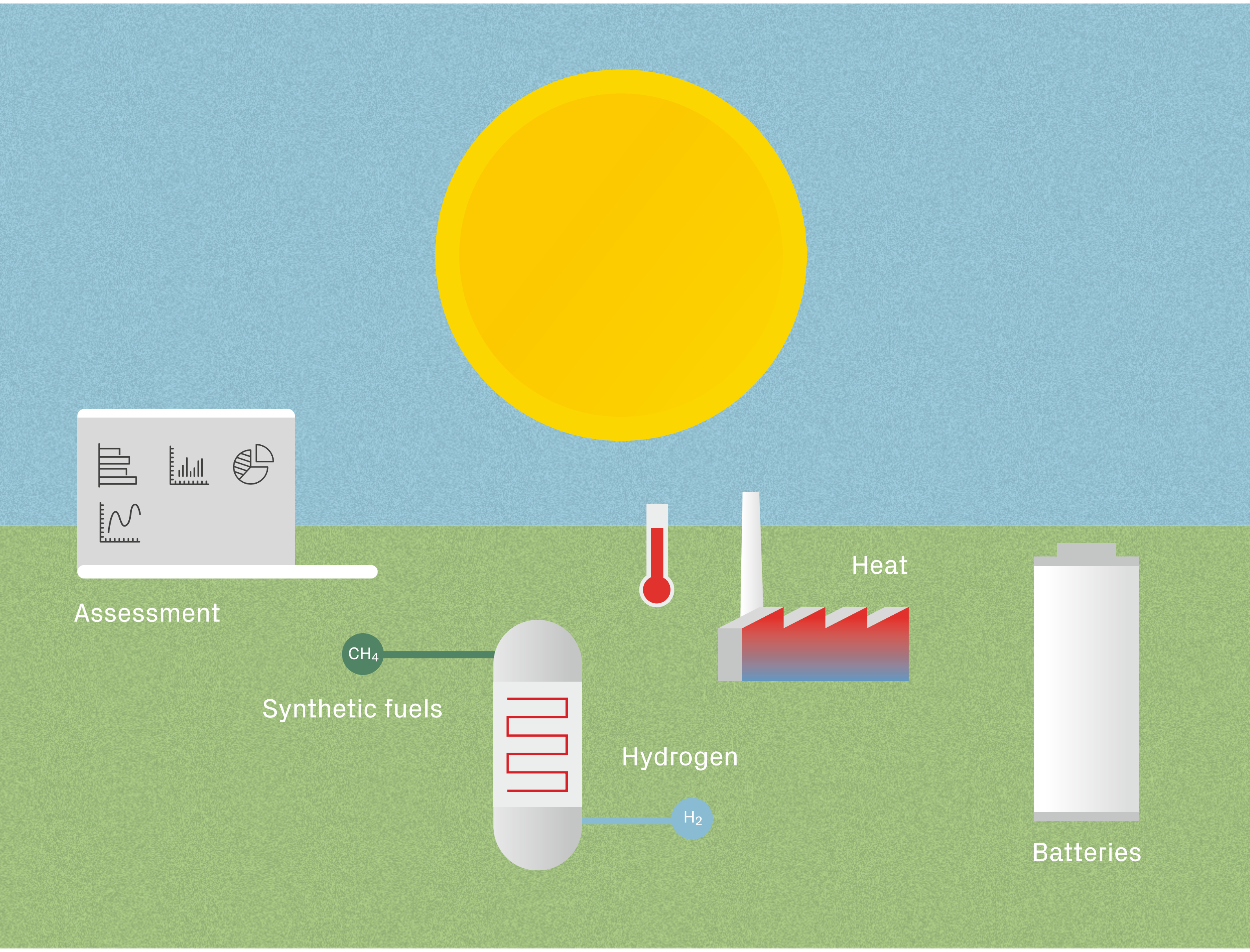

Handbook
Energy Storage

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Contents

Key messages

1. Energy storage is crucial for the successful implementation of the Energy Strategy 2050. A variety of storage technologies will balance out short- and long-term energy fluctuations foreseen at an increased share of intermittent renewable energy sources and strengthen the resilience of the Swiss energy supply.

2. From today's perspective, the Energy Strategy 2050 is technically achievable. The necessary storage technologies are already available, are currently on the market, have proven to be commercially sound or are at least demonstrably feasible.

3. Investments in storage infrastructure are economically sustainable. They replace the enormous recurrent expenditure of CHF 12 billion annually on imported energy sources, such as oil, gas and uranium, with facilities that utilise locally available renewable energy.

4. The use of energy storage technology increases the energy efficiency of the overall energy system, improves its environmental compatibility, enables the integration of renewable energy and reduces local and global risks.

5. Seasonal energy storage systems are necessary for a climate-neutral society in order to replace fossil fuels for both the transport sector and for heat generation in winter.

6. Grid fees, together with the taxation of stored electricity and the subsidisation of fossil fuels through inappropriate CO_2 prices, are hampering the competitiveness of available storage technologies.

7. Batteries, compressed air storage, pumped hydro storage, heat storage as well as power-to-X systems are able to absorb the increasing supply of electricity produced in summer and make it available again in the medium term or, even later, in a different season.

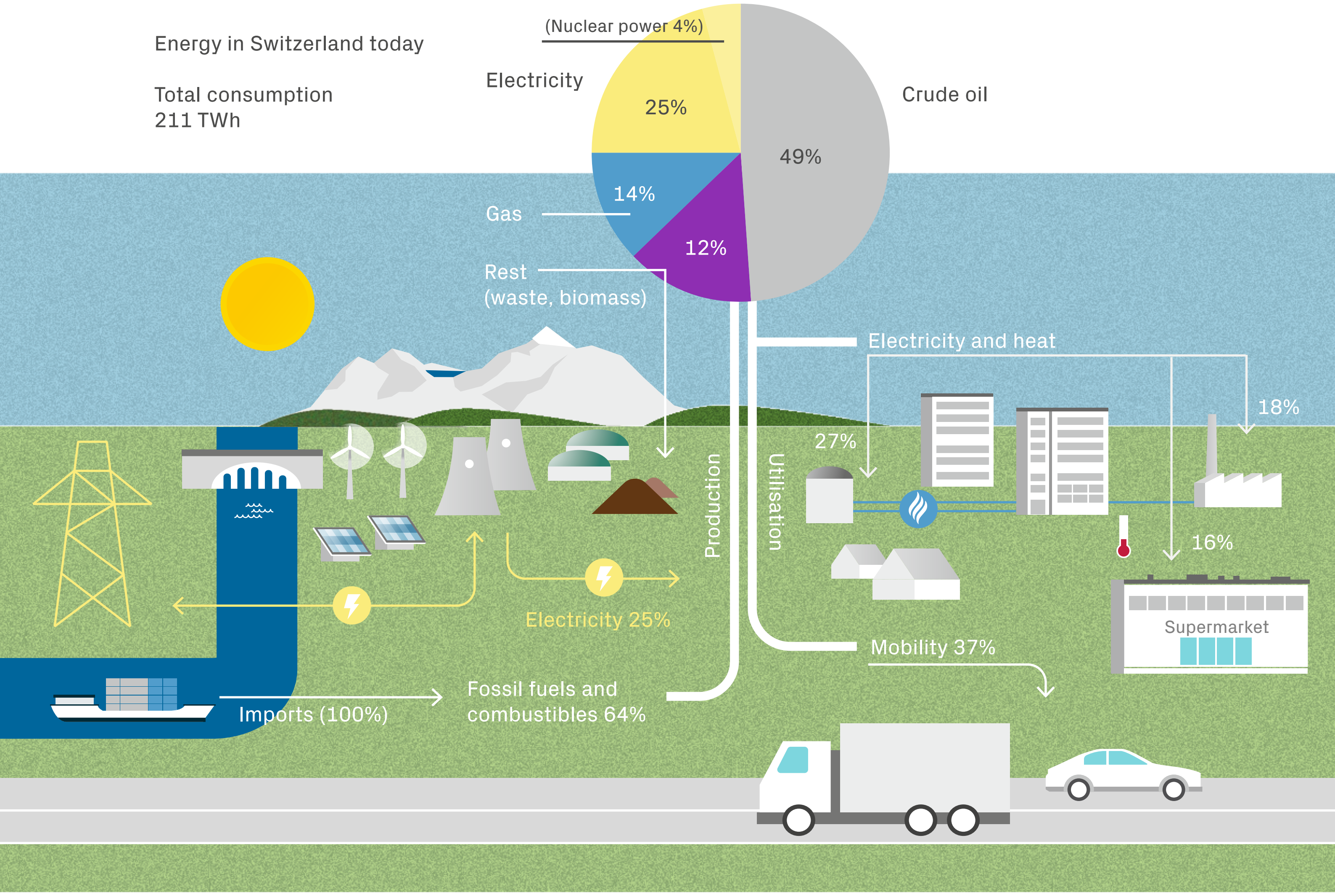
8. Today, 50 percent of Swiss energy consumption is used to generate heat. Heat storage systems therefore play a significant role in the success of the Energy Strategy 2050, since they accommodate seasonal fluctuations in demand. By optimising materials, heat storage facilities can be made more compact, thereby reducing space and land requirements, which are so critical for Switzerland.

9. The SCCER research and development work enables the optimisation of the energy efficiency of individual storage systems and a reduction in the use of critical materials such as precious metals (in catalytic systems) or cobalt (in Li-ion batteries).

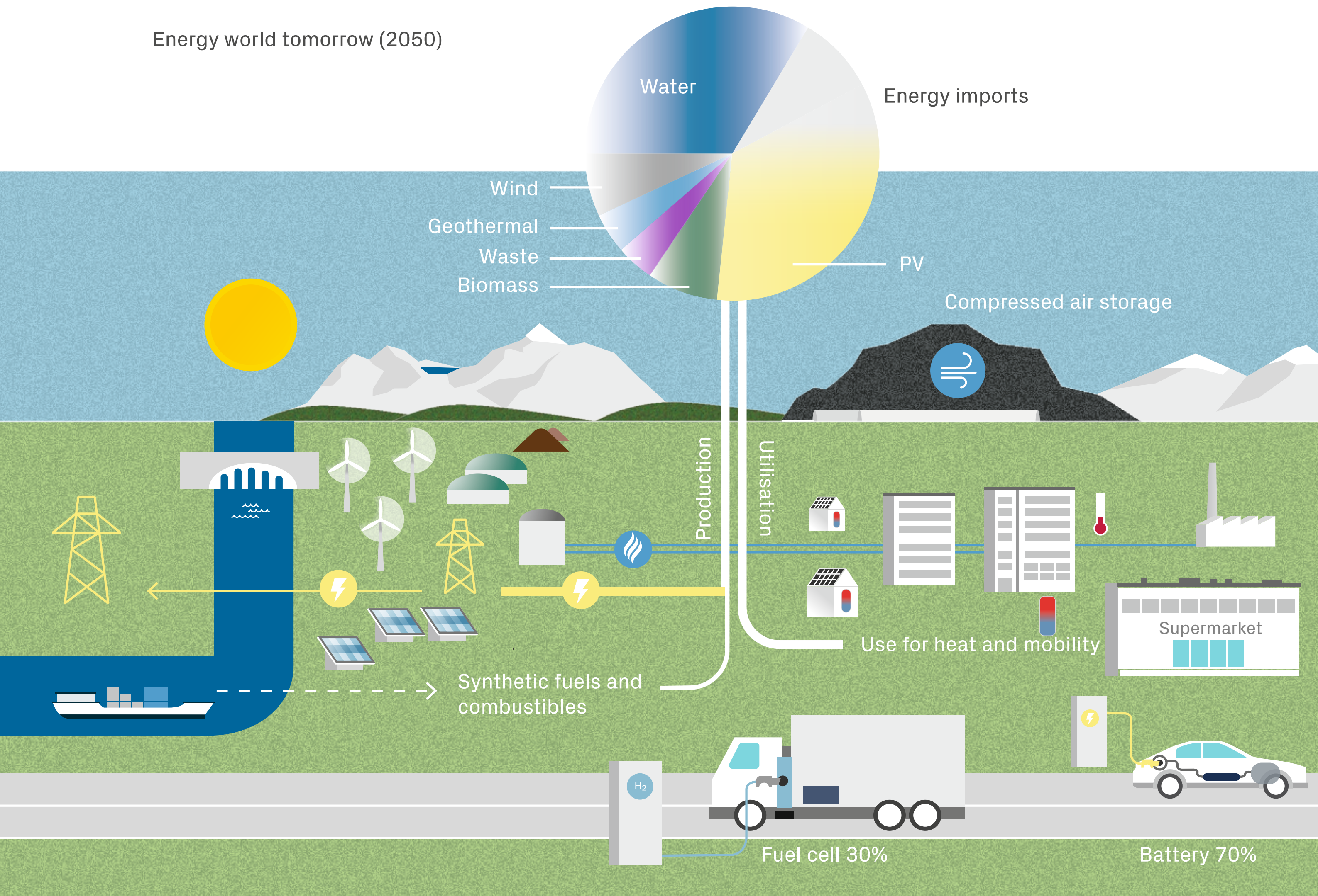
10. By linking the energy and chemicals industries, power-to-X systems represent essential technologies that enable a renewable energy economy based on hydrogen, methane and methanol. They pave the way to a society that can relinquish fossil fuels.

11. The SCCER HaE has developed a highly efficient compressed air storage system, suitable for medium term storage, that can be implemented in Switzerland.

1 New storage technologies – a must for the energy transition



Energy in Switzerland today
Total consumption
211 TWh
(Nuclear power 4%)
Electricity
25%
Crude oil
49%
14%
Gas
12%
Rest
(waste, biomass)
Electricity and heat
18%
27%
Production
Utilisation
16%
Supermarket
Electricity 25%
Mobility 37%
Fossil fuels and
combustibles 64%
Imports (100%)



Energy world tomorrow (2050)
Water
Energy imports
Wind
Geothermal
Waste
Biomass
PV
Compressed air storage
Production
Utilisation
Use for heat and mobility
Supermarket
Synthetic fuels and
combustibles
Fuel cell 30%
Battery 70%

1.1 Energy storage today and tomorrow: the route to a secure energy future

Today in Switzerland, energy is available on demand practically all the time. At the touch of a button everything starts: notebooks, coffee machines, heating systems and car engines. Lights switch on automatically as soon as we move. The saying: «Electricity comes out of the socket» summarises just how much we take this for granted. Ironically, this also shows things are not so simple. Whatever the energy source – electricity, wood, biogas, oil or natural gas – the benefits of power, heat or light depend on a shorter or longer supply chain, or even an entire energy system.

Today, in winter, around 40 percent of the heat in buildings is generated with oil-fired heatings.

Energy originates from a huge variety of sources: a nearby forest, oil wells in the Middle East, natural gas deposits in Russia or uranium mines in Niger, Namibia or Russia. Electricity is generated in hydroelectric power plants in the Alps or on major rivers, in nuclear power stations in the Swiss central plateau and in France, in wind farms in Spain and the North Sea or with solar panels on a neighbour's roof. An extensive supply infrastructure makes it possible to deliver energy to where it is needed. Tankers cross the world's oceans and sail up the Rhine. Pipelines and power lines cross continents as well as Switzerland. A dense network of filling stations also ensures the fuel supply for cars.

Energy storage – part of today's energy system

Distance is not the only issue. Just as challenging is the need to synchronise the production and distribution of energy with demand. This must take place against a backdrop of continuously fluctuating supply and demand: throughout the seasons, on a weekly or daily basis, or even in fractions of a second.

When Switzerland wakes up in the morning, the demand for heat instantly increases across the whole country. Thanks to the boiler or the warm water storage tank in each basement, there is always a hot shower. The boiler itself was heated either the day before with its own solar power or at night with electricity from the grid; alternatively, with biogas, natural gas or, less frequently, oil.

In winter, around 40 percent of the heat for buildings is generated using oil-fired heating systems. The oil tanks in the basements ensure the energy supply throughout the year. Together with the large tank farms, which store fuels for emergencies, these domestic oil tanks currently represent the largest energy storage facilities in Switzerland. In addition to oil, natural gas is of major importance for heat generation in winter. Natural gas is also stored for emergencies, in caverns in the French Jura, and the contents of the gas network represent an additional form of storage facility.

Moreover, just as extensive as the stocks of heating fuel are the facilities in which fuels such as petrol, diesel and paraffin are stored: in tank farms, at petrol stations or in the tanks of around six million Swiss motor vehicles.

The balancing of energy supply and demand in the power grid is particularly demanding. Its voltage and frequency must be maintained at all times, and adjustments must be possible in a fraction of a second, for example, when kitchen equipment is switched on at lunchtime and electricity consumption surges. Different types of power plants help to keep electricity supply and demand in balance. Nuclear and run-of-river power plants continuously supply base-load energy. Pumped hydro storage power plants can be switched on and off quickly to cover peak demand. They also enable seasonal compensation. Melting snow and the rain in summer fill reservoirs, ensuring water is available for electricity production in winter. During the day and especially in summer, photovoltaic systems feed a great deal of electricity into the grid – often more than is needed.

In these circumstances, batteries offer the possibility of storing the electricity generated during daytime for the night. Last but not least, wind turbines also contribute to energy production. They are, however, highly dependent on the weather. The potential of wind energy for electricity production in Switzerland is significantly lower than on the Atlantic and North Sea coasts, for instance, because the wind does not blow as constantly and has a lower velocity so electricity production fluctuates accordingly.

Switzerland needs energy efficient systems and more renewable energy.

With its Energy Strategy 2050, Switzerland is striving for a transition of its energy system. It aims to phase out nuclear energy gradually and at the same time become «climate neutral» by the middle of the century. These energy policy goals are ambitious. Nuclear energy and fossil fuels must be replaced as sources of energy supply both by reducing energy demand and by encouraging various forms of renewable energy. Today, nuclear energy still covers about four percent of Switzerland's total energy requirements, which corresponds to 17 percent of the country's electricity demand. Fossil fuels – natural gas, heating oil, petrol and diesel – account for two thirds.

Increasing dependence on the weather and the seasons

In particular, the replacement of fossil fuels and nuclear power by renewable energy represents an extraordinary challenge in terms of quantity and temporal availability. The availability of solar and wind energy always depends in the short-term on weather conditions and in the long-term on the seasons. Therefore, even with a major expansion, solar and wind energy will not be continuously available to guarantee the supply of base load energy as is possible with energy from nuclear power plants or easily storable liquid fuels.

The replacement of fossil fuels and nuclear power by renewable energy represents an extraordinary challenge in terms of quantity and temporal availability.

On top of this, energy requirements in winter are generally higher than in summer, whatever the source. Due to the high demand for heating in winter, the consumption of oil and natural gas show the largest seasonal fluctuations. In contrast, the additional consumption of electricity in winter is less pronounced. This situation is likely to change, however, with the continuous dissemination of heat pumps. In addition, electricity production in winter is already lower than in summer. Since solar energy is naturally more readily available in summer, the expansion of solar energy usage only makes a significant contribution to the energy transition when coupled with seasonal energy storage.

With the expansion of solar and wind energy, energy supply will depend more and more on weather conditions, as well as on the time of day and year. The temporal pattern increases the need to bridge the gap between energy supply and demand with the support of all kinds of energy storage. In contrast, the dependence on imported energy sources will decrease.

With the expansion of solar and wind energy, energy supply will depend more and more on weather conditions, as well as on the time of day and year. In contrast, the dependence on imported energy sources will decrease.

More storage capacity for decentralised energy systems

The energy transition is also changing the structure of energy supply. Today, a limited number of large power stations cover the bulk of electricity demand. In future, an almost incalculable number of wind and, above all, photovoltaic plants distributed across the whole country will feed electricity into the grid.

Additional storage solutions of all kinds are needed everywhere – in the buildings themselves and in the neighbourhood, on both regional and national levels.

Whether immediate or deferred, the on-site need for electricity will correspond to available supply in only a portion of these cases. For a detached house, the energy harvest from a photovoltaic system on the roof exceeds the home's requirements during the day. An in-house battery can absorb part of this electricity and provide short-term compensation. Once the battery is fully charged, electricity flows into the public grid, where, especially in summer, the available electricity may exceed immediate demand. Moreover, on the extensive roofs of an industrial estate, far more energy can be harvested in the middle of summer than is consumed locally or is required by the power grid. To ensure that this valuable energy is not lost but remains available to meet later demand, additional storage solutions of all kinds are needed everywhere – in buildings themselves, in the neighbourhood, within a region and on national level.

Batteries, hydrogen and synthetic fuels

Batteries are one of the most common technologies to store electricity directly, but only for a relatively short period of time. Research and development in this field is in full swing.

On a larger scale, pumped hydro storage power stations use cheap electricity to pump water up a mountain and then utilise this water again to produce electricity when needed.

Large compressed air reservoirs are still in the development stage (cf. 2.3, p. 44). In this case, air from the atmosphere is forced into a cavern by a compressor. At a later stage, the compressed air is expanded in a turbine to generate electricity again.

Through electrochemical processes, electricity can be converted into more readily storable chemical energy which can either be used as such or converted back into electricity. Thus, with the help of electricity, hydrogen (H_2) can be obtained (cf. 3.2.2, p. 70) which can be used for electricity production in a fuel cell on demand. In a further step, with the addition of carbon dioxide (CO_2), hydrogen can be converted into synthetic methane gas (cf. 3.3.4, p. 92) or other synthetic fuels. One problem with such «power-to-X systems» (P2X) is the associated waste heat, which for the most part cannot be used. If electricity from renewable energy is available in large quantities and inexpensively, as is often the case on summer days, or if the waste heat can be utilised effectively, for example in industrial processes, P2X systems could prove to be viable alternatives for the future.

If electricity from renewable energy is available in large quantities and inexpensively, P2X systems could prove to be viable alternatives for the future.

Vehicles with batteries or renewable fuel tanks

In the mobility sector, the energy transition requires cars, trucks and buses to be CO_2-neutral in the future, that is, running primarily on electricity from renewable sources or with renewable fuels. At present, 60 percent of Switzerland's energy demand in this sector, around 80 terawatt hours (TWh) per year, depends on fossil sources[1] and must be replaced in a climate-neutral way all year round.

To this end, batteries (cf. 2.1.1, p. 26 and 2.1.2, p. 30) and hydrogen or synthetic methane tanks are replacing existing petrol and diesel tanks as energy storage devices. The onboard energy storage can play a significant role in the entire energy supply system, whether it is a battery or tank. If electrically powered vehicles are connected to the power grid, their batteries could help to balance the grid. During the day, they can store surplus solar and wind power and thus relieve the grid; after sunset, they can feed it back into the network. All in all, the potential of having millions of electric vehicles in Swiss garages could, subject to appropriate user behaviour, provide an enormous electricity storage facility.

Other vehicles can run on easily storable synthetic fuels such as hydrogen or methane. If the transport sector is to become climate-neutral and thus fossil-free, as envisaged by energy and climate policy, it is essential to produce during the summer months sufficient electricity to cover immediate needs as well as the additional energy required for the rest of the year. The energy demand of vehicles is already decreasing due to the higher efficiency of electric vehicles. Depending on the technology used, this could go down to around two thirds of the current energy level of fossil fuels used in road transport today.

> At present, 60 percent of Switzerland's energy demand in the mobility sector depends on fossil sources and must be replaced in a climate-neutral way all year round.

Water and the underground for heat storage

Heat is the kind of energy Switzerland requires most. Around half of the final energy consumption is used for heating purposes. In private households, for the provision of heating and hot water, this amounts to 80 percent and is mostly derived from fossil fuels such as oil and natural gas.

Even if the demand for heat decreases in future as a result of energy-saving measures and climate change, it will not be possible to dispense with chemical energy sources unless there is a substitute to cover the demand for heat in winter. As in the transport sector, the challenge is to replace fossil energy sources with alternatives such as biomass, synthetic energy sources, renewable electricity and seasonal heat storage.

In many places, heat pumps are already in operation today. They release several times more energy in the form of heat than they take up in the form of electricity by making efficient use of ambient heat. If heat pumps are combined with heat storage, a temporal decoupling can be achieved. In such systems, a heat pump charges a heat storage tank when the photovoltaic system on the roof generates the most electricity at midday or at a time when it is least expensive to obtain renewable electricity from the grid

> Heat is the kind of energy Switzerland requires most. Around half of the final energy is used for this purpose.

***Table 1:** Overview and brief assessment of various storage technologies:*
**** most suitable/ readily available*
*** suitable/available*
** not ideal/niche markets*

Assessment / Storage type	Chapter	Temporal utilisation: *short-term (minutes–hours)*	Temporal utilisation: *medium-term (hours–days)*	Temporal utilisation: *long-term (weeks–months)*	Performance: *economic viability*	Performance: *environment*	Performance: *energy efficiency*	Performance: *safety*	Available on market
Electricity									
lithium-ion batteries	2.1.1	***	**	–	***	**	***	**	***
sodium-ion batteries	2.1.2	***	**	–	(*)	**	**	***	*
redox-flow batteries	3.2.3	*	***	*	(*)	***	*	***	*
pumped hydro storage plants		***	***	*	**	**	**	**	***
adiabatic compressed air storage	2.3	**	***	*	**	***	**	***	*
Chemical energy carriers									
Hydrogen									
pressure tank		***	***	*	*	***	**	***	***
salt caverns		–	–	***	**	***	**	***	*
metal hydride	3.2.1	–	***		**	***	**	***	**
Synthetic methane gas	3.3.4								
pressure tank		*	***	**	**	***	**	***	***
underground repository		–	*	***	***	***	**	***	*
gas distribution system		***	***	**	**	***	**	***	***
Hydrogen / electricity reconversion									
fuel cells: heat/electricity		*	**	***	*	**	**	**	***
Hydrogen: other applications									
trucks		*	***	***	*	**	*	**	**
industrial raw material		***	***	***	**	***	**	***	**
Methane / electricity reconversion									
cogeneration: heat/electricity		***	***	***	***	*	*	***	***
gas power plant: electricity(/heat)		***	***	***	**	**	**	***	***
Methane and other applications									
hot water		***	***	***	***	*	**	***	***
vehicles		***	***	***	***	*	*	***	***
Heat storage									
Sensible heat storage	3.1.1	***	**		***	***	***	***	***
short-term water storage		**	***	***	**	***	***	***	***
long-term water storage			***	***	***	***	**	***	***
earth		*	**	***	***	***	**	***	**
Latent heat storage									
ice	3.1.2	**	***	***	***	***	***	***	***
latent storage at higher temperatures	2.2.1 2.2.2	***	**	*	**	***	***	***	**
Thermochemical heat storage									
sorption (such as NaOH)	3.1.3	*	**	***	*	***	***	***	*
chemical reactions		*	**	***	*	***	***	***	*

A variety of storage systems allow heat to be stored seasonally – in the ground or in (water) tanks (cf. 3.1, p. 51). One special form of this is ice storage (cf. 3.1.2, p. 58), where the heat is extracted down to freezing point. When the water freezes, as much heat is released as when water is cooled from 80 °C to 0 °C. An ice storage tank with a volume of ten cubic metres, for example, contains the same amount of energy as 110 litres of heating oil. Moreover, depending on the choice of material for the heat storage unit, the liquid to solid transition temperature (0 °C for ice) can be selected, for example 60 °C for domestic hot water or 30 °C for heating buildings. The challenges of heat storage units lie in the required volume and the quality of the thermal insulation. Good insulation must ensure that as little heat as possible is lost between storage in summer and use in winter. Another type of heat storage, so-called sorption storage units (cf. 3.1.3, p. 62), also known as «chemical heat pumps», do not lose heat over time unintentionally. They contain materials that can absorb a great deal of water and release heat in the process. If the sorption material is «dried» in summer, this process can be used to generate heat in winter.

New, high-performance storage systems are essential in order to achieve the energy transition.

Increased energy independence and economic benefits

New, high performance storage systems are essential in order to achieve the energy transition. They are necessary to balance the energy system in the short and medium-term. Storage systems are needed in particular to store the large amounts of solar energy available in summer. Long-term storage can eliminate the need for fossil fuels for transport and heating. At the same time, the expansion of energy storage systems brings significant advantages. These systems lay the foundation for sustainable use of locally and regionally available energy resources.

Energy storage systems are gradually replacing the import of energy sources such as uranium, oil and natural gas, thereby reducing dependence on foreign countries.

Energy storage systems are gradually replacing the import of energy sources such as uranium, oil and natural gas and thereby reducing dependence on foreign countries. In financial terms, there is a shift from operating costs to investment costs, where valuable investments in long-lasting storage facilities are replacing the cost of purchasing imported energy sources.

1.2 High expectations of storage technologies

Storage technologies should be as efficient and inexpensive as possible but also environmentally friendly and safe.

New technologies are required to meet high standards at all times. Clearly, this also applies to storage technologies; they should be efficient and as inexpensive as possible, but also environmentally friendly and safe. When evaluating the individual technologies, however, these criteria can only be applied in absolute terms to a limited extent, since each technology contributes to the performance of the system as a whole. The production of synthetic fuels, for example, causes heat loss even with improved processes. However, if cheaper solar or wind power is used for this process, the overall balance is positive. It is therefore worthwhile to compare systems as a whole.

Efficient? – It depends!

Every energy conversion, including the deployment of storage technologies, is associated with losses, which are reflected in the reduced efficiency of individual technologies.

Systems for short-term storage are generally more efficient than those for long-term storage. In the case of heat storage systems, the heat loss over time depends primarily on the surface area, among other factors. Larger storage tanks have a smaller surface to volume ratio; thus, they lose less heat and are more efficient. Chemical storage systems, such as hydrogen or synthetic gases and fuels, do not experience losses during long-term storage. Yet, they are associated with higher losses in the form of waste heat during the conversion process.

The efficiency of the storage system should be viewed as part of the overall system of provision, storage and use.

The efficiency of the storage system chosen should be viewed as part of the overall system of provision, storage and use. The question is therefore whether a particular type of storage contributes to improving the efficiency of the system as a whole. This is illustrated by an example using automobiles. Lithium-ion batteries in electric vehicles experience power losses of around 10 percent during charging and discharging. On the other hand, electric vehicles themselves achieve an overall efficiency of 70 to 80 percent. In contrast, only a minimal amount of petrol is lost from the tank of a car through evaporation. The internal combustion engine, however, only achieves a maximum efficiency of 30 percent. Moreover, waste heat losses during the production of hydrogen or synthetic gases and fuels can be put into perspective if processes are combined in a suitable way. For example, the waste heat can be used in other industrial processes to considerably improve overall efficiency.

Storage systems, even if they have a low degree of efficiency, make it possible to use energy that would otherwise be lost but is urgently needed. Pumped hydro storage power plants, which pump water up the mountain to reuse it for electricity generation, achieve an efficiency of 80 percent. At present, they use cheap electricity at times of low demand. The same applies to all storage technologies that use solar, wind and hydro power when there is no electricity demand at that particular time. Not only do they make full use of the technical possibilities, they also benefit from low electricity prices.

Safety of future storage technologies

Energy storage systems concentrate a lot of energy into a small space. Inevitably, and regardless of the technology, there is a risk that an uncontrolled escape of energy can occur. The greater the energy density of the carrier, the greater the potential damage. Hydrogen, petrol and diesel are valued precisely because of their high energy density. The associated risk is obvious with petrol and diesel.

In Switzerland, between 2,500 and 3,000 cars catch fire annually[2], in Germany 15,000.[3] Highly flammable fuels can thus cause a substantial amount of damage. This risk will decrease, however, in line with the transition of heat generation and mobility to other energy sources. On the other hand, new risks will arise which must be taken into account. Safety aspects, therefore, always have high priority in all research and development projects.

Most of the new storage technologies are based on improved and optimised technologies. Especially in the case of electrochemical processes, industry has decades of experience in handling similar technologies and employing appropriate safety management concepts, such as the automatic shutdown of electrolysers. Some technologies, such as heat storage, are generally rather «good-natured» with low hazard potential.

Possible risks when operating a compressed air storage system, for example, are assessed by a comprehensive risk analysis of the specific plant and system, minimised by appropriate mechanisms and monitored by measurement technology. Procedures in the event of a potential incident are defined and implemented, further minimising the impact of risks. In particular, the risk of compressed air escaping explosively is minimised by the choice of location (rock quality), the underground plant design (distance between the pressure chambers and from the surface) and structural measures. The deformation of the pressure chambers, the pressure itself and other variables are continuously monitored so that the pressure can be reduced immediately by emergency valves in the event of atypical behaviour.

With the increased use of storage facilities, even small risks take on greater significance. Decentralised use means that risks are also decentralised; they are distributed widely but are smaller. This is particularly true of batteries, which are now in widespread use but harbour the potential risk of overheating and spontaneous combustion. These risks are the result of production errors, damage or incorrect handling, such as improper charging.

> Storage systems, even if they have a low efficiency, make it possible to use energy that would otherwise be lost.

Different types of batteries vary in their ease of use. Technical developments and in-depth analyses[4] are making significant contributions to increasing the inherent safety of battery systems, for example by improving the construction of batteries or using new types of electrolytes.

However, it is again necessary to take an overall view of the respective systems. Statistics indicate that incidents of cars catching fire are 20 to 50 times less common with electric cars than with petrol or diesel cars, even with today's battery technology.

Cheaper in the future

In addition to the construction costs of an energy storage system, that is, the investment costs, the operating costs must also be taken into account. These include electricity costs for operating a heat pump as well as costs incurred by energy losses. Overall, an extraordinarily wide range of costs is involved. As a rough estimate, this can range from around one thousandth of a franc per kilowatt-hour per year for tanks containing heating oil, petrol and diesel, to several francs for reservoirs. The reason for the low storage cost of fuel is the relatively simple low-tech installations in tank farms. In addition, fossil fuels are not traded at full cost. Instead, they are subsidised to the extent that the cost of environmental damage caused by greenhouse gases is not fully carried over to the cost of heating and transport fuels.

> As a general rule, short-term storage facilities cost less per unit of energy than long-term storage facilities.

Compared to the pure storage costs of fossil fuels, all other storage technologies are more expensive, especially those that use complex control systems or expensive materials.

Facilities for short-term storage, provided they are filled and emptied frequently, cost less per unit of energy than those for long-term storage, as a general rule. With respect to heat storage, large storage units are cheaper per unit of energy than smaller ones since enclosing a large volume is cheaper relative to a small volume.

The investment costs of large pumped hydro storage systems (more than 100 MW), for example, are between CHF 1000 and CHF 4500 per kilowatt (CHF/kW) of installed capacity. The costs for compressed air storage are considerably lower; they are estimated at 220 to 1100 CHF/kW of installed capacity or 200 to 300 CHF/kWh of storage capacity. The lower end of the calculated costs is based on experience gained from the storage facility built in Biasca, which was developed with significant contributions from the SCCER. For stationary Li-ion batteries, the upper limit of current storage costs is estimated at around 1400 CHF/kWh of storage capacity or 420 CHF/kW of installed capacity. For storage systems based on power-to-gas-to-power technology, the costs are between 1000 and 5500 CHF/kW if methane is used; the costs are considerably lower if hydrogen (500 CHF/kW) is used.[5]

Operating costs of energy storage facilities are distorted by current legal provisions.

The operating costs of energy storage facilities, with the exception of pumped hydro storage power plants, are distorted by current legal provisions. Today, storage facilities are regarded as end users and subject to the relevant user fees and value-added taxes. In addition, the use of storage facilities for grid stabilisation is not adequately rewarded.

A change is in sight for storage power plants, but how to compensate for the provision of storage capacity is still a matter for discussion.[6] Moreover, the environmental costs of fossil reference technologies, primarily the costs of CO_2 emissions, are not taken into account sufficiently.

Experience shows that both technological and market developments will lead to a reduction in the costs of energy storage. This applies at least to storage facilities based on high-tech technologies. The costs of stationary Li-ion batteries are expected to be halved by 2030.[7] The costs for low-tech storage facilities, such as tank farms but also storage facilities for sensible heat, are not technology-dependent. They are determined by land or construction costs.

It is not yet clear which business models will prevail or who will bear the costs and when. At the moment, with respect to buildings, it is mainly private individuals who install batteries or heat storage units to optimise their energy bill. Other investment models are required for larger heat storages or compressed air storage facilities, such as service providers who build the systems and market the stored energy. It can also be expected that energy will be traded at higher prices in winter than in summer, regardless of whether or not the Swiss energy system has its own storage facilities. It remains to be seen whether the price difference will be passed on to consumers directly or averaged over the year.

Progress in environmental and social responsibility

Like any technology, energy storage has an impact on the environment. Relevant aspects include the materials used and the amount of land or space required as well as the impact on the landscape or greenhouse gas emissions. The environmental impact of individual storage systems depends on numerous factors, in particular on the specific application and the efficiency or service life of the respective system.[8]

Reduction or avoidance of critical materials

Various storage technologies use rare materials, available only in limited quantities, such as lithium, cobalt, gold or iridium, or substances whose extraction and processing are potentially associated with environmental pollution. Working conditions in some mining regions are problematic from a social perspective. Geopolitical risks sometimes apply due to the low number and location of mining sites. These materials are used because they enable greater storage capacities, are more efficient catalysts, ensure better conductivity or deliver stored energy more quickly. As the demand for such materials increases, so do potential difficulties, and the question of scarcity also arises. The declaration and enforcement of environmental and social standards would create the conditions for improving the environmental and social conditions in the mining industry. However, the stronger the monopoly position in a particular mining region is, the more difficult this becomes. In the case of cobalt, for example, 60 percent of global production comes from small-scale mines in the Congo. In the case of lithium, the largest known deposits are found in the salt lakes of the Atacama desert in the border region of Chile, Argentina and Bolivia. Mining takes place under questionable environmental conditions (including falling groundwater levels and air pollution). Accordingly, strategies that reduce the need for new materials are gaining in importance. In the case of lithium, only a tiny proportion of the material that is used is currently recycled, which is due, among other things, to the small amount of material deployed. As demand increases, however, it will become necessary to increase recycling. On the other hand, research and development efforts are seeking solutions to reduce the need for critical materials or dispense with them altogether. For example, new types of catalysts developed within the framework of the SCCER for CO_2 electrolysis require little or no iridium (cf. 3.3.1, p. 80).

Experience shows that both technological and market developments will lower the cost of energy storage.

Heat storage requires substantial space

Heat storage facilities, as well as compressed air storage tanks, occupy a substantial amount of space, mostly underground, but sometimes above ground or in buildings themselves. If areas are chosen above ground, the impact on the landscape will be similar to that of the hot water storage facility in the valley basin in the Canton of Schwyz. The space required for the heat storage unit is directly dependent on the heat capacity of the medium used. Developments within the framework of the SCCER show there are possibilities for increasing the storage potential of both high- and low-temperature storage by deploying specific materials, thereby reducing the volume required (cf. 2.2.1, p. 34 and 2.2.2, p. 38). Skilful control of the charging and discharging process can also contribute to marked reductions in the space requirements of sensible heat storage units.

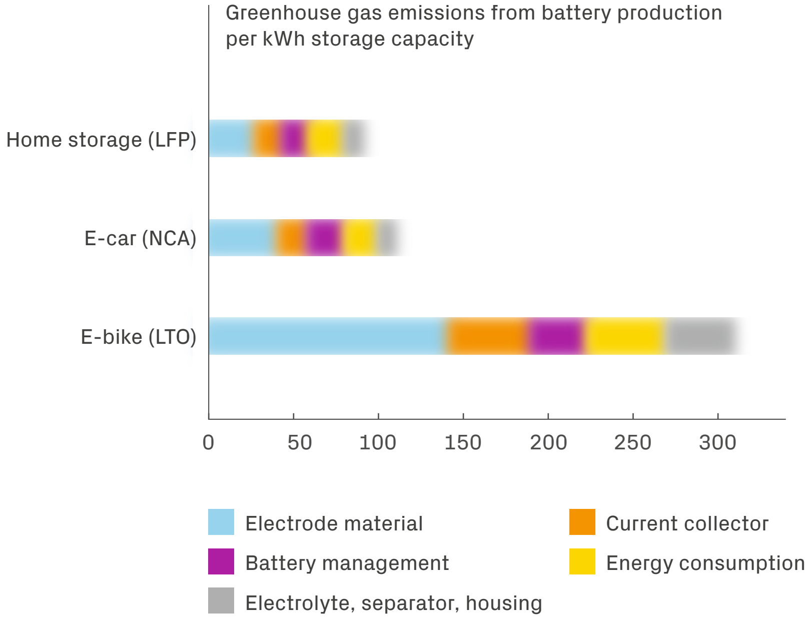
New types of catalysts developed within the framework of the SCCER for CO_2 electrolysis require little or no iridium.

Batteries with a good CO_2 balance

The reduction of greenhouse gases is a central goal of the energy transition. This also raises the question of the CO_2 emissions associated with the production, operation and disposal of energy storage facilities. Today the manufacture of common lithium-ion batteries, for example, causes greenhouse gas emissions of around 100 kg per kWh of storage capacity.

Figure 1: *Greenhouse gas emissions caused by the production of various lithium-ion batteries per kWh of storage capacity.*
LFP: iron phosphate
LTO: lithium titanium oxide
NCA: nickel-cobalt aluminum

Source: based on Schmidt et al. [2019][9], modified from Cox et al. [2020][10].



The exact amount depends on the particular materials used, the way in which the electricity and heat necessary for manufacture are generated and the degree to which the production process is energy-efficient (cf. Fig. 1 [9,10]).

These emissions must be considered in the context of how batteries are used. For stationary battery applications, their relative environmental balance is highly dependent on usage behaviour and the CO_2 intensity of the stored electricity. In Switzerland, stationary intermediate storage results in roughly a doubling of the CO_2 load of the electricity.[11] If electricity is stored over the short to medium term, that is for a maximum of a few hours, batteries provide the best CO_2 balance compared to other storage technologies. For medium to long-term storage, the advantage lies with other options: compressed air and pumped hydro storage as well as power-to-X systems, especially when large amounts of energy have to be stored.[12]

Reduction of greenhouse gases is a central goal of the energy transition.

There are a number of ways to further reduce CO_2 emissions from Li-ion batteries in the future. Batteries could be produced using renewable energy and not, as is currently the case in Asia, with electricity mainly from coal-fired power stations. Recycling could also significantly improve the balance sheet. Finally, batteries from electric cars can be redeployed at the end of their life as stationary power storage devices and, as such, gain a «second life». It can be assumed that the specific storage density, i.e. the number of kilowatt-hours that can be stored per kilogram of battery, will increase significantly. All these measures should become common practice in a few years' time and help to further improve the environmental balance of batteries.

Rapidly growing storage requirements

Each storage system has its specific advantages and disadvantages, and the energy system sets different requirements for storage. It is necessary to regulate short-term fluctuations in seconds, to manage reserves by the hour or, with the increasing restructuring of the energy system, to create a seasonal balance. The focus on seconds and hours is already relevant to the market today. Regarding seasonal shifts, this is also the case, albeit on a rudimentary level, for hydroelectric reservoirs, where the focus is primarily on the electricity sector.

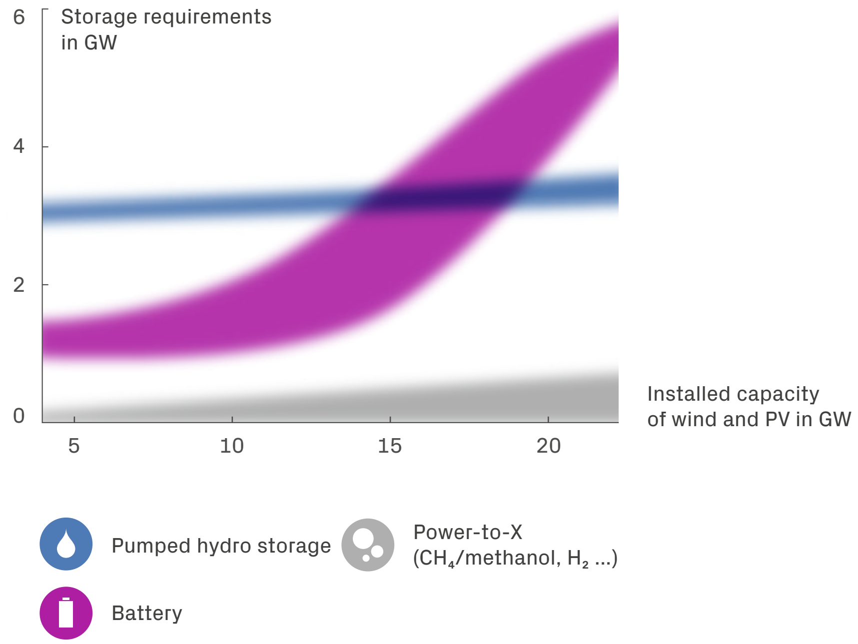


Figure 2: *Storage demand (in GW) depending on installed capacity in wind and photovoltaic plants (for all scenarios, without network expansion).*[13]

Apart from pilot projects, heat is only stored in private households or in heating networks for intervals of several hours to a few days. The good news is that storage solutions for this demand, varying from seconds to days, are technically available and, in the form of batteries, pumped or hot water storage systems, are mature enough to be made available to end users. This is not generally the case for seasonal storage since up to now this field has been dominated by fossil fuels.

Batteries and power-to-X storage systems play a crucial role in balancing the growing share of solar and wind energy and in stabilising the energy system. Pumped hydro storage plants are designed to balance medium to high grid voltage levels. Wind turbines and solar photovoltaics, on the other hand, work at medium to low voltage levels, where batteries are ideal for balancing supply and demand. Accordingly, it can be assumed there will be a significant increase in the demand for battery storage capacity (cf. Fig. 2 [13]), which will ultimately greatly exceed that of pumped hydro storage plants. In view of the growing supply of low-cost solar power in summer, however, power-to-X paths are also an attractive seasonal storage option. Driven by the seasonal difference in electricity generation costs, in future up to 900 GWh of electricity per year could be stored in summer in the form of hydrogen and natural gas, according to scenarios examined in the SCCER.

If electricity is stored for a maximum of a few hours, batteries perform best in terms of CO_2 balance compared to other storage technologies.

This would be available for use in the transition periods or in winter, whether in the transport sector or for stationary applications. According to the scenarios, around 13 percent of the electricity generated from variable renewable sources in summer would be available for seasonal storage in future.[14]

With the increased use of different storage and other technologies, the energy system as a whole becomes more robust and safety risks are reduced overall. The current energy system is disproportionally based on fossil energy sources and is subject to corresponding consequences for security of supply.

Batteries and power-to-X storage systems play a crucial role in balancing the growing share of solar and wind energy and in stabilising the energy system.

In view of the growing supply of low-cost solar power in summer, up to 900 GWh per year of electricity could in future be stored in the form of hydrogen and natural gas.

For example, tensions in the Strait of Hormuz can make themselves felt all over the world, not least at the nearest filling station.

SCCER contributions to the Energy Strategy 2050

SCCER has met its stated goal of providing a well-stocked toolbox for addressing the challenges posed by the Energy Strategy 2050 in the field of storage technology. From today's perspective, the Energy Strategy 2050 is thus technically feasible.

With its research and development work over the last seven years, SCCER has made essential contributions to improving the technical performance of various energy storage systems in terms of efficiency, storage density or energy supply. Also, SCCER investigated the significance of storage systems for Swiss society. Pilot plants have demonstrated feasibility and marketability proven. In the beginning, many approaches were pursued at all levels.

With the increased use of different storage and other technologies, the energy system as a whole becomes more robust and safety risks are reduced overall.

The most promising technologies were developed to the next level, while others were discarded because, from today's perspective, they are still too rudimentary to be relevant to the Energy Strategy 2050. In this process, solutions to two major challenges have been further developed or newly developed:

1. Short- and medium-term storage of electricity and heat. The low-cobalt Li-ion battery is relevant here (cf. 2.1.1, p. 26), as is adiabatic compressed air storage, which is also a field of application for high-temperature heat storage (cf. 2.3, p. 44 and 2.2.2, p. 38).
2. Seasonal balancing by means of heat storage and chemical energy sources. Different heat storage concepts were investigated and developed into functional systems (cf. 3.1, p. 51). In the field of chemical energy carriers, hydrogen production and storage, the use of CO_2 as a raw material for renewable methanol and methane and the formic acid cycle were considered.
   In addition to the classic catalytic approaches, the electrochemical production of hydrocarbons from CO_2 and water, the researchers developed a 200-cm² co-electrolysis cell starting from theoretical principles. This could supply both the transport sector and industry with renewable fuels and bulk chemicals (cf. 3.3.4, p. 92).

These issues are of great importance as the aim is to replace the 64 percent of energy demand with renewable energy, currently satisfied by imported fossil fuels. At the same time, 20 percent of the current electricity sector must also be covered by renewable energy all year round.

The central focus of the research work of the SCCER is on natural science and engineering as well as on socio-economic issues. The SCCER has created tools to answer critical questions regarding environmental compatibility as well as more systemic concerns. Various scenarios have been studied to investigate how storage solutions in the energy system should be developed, temporally and spatially, in order to sustainably meet energy demand at all times. The role power-to-X can play was examined separately in a white paper[15] together with three other SCCERs. In the field of economical life cycle assessment, a comparative analysis of Li-ion and Na-ion batteries showed that although the Na systems use more environmentally friendly components, they do not perform better than the Li systems in the overall balance since they require twice the amount of resources.

As shown in this chapter, a wide range of different storage technologies is required to cover the whole field optimally in terms of space, time and application.

The SCCER has proven in numerous demonstrations that storage technologies are essentially available and usable. Now it is necessary, above all, for political decisions to be taken in the interests of a coherent energy policy in order to reduce the regulatory obstacles that currently impede or make impossible the economical use of energy storage. This can guide business models and investment decisions necessary to advance the technologies developed in the SCCER and bring them from the laboratory into the ultimate energy system of the Energy Strategy 2050.

The following two chapters present in detail the storage systems which the SCCER has investigated and discuss the technological and economic opportunities and obstacles that arise in each.

Political decisions must now be taken in terms of a coherent energy policy in order to reduce the regulatory obstacles that currently impede or make impossible the economical use of energy storage.

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2 Short-term storage

2.1 Batteries

Lithium-ion batteries

Advantages
- mature and in mass production
- very high storage density
- durable
- continuous performance improvement due to worldwide research and development

Disadvantages
- contains geopolitically critical materials such as lithium
- contains the critical raw material cobalt
- high price in relation to storage capacity for large-format cells
- cell manufacturers almost only in Asia

Maturity of the technology
Technology readiness level (TRL):
- 9 for current products
- 4 for new types of cells, for example with solid electrolyte

Milestones of SCCER
- new cathode materials with lower cobalt content
- new electrolytes for reactive cathodes
- cells with optimised «thick» electrodes with high energy density

Further research needs
- complete absence of critical materials
- longer service life with new concepts
- cheaper materials for existing technologies
- further increase in safety and reliability
- improved performance at low temperatures

Sodium-ion batteries

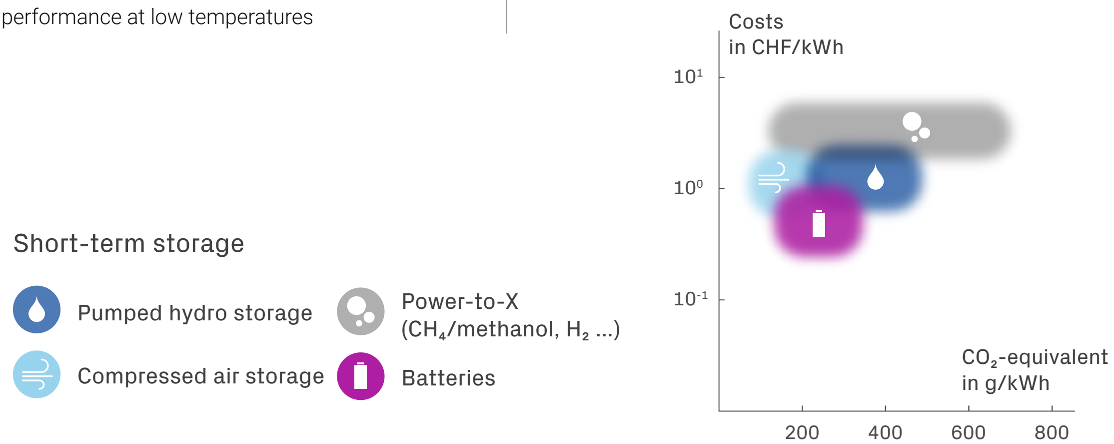
Advantages
- high currents
- abundant raw materials available
- same infrastructure as for lithium-ion battery production can be used

Disadvantages
- lower energy density
- still requires much more research and development on electrode materials

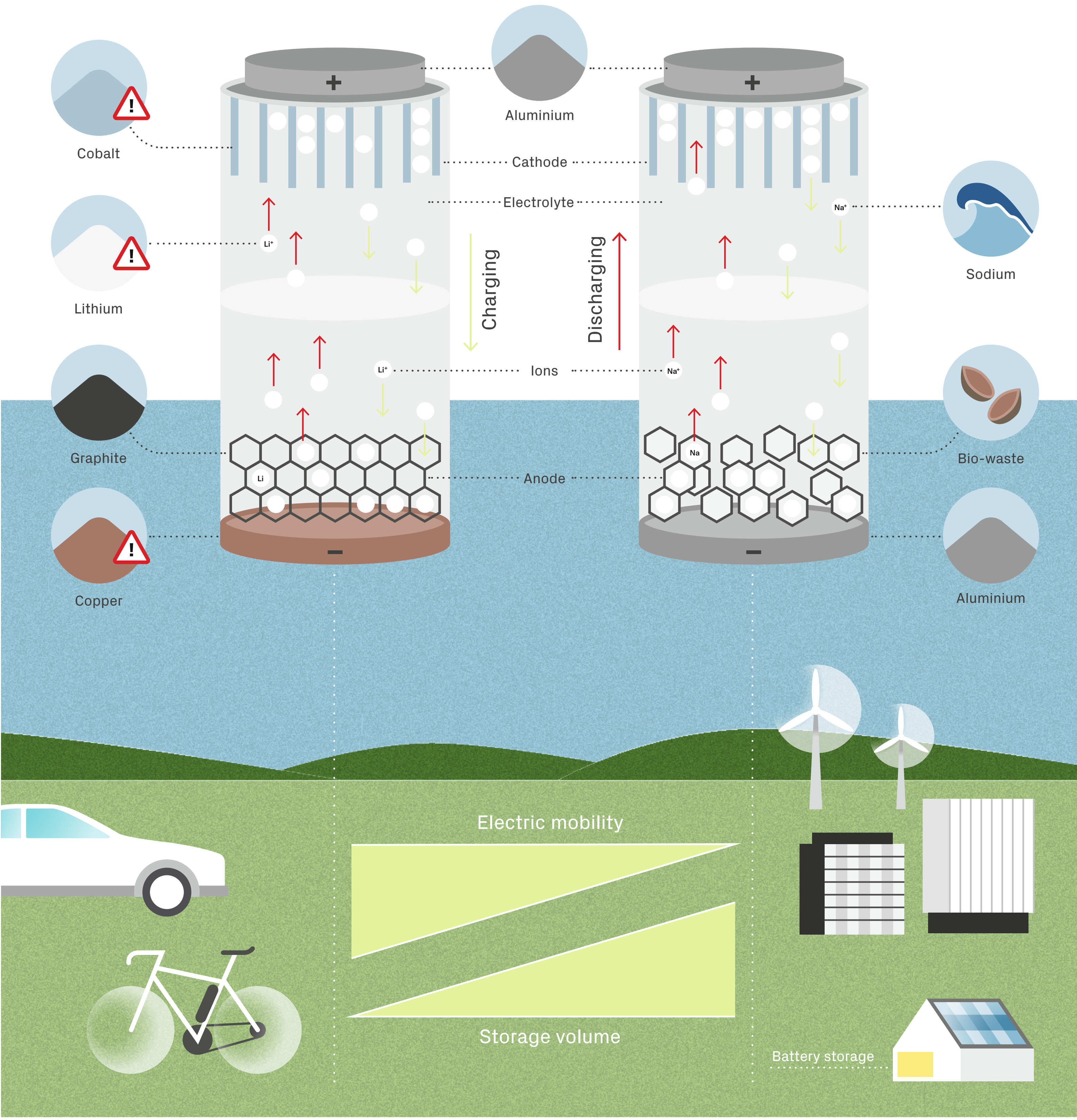
Maturity of the technology
Technology readiness level (TRL): 3–4

Milestones of SCCER
- investigation of new electrode materials

Further research needs
- further research into new materials



The principle of lithium-ion and sodium-ion batteries



2.1.1 Lithium-ion batteries

Significance for the Energy Strategy 2050

Lithium-ion batteries have already become an integral part of everyday life, like the portable electronic devices they power. They power laptops, smartphones and tablets as well as e-bikes and electric cars. Li-ion batteries make electricity portable, and the world would look very different without them. The Nobel Prize Committee recognised this and honoured the development of Li-ion batteries with the Nobel Prize for Chemistry in 2019. Li-ion batteries are one of the key technologies that could make a society without fossil carbon possible. Their importance is reflected in their production growth forecast. The global demand for batteries is expected to increase tenfold from around 300 gigawatt hours in 2020 to nearly 3000 gigawatt hours in 2030, mainly for the electrification of cars. Batteries are also suitable for balancing the supply and demand for electrical energy on time scales ranging from minutes to several days. This means they can play a decisive role in integrating strongly fluctuating renewable energy sources such as sun and wind into the power grid.

Yet, there is another side to Li-ion batteries. Their manufacture requires a variety of different materials. Today, lithium is extracted mainly in Australia and Chile. Time and again, experts fear this coveted metal could fall victim to political disputes and thus become inaccessible. Battery electrodes also contain cobalt, which is listed as a critical raw material for the European economy. Furthermore, it is mined in some countries under questionable environmental and working conditions. Research in recent years has therefore concentrated on developing batteries that use less, or preferably none, of these controversial materials. At the same time, researchers hope to develop new materials that can achieve a higher energy density which would allow electric cars to travel longer distances, enable a longer service life and provide the highest possible level of safety.

Production costs account for around a quarter of the total costs of the battery. This determines whether electric cars will one day be as affordable as cars running on petrol or diesel. Moreover, if the production costs of batteries fall, it will become even more interesting for homeowners to store their solar power locally and thus substantially increase consumption of their own electricity. In this way, they can help to relieve the burden on electricity grids.

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Lithium-ion batteries – operating principle

Commercial Li-ion batteries currently consist of a negative electrode made of graphite, an electrolyte and a positive electrode made of a metal oxide most often based on nickel, manganese and cobalt. The contacts are made of copper at the negative pole and aluminium at the positive pole. In a charged state, lithium resides in the graphite. When discharged, lithium releases an electron and moves as a positively charged Li-ion to the positive electrode, where it is incorporated into the crystal lattice of the metal oxide. When the battery is charged, the reverse process takes place. The Li-ion moves to the graphite electrode where it picks up an electron.

The positive electrode, the negative electrode and the electrolyte change with prolonged use of the battery. If further advances are to be made the ageing processes of Li-ion batteries must be better understood.

At the negative electrode (graphite), it is particularly important to study the charging process. Sufficient time must be given for the depositing of Li-ions so they can penetrate the graphite particles. Otherwise, the graphite electrode surface will be plated by metallic lithium and its dendrites may start to grow, which, in extreme cases, can lead to an internal short circuit as soon as they reach the positive electrode. The Li-ion diffusion speed and thickness within the electrode as well as the geometry and arrangement of the graphite particles play a role here. The thicker the electrode, the more energy the cell can absorb, but the slower the charging and discharging rate, which limits performance.

The detailed processes at the positive electrode (cathode) are very complex. There is often a change in the crystal structure during charging and discharging, accompanied by mechanical stresses within the cathode particles, which can lead to a drop in long-term performance due to structural degradation of the active materials. This must be addressed in order to improve cycle stability and service life.

The electrolyte is an organic fluid containing lithium salt in which the lithium ions should move with the lowest resistance possible. The cell voltage of a charged Li-ion battery is well over 3 volts, with the actual voltage depending on the cathode type. The electrolyte must be stable under such conditions. Water and many organic solvents are therefore not suited as electrolytes since they decompose readily, causing gas to develop. The electrolytes used today react somewhat with the electrode surfaces. The electrolyte must be adapted to the cell voltage of the battery system to mitigate such effects.

In future, batteries will have a higher energy density, withstand many thousands of charge/discharge cycles without loss of capacity and forgo materials that are scarce or pollute the environment.

Research at the SCCER

The SCCER research teams have gained valuable scientific insights contributing to the development of the next generation of Li-ion batteries. In future, batteries will have a higher energy density, withstand many thousands of charge/discharge cycles without loss of capacity and forgo materials that are scarce or pollute the environment. At the same time, production costs will be reduced even further to a level well below that of today's small and mass-produced consumer cells. Surprisingly, large-format cells are still 40 percent more expensive, in relation to storage capacity, than small consumer cells such as those used in notebooks and mobile phones.

SCCER researchers have succeeded in developing cathode materials with optimised particle shape, which contain only one third the amount of critical raw materials. The research team can already produce several hundred grams of this superior cathode material per batch. Naturally, this is still too little for mass production.

Researchers all over the world expect low-cobalt – one day perhaps cobalt-free – Li-ion batteries to be on the market in just a few years.

The work does, however, raise hopes that an upscaling towards mass production is possible in the next few years.

The SCCER has also succeeded in developing a new generation of cathode materials, so-called single-crystalline materials, which promise significantly better long-term cycle stability.

At the same time, efforts to synthesise cobalt-free materials are continuing. A lower cobalt content in the cathode is associated with a higher voltage. As a result, the energy density of the battery increases, while the overall costs fall. But there is one disadvantage. Cathode materials with little cobalt are characterised by very high surface reactivity; they decompose the electrolyte more quickly and, after just a few charge/discharge cycles, the battery can store less and less energy. To prevent this, the SCCER researchers have developed new electrolytes that stabilise the surface of these low-cobalt, more reactive materials. After 200 cycles, the batteries still reach 91 percent of their original capacity.[16] This is still far too little for a mass-produced product, but researchers around the world expect low-cobalt – one day perhaps cobalt-free – Li-ion batteries to be on the market in just a few years.

Another focus of SCCER's work has been on the development of thick positive and negative electrodes with high energy density. Today, such batteries achieve a capacity retention of 85% after 500 cycles. This means that these electrodes have so far only been suitable for applications with short life span. However, the research team is already developing an electrolyte with a higher conductivity of lithium ions using these thick electrodes, which should enable faster charging and discharging and hopefully a longer life span.

The thick electrodes are part of a demonstration cell, which is being manufactured in a pilot line set up within the SCCER. It is expected to reach 275 watt-hours per kilogram, in line with international roadmaps for battery technology. In cooperation with industrial partners, the team has developed new, thicker graphitic anodes that have twice the storage capacity of current graphite-based anodes. The results of the SCCER form the basis for a major EU project within the framework of «Horizon 2020», involving eleven European partners from seven countries, including the European Giga factory Northvolt. The European Commission is funding the SeNSE project with over ten million euros. It was launched in February 2020 and is coordinated by Empa.[17] The SCCER programme also led to participation in another EU research project («HIDDEN»).

Technical perspective

The Li-ion battery technology developed in the SCCER will be ready for market in a few years. Other battery concepts like solid state batteries or batteries with lithium metal anodes still require a few additional years of research. This also applies to optimising the stability of the electrolyte, for example by adding ionic liquids. One focus of future work will be on scaling up the processes - from batches weighing a few grams to tens, then hundreds of kilograms. In addition, new battery types will have to prove in extensive tests that they can achieve a comparable service life and safety level to those in mass production today.

Economic perspective

Li-ion batteries were originally developed for the portable electronics market such as notebooks and smartphones. However, batteries continue to conquer new markets: they are electrifying mobility and increasing flexibility in the electricity sector.

Cooperation in research projects with industrial partners underpins Switzerland's important position in the EU's large-scale battery research initiative.

By 2025, the battery market in Europe will reach a volume of €250 billion. The demand for batteries worldwide is expected to increase tenfold – from 300 gigawatt-hours in 2020 to almost 3000 gigawatt-hours in 2030. The rapidly growing demand is currently being satisfied mainly by battery cell manufacturers in Asia. The European economy is therefore highly dependent on Asian manufacturers. There is, however, a strong industrial base of material and equipment suppliers in Europe and Switzerland, which should, through substantial investments, be motivated to build up European cell production. With the aim of promoting cooperation within this industry and across the research landscape in Switzerland, the association of the Swiss battery industry, BATTMAN, was founded.

Within the framework of the SCCER, several new academic working groups for battery research have been established, while existing ones have shifted their focus towards batteries. This contributes to the training of a new generation of battery specialists in the fields of science and engineering in Switzerland and reinforces the transfer of trained personnel to the Swiss and European battery industry.

Numerous examples of cooperation in research projects with industrial partners, on a national and international level, show how much this know-how is in demand. They underpin Switzerland's important position in the EU's large-scale battery research initiative and strengthen Switzerland's position along the entire value chain of battery production. Switzerland can thus assume a long-term leading role in existing markets such as electromobility and stationary energy storage, as well as in future emerging applications such as robotics, aerospace, medical technology and the Internet of Things.

2.1.2 Sodium-ion batteries

Significance for the Energy Strategy 2050

At present, sodium-ion (Na-ion) batteries are not making a major contribution to the restructuring of the energy system. However, there are fields in which this technology could be applied when it is fully developed. Na-ion batteries have an advantage over the established Li-ion technology, particularly in applications that require very high currents. In addition, Li-ion technology is based on several rare and expensive raw materials. If there is a shortage of these, Na-ion batteries could offer a cheaper and more environmentally friendly alternative.

Thanks to the ready availability of raw materials and the environmental benefits, it seemed ten years ago that Na-ion batteries could replace or at least complement Li-ion technology in a number of applications. This has not yet happened. The reason for this lies in the electrochemical properties of sodium ions. They are larger and heavier than lithium ions, resulting in a lower energy density. This means that a battery with the same volume or weight stores less electrical energy if it is based on sodium instead of lithium. With a Na-ion battery, smartphones would be thicker and heavier or, if they maintained their original size, could only be used for a shorter time; electric cars would either have a reduced range or the boot would have to be smaller to accommodate a larger battery. For thermodynamic reasons, the electrical voltage of a Na-ion battery cell is about 0.3 volts lower than that of a comparable Li-ion battery cell. To achieve a technically meaningful voltage of several hundred volts, a larger number of cells would therefore be necessary.

The advantages of Na-ion batteries are the higher mobility of the Na- ions in the electrolyte and the faster reaction within electrodes. If optimally designed, such batteries could absorb or release higher currents than their lithium counterparts. This means that electric cars could be charged more quickly. It is also a useful property for storing electricity from renewable energy. If all the heat pumps or cooling systems in a block of flats are suddenly switched on, high currents must flow instantly. With Na-ion batteries this would be possible without negative effects on the electricity grid.

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Sodium-ion batteries – operating principle

Na-ion batteries do not differ fundamentally in their construction from Li-ion batteries. The way they operate is identical to the processes and basic requirements described in Chapter «2.1.1 Lithium-ion batteries». The challenge is to select materials in such a way that, with respect to the specific properties of sodium, they are as highly optimised as are today's Li-ion systems. For example, graphite is used in the anode in a Li-ion battery. But, in combination with Na-ions, graphite does not function well and is thus not an optimal anode material for the Na-ion battery. The same applies to the electrolyte and cathode. This is the point at which research work begins.

An important aspect, in addition to the advantages mentioned above, is that machines currently used for the manufacture of Li-ion batteries could be used to produce Na-ion batteries, and no new factories would have to be built. Despite a few disadvantages, Na-ion batteries can deliver important benefits, motivating continued research into this technology. The scientists at the SCCER are convinced such research is worthwhile.

Research at the SCCER

The electrode materials are decisive for the power and energy density of batteries. The anode on the negative side and the cathode on the positive side are composed differently but need to be optimised together since the weakest link limits the energy density. Starting from theory, the SCCER researchers calculated the maximum energy density of known materials. Based on this pre-study, the team created Na-ion battery electrodes for small-scale testing. While some paths proved to be dead ends, others produced encouraging results. The following is an overview of some of the results.

Materials for the anode: The task here was to discover a material that could store the relatively large Na-ions. Carbon proved to be particularly suitable, though not in its ordered form graphite, but rather in its amorphous form as it occurs in coal. Such carbon is usually produced from valuable industrial products such as sucrose from sugar beet or polyacrylonitrile, used in the production of clothing fibre. From the perspective of sustainability, this is not ideal. The researchers found an alternative: organic waste. This would not only reduce costs but, through recycling, would also contribute to a sustainable economy. Anodes for Na-ion batteries based on bio-waste achieve a specific charge of 280 milliampere-hours per gram for more than 100 charge-discharge cycles at a C-rate of 3. Such a C-rate means, for example, a small battery of the standard AAA size with 1000 milliampere-hours would be discharged with a current of 3000 mA, a very high value. The observed C-rate raises hope that high-performance batteries can be produced that are capable of storing and delivering large amounts of electrical energy quickly, for example from photovoltaic systems or wind turbines, when many electrical appliances are switched on simultaneously in households or industrial plants. This charge value was achieved for more than 100 charge-discharge cycles. Although 100 cycles is not yet sufficient for industrial use, the potential exists and work on further optimisation is continuing.

In addition to carbon, the SCCER researchers also tested completely new alternatives, including metal alloys based on tin. By adapting the electrolyte and the alloy, it was possible to produce an anode that remained stable in tests despite a high number of charging and discharging cycles. However, this would make a Na-ion battery so expensive that the anticipated cost advantage over Li-ion batteries would be lost. The team has therefore not pursued this approach further.[18]

Materials for the cathode: In this instance, the researchers set out to modify the proven layered oxides in such a way that there would be no need for cobalt. This raw material is expensive and problematic as there are also ethical concerns related to cobalt mining. The result of the development efforts is the cobalt-free material $Na_{0.67}Mn_{0.6}Fe_{0.25}Al_{0.15}O_2$ (NaMFA), which is inexpensive, non-toxic and has good electrochemical properties.[19] Nonetheless, the researchers concluded that a Na-ion battery based on this material would not be competitive with Li-ion batteries in terms of specific energy, costs and production-related greenhouse gas emissions.[20]

The hopes for high-performance, low-cost, long-lasting and ecologically sustainable Na-ion batteries are realistic.

The research team therefore decided to start over and search for radically new materials to bring Na-ion batteries to a higher performance level. Novel cobalt-free layered and polyanionic materials, which were previously only known from theoretical calculations, are now expected to lead to the realisation of Na-ion batteries which are competitive with standard Li-ion batteries.

In parallel, the research team investigated alternatives with environmentally friendly water-based electrolytes with a high salt concentration. Such concepts are interesting for applications where safety is paramount and high energy density is not required. Researchers extended the stability window of the water-based electrolyte from 1.23 volts to more than 2 volts, ensuring a higher specific energy than conventional water-based battery cells.[21]

Because of the enormous potential of the technology, it is both necessary and sensible to make further efforts in materials development.

In combination with selected electrode materials, the development team achieved promising results with exceptionally high capacity and excellent cycle stability.

Technical perspective

The hopes for high-performance, low-cost, long-lasting and ecologically sustainable Na-ion batteries are realistic. Despite its lower energy density, this technology has the potential to complement and partially replace Li-ion technology. However, research efforts in the SCCER indicate that the path to this goal will be longer than expected. The energy stored in Na-ion batteries is currently more expensive and less environmentally friendly than once hoped. Above all, there are still no materials for the cathode that meet all requirements for high energy density and higher cell voltage. The known electrolytes are not sufficiently stable.

Because of the enormous potential of the technology, it is both necessary and sensible to make further efforts in materials development. Metallic anodes in particular offer great opportunities but remain largely unexplored. This also applies to solid state electrolytes for sodium systems, which could offer a higher level of safety.

Assuming a similar steep development path to that of Li-ion cells, a four-fold increase in energy density for Na-ion batteries seems realistic by 2045. If research activities are given high priority, development could proceed more quickly because the structural similarity of the Li-ion and Na-ion battery allows researchers to draw on the experience of the rapid and continuing development of Li-ion technology worldwide.

Economic perspective

Na-ion batteries are currently a niche technology. There are only a few start-up companies in the world that are engaged in this field. Although their products are nearly ready for mass production, their energy density is not yet competitive with that of Li-ion batteries. The excellent cycle stability, however, opens up many business opportunities for applications where the cost per kilowatt-hour per cycle is more important than energy density. In addition, even now the power that can be drawn from Na-ion cells is very high and thus they already represent a better alternative to electrochemical supercapacitors in terms of energy stored.[22] In fact, Na-ion batteries combine high power (similar to a supercapacitor) with excellent cycle stability and energy density, exceeding supercapacitors by a factor of five. Accordingly, they offer an economic potential that has not yet been fully exploited.

Once these technical challenges have been overcome, the industrial development of Na-ion batteries could progress rapidly since their manufacturing process is very similar to that of Li-ion batteries. Production capacities will probably be built up initially in those places where Li-ion batteries are already manufactured today, that is, primarily in Asia. But the chances for production deployment in Europe are also good. If incentives are right, rapid development is possible as demonstrated by the high investments currently being made in gigafactories. The gigafactories produce rechargeable batteries for electromobility which are also suitable for energy storage in the power grid. It is rather unlikely that such oversized battery factories will be built in Switzerland. Nonetheless, opportunities are opening up for the Swiss economy, as production facilities require extensive know-how in automation and quality assurance, for instance. Moreover, Asian companies frequently rely on machines and systems that are developed in high-wage countries in Europe to produce their batteries.

If Switzerland wants to secure a share of this market, it is necessary to master battery technology in addition to process know-how. There are opportunities in this field for the chemicals industry, which manufactures primary products for electrodes and cells, as well as for small and medium-sized companies that contribute precision parts, production machinery and process automation.

If Switzerland wants to secure a share of the market for Na-ion batteries, it is necessary to master battery technology in addition to process know-how.

2.2.1 High-power, low-temperature, latent heat storage

Advantages
- high storage density
- fast charging and discharging
- higher efficiency and degree of self-consumption of renewable energy sources (solar thermal/photovoltaics)
- high CO_2 reduction potential
- cost-effective storage of energy in the form of heat

Disadvantages
- some concepts still require optimisation
- acceptance of the necessity of thermal energy storage in present-day and future energy systems (building construction and industrial processes)

Maturity of the technology
Technology readiness level (TRL):
- 9 for commercially available latent storage tanks with immersed heat exchanger
- 5–7 for macro-encapsulated latent storage and phase-change dispersions
- 3 for direct contact concepts

Milestones of SCCER
- optimisation of latent storage with immersed heat exchanger
- founding a start-up for macro-encapsulated latent storage
- development of new storage concepts

Further research needs
- bringing advanced technologies to market-readiness, possibly with additional start-ups
- construction of pilot plants in the field with a realistic business model
- further development of less mature concepts

Significance for the Energy Strategy 2050
The energy transition can only be achieved through the defossilisation of heat generation since the consumption of heat and cold accounts for half of all final energy in Switzerland.[23] Switzerland has taken this into account in the Energy Strategy 2050. If growth continues as expected, 450,000 heat pumps with heat storage and photovoltaics will be installed in Switzerland by 2035.[24] Compact, high-power latent heat storage systems could become the standard storage solution. Thus, decentralised storage units in buildings could increase the self-consumption of energy from PV systems and relieve the load on the electricity grid at times when there is an abundance of sunshine.

For the energy transition to be successful, it is therefore important to obtain thermal energy from renewable sources. Thermal energy storage is crucial in this context because it decouples generation and consumption. A typical example is seasonal heat storage which is dealt with in chapter 3.1 of the white paper [25]. In the summer months, heat generated by PV systems is gathered in the storage tank and, during the winter heating season, it is slowly released again. There are, however, many applications where it is useful to store heat for shorter periods of time. Examples are the provision of domestic hot water in buildings and also heat recovery either in combined heat and power plants or in industrial processes which generate waste heat that can be reused. If the waste heat from all these industrial processes were collected, Switzerland could save three percent of its final energy demand.

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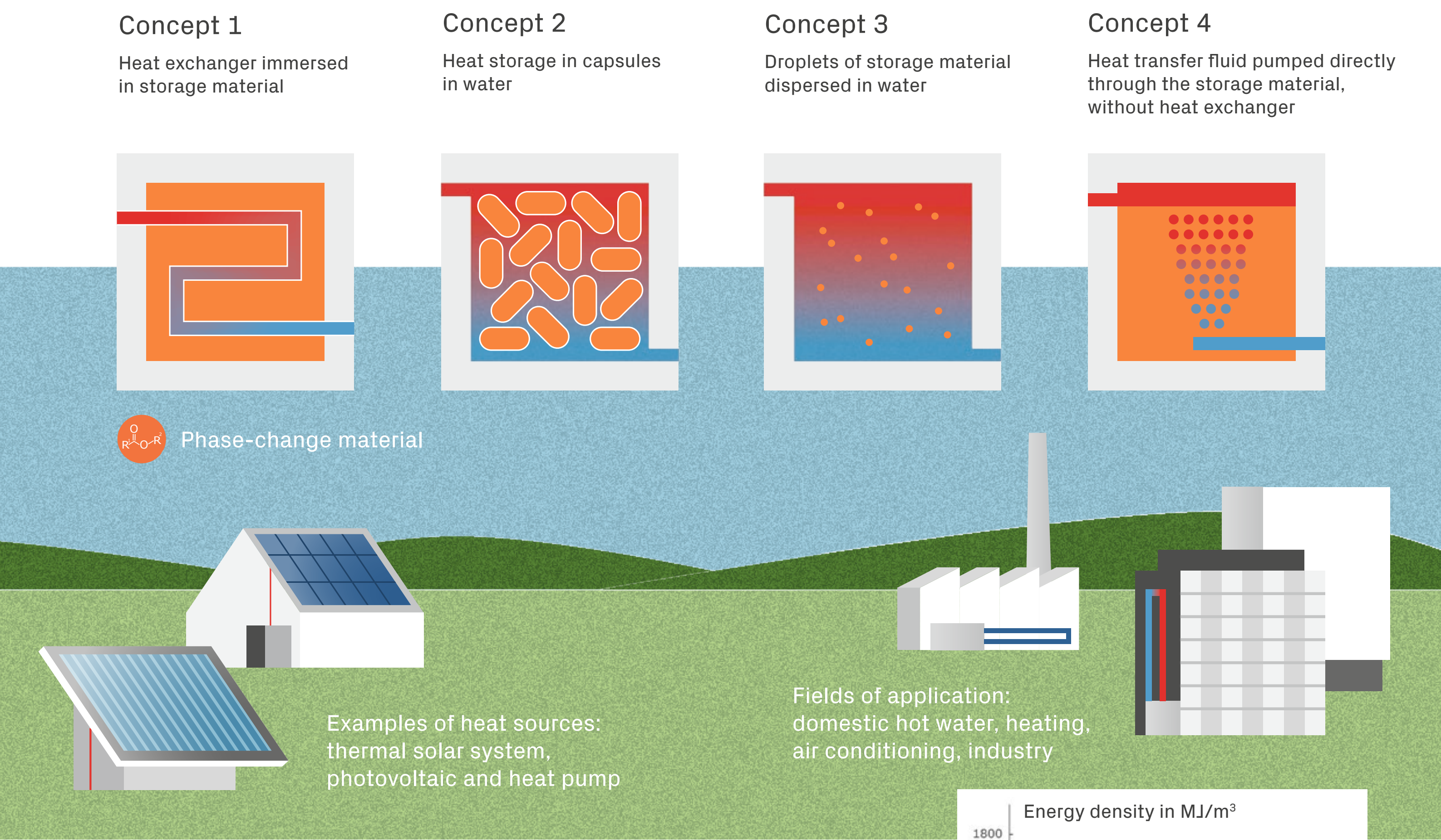
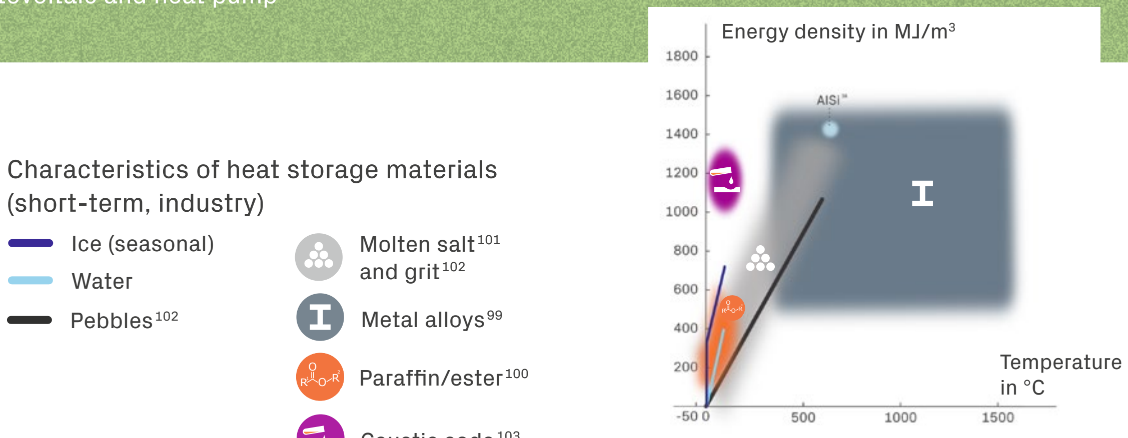
The structure of high-performance low-temperature heat storage





Source: *Plot modified from Ding et al. (2013)*[99].

High-power, low-temperature heat storage – operating principle

It would be hugely advantageous, in many cases, if it were possible to store a greater amount of heat in a more compact way. Imagine if today's hot water tank (1 m³) were only a small «thermal battery» that nevertheless could store considerably more energy! This is the goal of latent heat storage research.

Latent heat storage uses the phase change of a medium, for example from ice to liquid water, to accumulate heat. When the storage medium solidifies, it releases heat for heating. Materials that are used in such storage systems are called phase change materials.

The big challenge here is to store heat quickly and then release it again with high power on demand. Ensuring sufficiently high performance output is important to guarantee, for example, that water for the shower is hot enough and not just lukewarm. High-power storage tanks require intelligent and cost-effective concepts that enable a high level of heat transfer.

When charging these storage units, the heat required to convert the storage medium from solid to liquid must be supplied very quickly. When discharging (solidifying the storage material), it is challenging to extract the heat quickly enough. The reason is the low thermal conductivity of the phase change materials used. Although this cannot be increased, there are technical tricks that make it possible to conduct the heat into and out of the storage unit much more rapidly. Researchers within the SCCER have carried out important development work on this topic.

Research at the SCCER

Within the framework of the SCCER, the Lucerne University of Applied Sciences and Arts has set out to develop affordable and sustainable high-power latent heat storage systems that can be charged and discharged quickly and flexibly. The team has pursued four concepts.

Concept 1 – «Storage tank with heat exchanger»:
In this concept, the heat exchanger is immersed in the storage material. This concept is the most mature and already commercially available. The research team has developed simulation-based design tools for leading manufacturers of such storage systems. The team has also demonstrated the suitability of heat exchangers, used in air conditioning systems for trucks, for rapid charging and discharging of latent heat storage systems. Together with an industrial partner, the researchers have also developed a latent heat storage system which is suitable for industrial cooling processes (e.g. pharmaceutical processes) and for the transport of temperature-sensitive products such as foodstuffs at temperatures between −35 °C and −20 °C. This represents a compact alternative to water-glycol storage.[26]

Concept 2 – «Storage in capsules»:
Capsules containing-phase change material are inserted into the water tanks of existing heaters, thereby quadrupling the storage capacity. In combination with a heat pump, this helps to increase the self-consumption of photovoltaic electricity. This novel and promising development of latent heat storage at the Lucerne University of Applied Sciences and Arts, within the SCCER, is being commercialised in a spin-off company (Cowa Thermal Solutions).

Concept 3 – «Phase-change material in dispersion»:
In this technological process, nanodroplets of the storage material are dispersed in water. At a certain temperature, the selected material has a very high cooling and heating capacity. In addition, the liquid can be pumped which enables a high and flexible power output.[27]

Concept 4 – «Latent heat storage in direct contact»:
In this concept, the heat transfer fluid is pumped directly through the phase-change material without the need for an additional heat exchanger. On the one hand, this saves the cost of the heat exchanger, and on the other, very short charging and discharging times can be achieved.[28]

As part of the SCCER activities, the Lucerne University of Applied Sciences and Arts has also developed new storage materials which are less expensive, have a higher energy density and are more environmentally friendly than most conventional phase-change materials.[29] These include materials with a phase change at 35 °C for floor heating, at 58 °C for hot water heating and at −21 °C for cooling processes.

Technical perspective

The four concepts being explored by the Lucerne University of Applied Sciences and Arts are at different stages of marketability. Latent heat storage systems with the heat exchanger embedded in the phase-change material (Concept 1) are already available on the market. Nevertheless, they have the potential for further optimisation.

The capsules filled with storage material (Concept 2), are now in the process of commercialisation through a spin-off company from the Lucerne University of Applied Sciences and Arts and are expected to be on the market in two to three years. For Concept 3, phase-change material in dispersion, HSLU has already licensed its patents to industrial implementation partners. Concept 4, the very attractive option of direct contact storage, will take another five to ten years before commercialisation.

The right course must now be taken to help these promising approaches reach commercialisation. In collaboration with start-ups, mature technologies such as automotive heat exchangers or storage capsules should be tested in pilot projects to determine their suitability for everyday use and their economic feasibility. This should take place under realistic operating conditions, for example in a building in combination with renewable energy sources (solar thermal or PV). Less mature technologies like the concept of direct contact storage and the development of phase change materials derived from organic, sustainable raw materials need further basic research to advance.

Finally, in order to achieve the successful dissemination of these technologies, it is important that potential customers are aware of the economic and ecological advantages of heat storage systems. Moreover, contributions must be made on a political level through measures which promote such technologies.

Economic perspective

Thermal storage systems are already economically feasible today and will be even more so in future. One example where latent heat storage already makes sense is the combination of photovoltaics and heat pumps.

> There is a great need for technologies that increase the self-consumption of solar power by private households.

This is a key technology for decarbonising residential buildings. However, if no storage is used, the crucial point of the time lag between energy generation and consumption arises. The generation of electricity by the photovoltaic system peaks around midday, while the heating requirements of the building or the electricity demand of the heat pump come into effect mainly in the evening.

The self-consumption of photovoltaic electricity in residential buildings without thermal storage is only 30 percent; about 70 percent of the electricity must be drawn from the power grid. If homeowners could cover the greater part of their electricity requirements themselves from the photovoltaic system, they would save between CHF 500 and CHF 1000 per year in energy costs and relieve the strain on the electricity grid. There is therefore a great need for technologies that increase the self-consumption of solar power by private households.

Latent heat storage systems make it possible to store surplus photovoltaic electricity as heat during the day and then release it when needed, even when the sun is not shining. The storage capsules of Concept 2, which the Lucerne University of Applied Sciences and Arts developed with its spin-off, increase the storage capacity of a heat pump buffer tank by a factor of four. This also increases the proportion of self-consumption of solar power and significantly reduces the electricity bill for the user. In addition, it makes residents more independent in terms of their energy supply since they can use their own photovoltaic electricity.

2.2.2 High-temperature heat storage

Advantages
- temporal decoupling of heat generation and consumption
- suitable for storing electrical energy
- heat storage for high-temperature applications
- constant discharge temperature
- combines latent heat storage and sensible heat storage
- sector coupling

Disadvantages
- not yet economical because heating with fossil fuels is too cheap

Maturity of the technology
Technology readiness level (TRL): 5

Milestones of SCCER
- metal alloys for latent-heat storage for 525 °C and 575 °C
- optimisation of the service life of the latent heat storage system
- construction of a laboratory test stand for sensible and/or latent high-temperature heat storage
- design and operation of a combined heat storage system for use in adiabatic compressed air storage
- simulation to optimise the operation of high-temperature heat storage systems

Further research needs
- optimisation of heat exchange and service life
- scaling and testing in real applications
- development of heat storage systems ready for mass production

Significance for the Energy Strategy 2050
High-temperature heat storage systems are crucial for increasing the efficiency of industrial processes (e.g. aluminium processing), are essential for the efficient storage of electricity through adiabatic compressed air energy storage and can improve the electricity production of conventional combined heat and power plants. High-temperature heat storage systems therefore play an important role in the energy transition. This is especially true for fields of application in which integrating sustainable energy sources is challenging, such as in fields that rely heavily on fossil fuels and use batch processes.

High-temperature heat storage systems decouple the generation of renewable (high-temperature) heat from consumption. In the industrial sector, in particular, they enable the use of renewable energy for heat generation and thereby reduce energy consumption and lower CO_2 emissions.

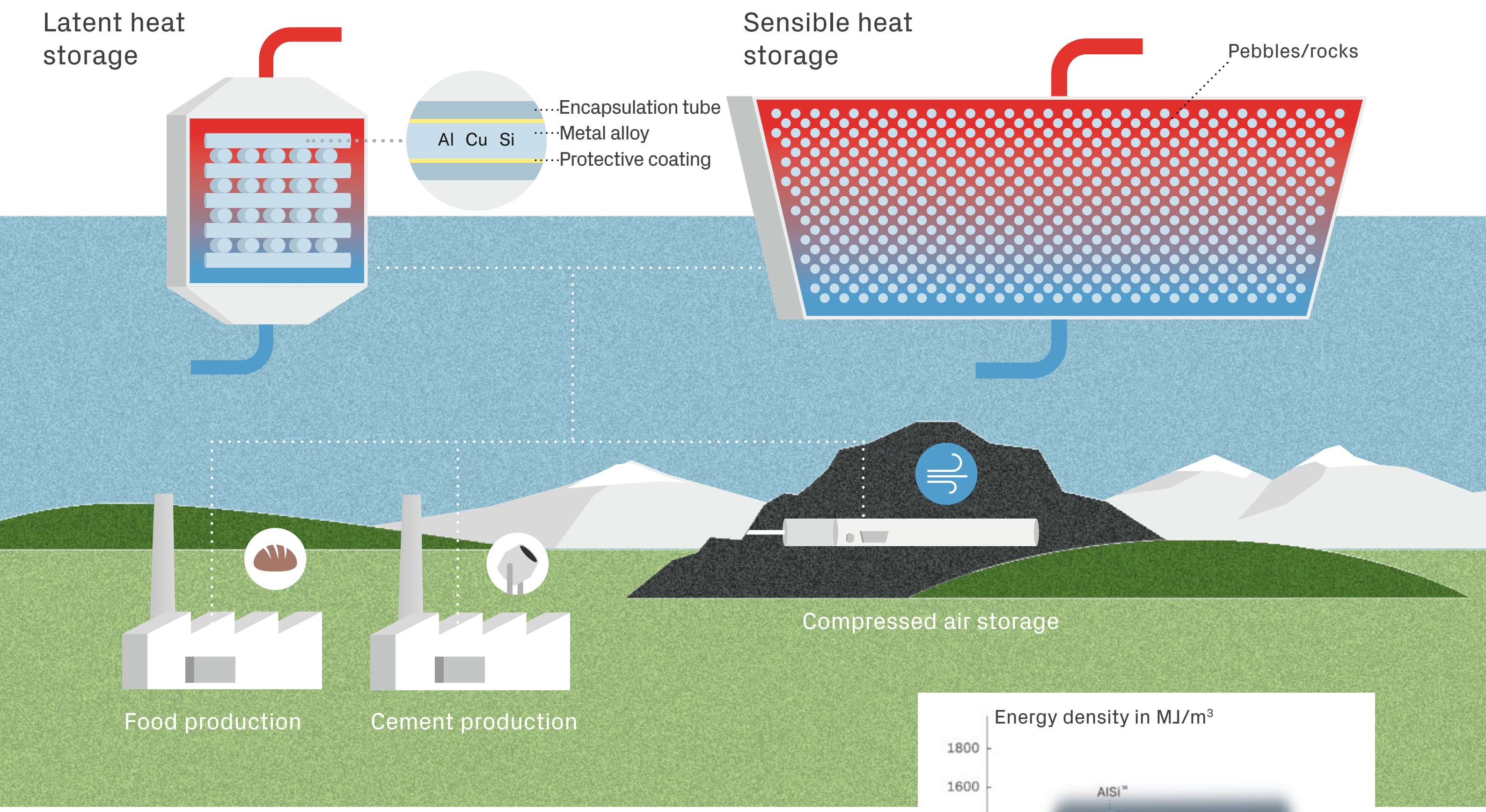
By decoupling heat generation and energy consumption, high-temperature heat storage can relieve peak loads on the power grid (electric furnaces, heat pumps) and generally dampen fluctuations in the network. In addition, high-temperature heat storage can contribute to electricity storage as parts of adiabatic compressed air energy storage systems. Overall, heat storage systems are an important element in improving the sector coupling of electricity and heat.

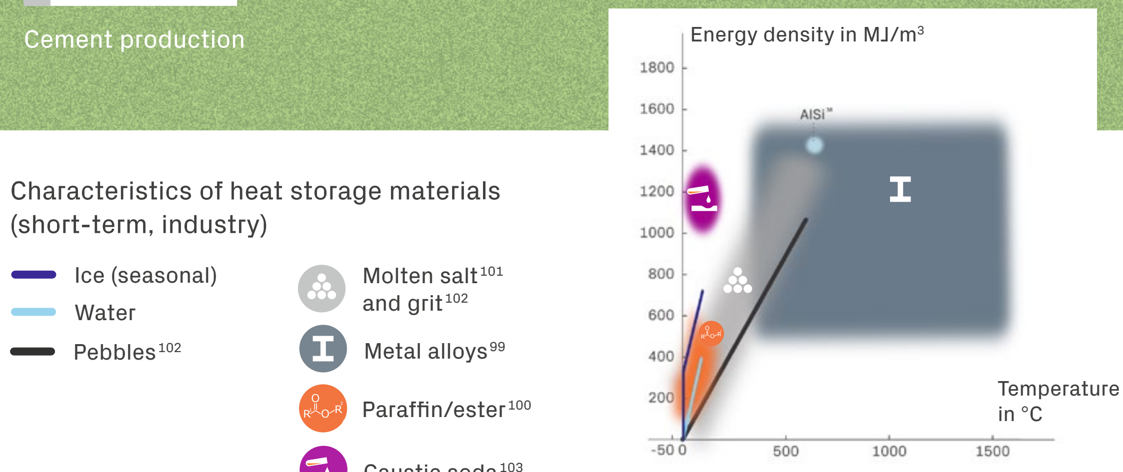
According to Swiss energy statistics for 2018, Swiss industry requires 19 terawatt-hours per year for process heating at various temperature levels. This represents 8 percent of the total Swiss energy consumption. Half of the heat is obtained from fossil methane (natural gas), 13 percent from heating oil and 6 percent from coal. The chemical industry has the greatest heat demand, consuming as much as 25 percent, followed by the cement industry (18 percent) and food production (14 percent).

Metal processing accounts for 8 percent.[30]
To achieve greater use of renewable energy for the generation of heat, heat production would have to be decoupled from heat consumption. Heat storage systems make this possible. They are able to extract heat from cooling processes in stages, to store it and to make it available later for preheating or as a heat source for heat pumps.

Appropriate heat pumps are already commercially available for temperatures up to 165 °C and outputs up to 660 kilowatts.[31] Heat storage systems can significantly improve the efficiency of a process chain and reduce CO_2 emissions. Process heat storage can also contribute to the more efficient use of electricity from renewable sources. If more electrical energy is available in the grid than is consumed, these storage units can absorb electrically generated heat and release it again when demand increases.[32] In Germany today, heat storage systems that enable process flexibility are already economically viable in industrial processes and for conventional thermal power generation.
In thermal power plants, steam production is not very dynamic.

The structure of high-temperature heat storage





Source: *Plot modified from Ding et al. [2013][99].*

The idea is that heat storage systems absorb heat at a constant rate of steam production in situations where a steam turbine has to be slowed down because of a temporary surplus of electricity in the grid. When electricity demand increases, this heat can quickly be made available for electricity production.[33]

Concentrated solar power (CSP) plants are another field of application for high-temperature heat storage, particularly in southern Europe, North Africa and the Middle East.[34]

These examples, especially for use in Germany, are interesting because appropriate heat storage systems are already being developed in Switzerland and represent a profitable niche.

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High-temperature heat storage – operating principle

Industrially used thermal energy storage, which operates at temperatures around 200 °C and higher (high-temperature), often work with steam storage boilers, known as Ruths' steam storage reservoirs, and sometimes with molten salt.[35] Both have disadvantages: Ruths' storage tanks only work up to about 200 °C at a maximum pressure of about 17 bar. Their storage density is relatively low, and the temperature drops when heat is extracted. Molten salt not only attacks the materials in the system, there is also carries a risk that the salt will cool down too much and solidify. The thermal conductivity of salt is low, which affects the charging and discharging rates. Furthermore, this process requires an additional heat exchanger.

Research within the SCCER has taken a different approach. It uses a latent heat storage system made of metal alloys encapsulated in stainless steel tubes, which achieves a high energy storage density of 300 kWh/m³ (300 kWh corresponds to 30 litres of heating oil). The design enables fast charging and discharging and allows the melting temperature to be finely adjusted. This is advantageous for processes that depend on a constant operating temperature such as in the food industry, for example in baking.

Heat storage using the technology developed by the SCCER would be charged at times when heat or electricity prices are low, for example at lunchtime, at weekends or on sunny and windy days, but would be able to provide constant heat around the clock. This would relieve the strain on electricity grids and reduce energy costs. Storage systems composed of metal alloys would also go well with molten-salt or steam storage.

High-temperature heat storage decouples the production of renewable (high-temperature) heat from consumption.

Combined high-temperature heat storage, which incorporates both latent and sensible heat storage, offers an interesting application with respect to compressed air energy storage. As described in «2.3 Adiabatic compressed air storage», the high-temperature storage unit absorbs the heat generated by the compression of the air during the charging process and releases it again when discharging.

Research at the SCCER

The University of Applied Sciences and Arts of Southern Switzerland (SUPSI), the EPFL and the ETHZ have joined forces to develop a process heat storage system for high temperatures.

The EPFL developed materials for stable encapsulated metal alloys for latent heat storage and design rules for a fast-charging system in its sub-project. The ETHZ project dealt with modelling the storage and the overall system. The researchers at SUPSI simulated the flow and investigated the dimensions, performance optimisation and construction of the heat storage system.

The researchers were interested, among other things, in whether and how latent heat storage systems age and how the alloy in the melt interacts with the encapsulation. They also investigated how the heat exchange could be improved, for example by a specific arrangement of the cylinders, by a sponge-like structure surrounding the typically used tubes or by stochastic high surface area modules. Further investigations were concerned with the dimensions of the latent and sensible heat storage systems and the way they are interconnected in order to optimise their utilisation and reduce costs. The SCCER research answered these and other questions. The prototype built for use in adiabatic compressed air storage systems has proved the feasibility of the concept.

The main focus of these investigations was on the alloy in the cylinders of the latent heat storage system. The researchers focused on alloys of aluminium, copper and silicon encapsulated in steel. This alloy has a melting temperature between 525 °C and 575 °C. The team tested the ageing process in experiments lasting several months. Based on the experiments, they derived a numerical model to predict when the latent heat storage unit would become mechanically unstable or lose energy capacity. To prevent such degradation and failure, the researchers applied a thin ceramic protective layer inside the stainless steel casing which acts as a diffusion barrier and thus extends the service life of the latent heat storage (cf. Fig. 3).[36] The research team was also able to show that a porous ceramic foam on the encapsulation significantly improves heat transport properties and allows the heat storage unit to be made more compact.[37] Detailed modelling of the charge and discharge processes also showed that convection is the key to rapid charging in latent heat storage systems based on metal alloys.[38]

The latent heat storage system for adiabatic compressed air energy storage consists of 296 stainless steel cylinders with a diameter of 3.5 cm and a length of 73 cm, which are filled with the Al-Cu-Si alloy. The research team has combined this latent heat storage with sensible heat storage, consisting of a bed of pebbles about 2 cm in size from river deposits. These are very inexpensive and can withstand temperatures of up to 550 °C. Experiments with small laboratory storage units and with large storage units in the tunnel of the compressed air storage plant have confirmed the results of the laboratory tests (cf. «2.3 Adiabatic compressed air storage», p. 44).[39] The combination of sensible and latent heat storage systems is attractive because it combines the advantages of both types. Sensible storage devices are characterised by a significantly lower energy density than latent ones but are significantly cheaper. If the two components are ideally sized, a combined storage unit can stabilise the outflow temperature at lower cost.

The combination of sensible and latent heat storage systems is attractive because it combines the advantages of both types.

The research team has developed a methodology for this purpose, which simplifies the dimensioning of the combined storage tank and the choice of materials.[40]

The steeper the temperature profiles in sensible storage units, the more compact they can be. The team therefore used simulations to investigate three methods of controlling the temperature profiles that reduced the temperature drop during the discharge process and thus helped make better use of the storage volume. If a small loss in efficiency can be accepted, the utilisation of storage based on air and molten salt as heat carriers can be improved by 39% and 73%, respectively.[41] With these simulations, the research team compared such methods systematically for the first time.

Technical perspective

The research team has built a pilot plant with 170 kWh_{th} latent heat storage capacity combined with 5 MWh_{th} sensible heat storage capacity. This plant has reached a technical maturity level between «test setup in operational environment» and «prototype in operational environment» (technology readiness level 5-6). To develop this approach to latent heat storage into a marketable product, production technology must be brought into operation and unit costs reduced. The development work needed for this would take a company between two and five years to complete.

Figure 3:
Centre: Latent thermal storage unit partially loaded with steel tubes. When completely loaded, the unit contains 296 steel tubes each filled with an aluminium-copper-silica alloy.
Left: Cross section through a tube without a diffusion barrier. After exposure to high temperatures for about 100 hours, a 250 µm thick intermetallic layer has formed.
Right: Cross section through a tube with a diffusion barrier; despite the high temperatures, no intermetallic layer has formed.

Sources: Sophia Haussener (left and right), Viola Becattini (centre).

Further research on foam-like structures to achieve better heat transferis just as important as studies of alloys to gain a wider temperature range or to withstand long and greatly varying operating times. In order to demonstrate the practicality and their advantages with regard to the performance, cost and sustainability of such efficient combined heat storage systems, it is necessary to install and test them in existing processes.

Economic perspective

One possible application for high-temperature heat storage is adiabatic compressed air storage systems. This is the purpose for which the researchers developed the combined heat storage system (cf. «2.3 Adiabatic compressed air storage», p. 44). High-temperature heat storage systems are also key elements in process optimisation in the food and metal industries.

A niche application for high-temperature heat storage is the storage of wind power in northern Germany. A large engine and machine construction company is currently developing a system that, in a similar way to adiabatic compressed air storage, uses an electrically operated heat pump to fill a sensible heat storage. By using the heat to drive a turbine and a generator, electricity can be produced again on demand.

As previously mentioned, there is already an economically interesting application for high-temperature heat storage systems in conventional thermal power plants, which cannot react well to fluctuating demand due to their inertia. Assuming constant steam production, the heat storage can help to slow down or accelerate the turbine and thus to reduce or increase electricity generation. Large companies involved in power plant construction are currently working on the development of such storage facilities. However, with increasing de-fossilisation, the importance of this field of application is diminishing. On the other hand, solar thermal power plants, which today work with molten salt as heat storage medium, could increase the demand for high-temperature storage.

Combining a latent heat storage unit of appropriate size for the relevant operating temperature and a sensible heat storage unit, in conjunction with a high-temperature heat pump, could reduce energy consumption and thus operating costs in industries with substantial heat requirements. This would, however, entail higher investment costs. Such a system – with a realistic performance factor of 3 – would reduce the heating energy requirement to one third. If heat generation could be decoupled from heat consumption, the cost savings would amount to the difference in energy price for charging the storage unit and the price for using the heat. Savings would also be possible if the storage unit preheated raw materials or pre-products.

As is the case for almost all storage technologies, there is little willingness to pass on the full costs of energy production and process management to end consumers, such as the costs of CO_2 emissions and the dismantling and disposal of plants. If these costs were taken fully into consideration, it would become worthwhile to reduce operating costs for energy generation and to accept higher capital costs for the construction of energy storage facilities.

Predicting storage potential is extremely difficult. Nonetheless, it is estimated that there is considerable global potential for compressed air storage with underground storage cavities.[42] If compressed air storage facilities were to be equipped with heat storage systems, the combined heat storage technology developed by the SCCER could represent an attractive commercial solution.

One possible application for high-temperature heat storage is adiabatic compressed air energy storage.

2.3 Adiabatic compressed air storage

Profile

Advantages
- environmentally friendly due to low consumption of resources and land
- efficient
- secure
- long-lasting

Disadvantages
- high investment costs

Maturity of the technology
Technology readiness level (TRL): 6

Milestones of SCCER
- increase in efficiency from 50% to 75%
- operation of a test facility near Biasca
- combination of several heat storage units
- investigation of suitable locations
- initial insights as to profitability in future electricity markets

Further research needs
- further investigation of profitability in future electricity markets
- behaviour when operating in the power grid
- further optimisation of heat storage

Significance for the Energy Strategy 2050
Compressed air energy storage is an important complement to pumped hydro storage when it comes to storing large amounts of electrical energy. While pumped hydro storage systems are criticised for their environmental impact, this is not the case for compressed air storage systems.
To help the technology achieve a breakthrough, a demonstration plant with around 10 megawatts should be built.

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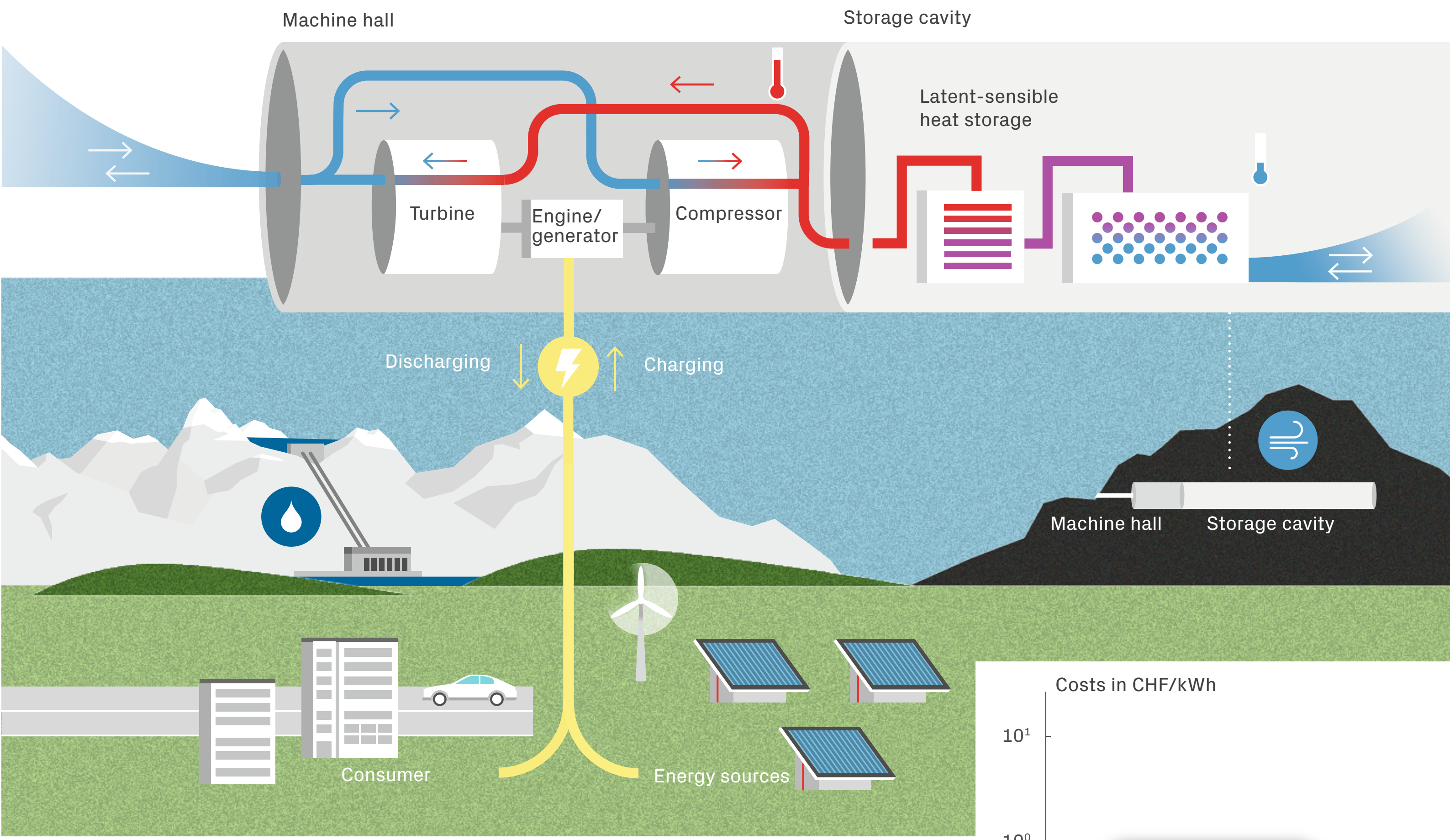
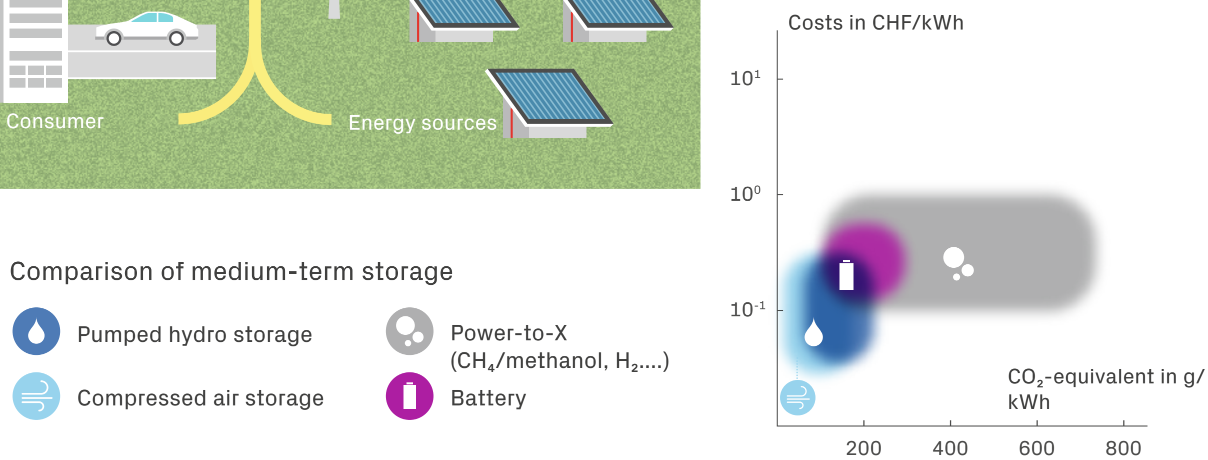
Adiabatic compressed air storage – operating principle

A compressed air storage system stores energy in the form of compressed air in an underground cavity. By expanding the compressed air in a turbine, energy can be generated again at a later point in time. This form of storage is comparable to a pumped hydro storage system in which energy is stored by pumping water to a higher elevation where it is kept in a reservoir for later use. Both technologies have significant advantages over batteries. No chemical conversions are necessary and therefore no rare raw materials or complex manufacturing and recycling processes are needed. The service life of pumped hydro and compressed air storage units is not only significantly longer than that of batteries, it is also independent of the discharge depth. Pumped hydro and compressed air storage systems are based on technologies that have been known and proven for around a century.

Nevertheless, research and pilot projects in recent decades have revealed some specific problems to be solved. Worldwide, there are many pumped hydro storage power plants in operation but only two compressed air storage facilities, one built in Huntorf, Germany, in 1978 and one in McIntosh, USA, in 1991. One of the reasons for this low number of compressed air systems is a fundamental physical disadvantage. When air is pressurised, it heats up.

The principle of adiabatic compressed air storage





If ambient air were compressed directly to 100 bar – one hundred times the ambient air pressure – it would heat up to around 1000 °C. Dealing with such hot air is a major challenge. The caverns for the compressed air storage at the plants in Huntorf and McIntosh have been excavated from salt deposits. These deposits cannot tolerate high temperatures. In both plants, air compression is a two-stage process, releasing heat into the environment after each stage. This keeps the cavern temperature low. However, this approach has its disadvantage. The heat emitted is no longer available for the expansion process during which the air cools down. This can lead to the turbines icing up. In the Huntorf and McIntosh plants, icing is prevented by mixing the air released from the caverns with natural gas and burning it. Perhaps this was considered environmentally friendly in the past. Today, such a solution is entirely out of the question. It does not make sense to generate electricity from wind and solar energy, store it and feed it back into the grid by burning natural gas.

The solution to the problem is obvious: the heat generated during air compression must be extracted from the air and stored. The cooled air can be stored in a cavern. During discharge, the cool air flowing out of the cavern is heated up with the previously stored heat and then expanded in the turbine. Because the heat released by the air compression is not wasted, the combustion of natural gas or other fossil fuels is superfluous. This creates a compressed air storage plant which does not release any greenhouse gases during operation.

The goal has been achieved of developing an advanced adiabatic compressed air energy storage system which temporarily stores the heat released during compression and which, with an efficiency of up to 75 percent, comes close to the efficiency of pumped hydro storage power plants.

Here is where research, partly under the umbrella of the SCCER, comes in. The research teams achieved the goal of developing an advanced adiabatic compressed air energy storage system (AA-CAES). The system temporarily stores the heat created by the compression and reaches an efficiency of up to 75 percent. This efficiency is close to that of pumped hydro storage power plants. For comparison, the efficiency of the plants in Huntorf and McIntosh is around 50 percent.

Research at the SCCER

Within the framework of the SCCER, researchers from the ETHZ, the University of Applied Sciences and Arts of Southern Switzerland (SUPSI), the EPFL and the Paul Scherrer Institute, together with their industrial partners ALACAES, MAN Energy Solutions Schweiz AG, BKW, Amberg Engineering AG, Swissgrid and AET, have worked intensively on adiabatic compressed air storage systems. For this purpose, the following three sub-projects collaborated closely, and the results of their research are summarised below.[43]

- Joint project «Electricity storage via adiabatic air compression» of the National Research Programme «Energy Turnaround» (NRP 70) of the Swiss National Science Foundation (January 2015 to December 2018) [44].
- Swiss Competence Center for Energy Research for Heat and Electricity Storage (SCCER HaE) of Innosuisse, Phase 1 (April 2014 to December 2016) and Phase 2 (January 2017 to December 2020).
- «Grid-to-Grid» project, Federal Office of Energy (October 2017 to June 2019)[45].

In these projects, the researchers focused on the following questions.

- Where are suitable locations for the installation of compressed air storage facilities in Switzerland?
- How can the heat released during compression be stored, and to what extent can the efficiency be increased in practice?
- How economical and environmentally friendly is a compressed air storage system?
- How do available industrial compressors and turbines behave during the charging and discharging phases?

A compressed air reservoir that is to make a significant contribution to stabilising the electricity grid must be of sufficient size. For these studies, a plant with a discharge capacity of 100 MW and a capacity of 500 MWh was assumed. The storage cavity required for this would have to be 177,000 cubic metres, which corresponds to a cube where each side is around 56 metres. The pressure in this volume would vary between 70 and 100 bar. The investment costs could be reduced if existing underground cavities could be used. However, the hope that disused Swiss army caverns could be taken over for this purpose has been dashed. Those investigated to date are all significantly too small and their expansion would be almost as expensive as a completely new construction.

The experts at SCCER HaE therefore propose to excavate underground cavities such as caverns or shafts in hard rock. The required expertise is available in Switzerland thanks to extensive experience with underground construction. The volume of 177,000 cubic metres, for example, would correspond to a tunnel with a diameter of 9.5 metres and a length of 2.5 kilometres, comparable to the new SBB tunnel through the Bözberg. Several parallel caverns or shafts would also be suitable. For example, four of the shafts excavated at Sedrun for the Gotthard base tunnel would have a similar volume. However, no detailed information is available yet on how hard rock reacts to strongly fluctuating air pressure.

For the realisation of a compressed air storage system, other sophisticated components can be used in addition to the well-proven technologies for excavating cavities. Electric motors, compressors, turbines and generators are available in many industrial performance classes and can be operated for decades with little maintenance. In principle, components available on the market are also suitable for use in a compressed air storage system. Nevertheless, there are some particular aspects that have to be considered. If the storage system is to store large quantities of energy, a maximum pressure of around 100 bar is required. This is not possible with a single compressor for the reasons described. Compression must therefore take place in two stages. After the first compression, the air enters a smaller cavity where the heat is extracted and stored in a first heat storage unit. A second compressor compresses the air to 100 bar and directs it into the large cavity of 177,000 cubic metres. There, heat is again extracted from the air and stored in a second heat storage system.[46]

The research group has investigated two system variants which differ, among other things, in the pressure after the first compression. In the first variant, the air is compressed to 33 bar and the temperature rises to 580 °C. In the second variant, the pressure is just 10 bar, so the temperature reaches only 320 °C. This means that common compressors can be used and investment costs are correspondingly lower. The lower temperatures also allow shorter start-up times, so that the compressed air reservoir can be charged and discharged more quickly. The storage unit can therefore absorb and provide energy to and from the grid more quickly and consequently attain higher prices on the electricity market.

The key component of an adiabatic compressed air storage system is the heat storage element. It absorbs the heat that arises when the air is compressed during charging and releases it again during discharging. It thus enables a system efficiency of 65 to 75 percent. The heat storage should fulfil the following requirements:

- low heat loss and high efficiency
- small volume with high energy density
- constant temperature during discharging
- low maintenance costs and long service life
- low costs

The research group investigated a combination of two heat storage systems and successfully tested this in the pilot plant near Biasca, Ticino.[47] The plant was constructed in a former supply tunnel that was built for the construction of the Gotthard Base Tunnel (cf. Fig. 4). With the help of two concrete closures, a cavity was sealed off in the tunnel which could hold compressed air at a pressure up to 33 bar and in which two heat storage units were housed. The sensible heat storage unit consists of a concrete tank filled with around 76 cubic metres of pebbles.[48] The adjacent latent heat unit has a volume of around 3.3 cubic metres and contains steel pipes filled with an alloy of aluminium, copper and silicon. This alloy melts at a temperature of around 525 °C and absorbs heat that is released again on solidification.[49]

During charging, the compressed air flows first through the latent heat unit, then through the sensible unit and finally into the cavity. When discharging the compressed air reservoir, the process is exactly the opposite: from the cavity, the compressed air first flows through the sensible heat unit, then through the latent heat unit. Because the temperature remains constant as the molten metal solidifies in the latent heat unit, it stabilises the temperature of the outflowing air. In this way, the turbines, which in turn produce electricity, can operate more efficiently.

Figure 4: *The heat storage in the pilot plant at Biasca.*
Left: The sensible storage unit filled with pebbles (3.1 m high, 9.9 m long and 2.4 m wide).
Right: The latent storage unit (about 1.5 m in height, length and width).
Source: Viola Becattini

By means of simulations, the research group also examined a variant of the sensible heat storage in which the storage unit is divided into several smaller containers connected by pipes and valves. Such so-called multi-tank storage units can be advantageous for compressed air storage for three reasons. Firstly, it is easier to accommodate several smaller heat storage units in the storage cavity instead of one large unit if the cavity diameter has to be limited for cost reasons. Secondly, the tubes and valves allow air to be circulated from one storage unit to the next during charging and discharging in such a way that the thermal energy per volume is greater than in a single large unit. This reduces the volume and consequently the costs of heat storage.

Finally, with a multi-tank storage system, the air can be guided through the tanks during discharging with the aid of the pipes and valves in such a way that the output of the turbines remains constant and the compressed air storage system feeds constant electrical output into the power grid. This is important because fluctuating feed-in power can impair the stability of the power grid.

Compared to pumped hydro storage, compressed air storage has the great advantage that the landscape above ground does not need to be changed.

Two aspects play a role in the environmental compatibility of compressed air storage systems. These are, on the one hand, the environmental impact and the materials used during construction and, on the other, the CO_2 emissions associated with operational inefficiencies. Compared to pumped hydro storage, compressed air storage has the great advantage that the landscape above ground does not have to be altered. In addition, the use of materials is lower because no dam is required. The excavation of the storage cavity and the disposal of the excavated rock are relatively insignificant. The metals used for the compressor, turbine, generator and latent heat storage unit can be recycled after the plant has been dismantled.

In terms of CO_2 emissions, compressed air storage and pumped hydro storage are comparable. The decisive factor, however, is the efficiency achieved by compressed air storage. Simulations and tests show that an efficiency of up to 75 per cent is realistic – that is, a quarter of the electrical energy used for compression is lost. By comparison, pumped hydro storage systems achieve efficiency values of up to 85 percent, Li-ion batteries 90 percent. With regard to CO_2 emissions, efficiency is important if the electricity used for charging is not CO_2-free. In the Swiss electricity mix today, around 100 grams of CO_2 are produced per kilowatt-hour.[50] Thus, if one kilowatt-hour is stored in a compressed air storage unit with 75 percent efficiency, the emission value increases to 100/0.75, that is, 133 grams due to the energy loss, even though the storage unit itself does not emit any CO_2 during operation.

From the point of view of climate protection, compressed air storage systems therefore make most sense if they primarily store fluctuating electricity from renewable energy sources such as wind and solar.

Taking all these matters into account, adiabatic compressed-air storage systems perform just as well as pumped hydro storage systems in terms of ecological balance. Because compressed air systems work with ambient air and not with water, they are not affected by regulations concerning residual water or possible alterations to the water cycle due to climate change. If the storage cavity leaks, air simply escapes. And in contrast to pumped hydro storage, compressed air storage does not require any intervention in the landscape because the storage facilities are located underground. This should contribute considerably to gaining the general population's acceptance of this technology.

Technical perspective

The technical components for the construction of adiabatic compressed air storage systems are fully developed and most have been in use for decades. The methods for building or enlarging existing storage cavities are also mature. In Switzerland in particular, many companies have decades of experience in the construction of tunnels, caverns and shafts. The concept for combined heat storage developed as part of the SCCER has proven itself. There are therefore no fundamental obstacles to the realisation of a compressed air storage system. The only issue still under investigation is the impermeability of cavities at high pressures.

Economic and regulatory perspective

All storage systems for electrical energy have to struggle with economic efficiency – from pumped hydro storage to batteries and hydrogen. In addition to the cost of generating electricity, the cost of storing it can make a technology unprofitable. If turbomachines had an ideal partial-load performance, a compressed air storage system with an output of 100 MW and a capacity of 500 MWh would have been profitable in the secondary control market as early as 2018.

From the point of view of climate protection, compressed air storage systems make most sense if they primarily store fluctuating electricity from renewable energy sources such as wind and solar.

This is due to the comparatively low capital costs estimated at around CHF 110 million for the compressed air system in question, about half of which is for the construction work and one third for the turbomachinery. The heat storage, which is crucial for the efficiency of the system, accounts for six percent. If the capital costs are calculated over the estimated 60-year service life of a compressed air storage system, they amount to only half that of a comparable battery storage system. Batteries are estimated to have a service life of only 10 to 15 years. They would therefore have to be replaced several times over a period of 60 years, which increases the capital costs accordingly. The researchers estimate the annual operating costs of compressed air storage systems at about two and a half percent of the capital costs, that is, at about CHF 2.2 million.

The bottom line is that, under ideal conditions, a compressed air storage system would be profitable on the Swiss secondary control market. On this market, energy supply companies offer electrical power to restore the balance between electricity production and consumption after a malfunction, such as a power plant outage. It would promote economic efficiency if compressed air storage systems were not considered to be energy consumers and consequently would not have to pay grid fees. This obstacle in the Swiss energy market is inexplicable since compressed air storage systems contribute to the stabilisation of the grid and should be rewarded accordingly. Pumped hydro storage is currently the only storage technology that is exempt from grid fees. This discrimination against individual storage technologies is a controversial topic in Switzerland. It is not yet clear which view will prevail.[51]

The bottom line is that, under ideal conditions, a compressed air storage system would be profitable on the Swiss secondary control market.

If compressed air storage were treated in the same way as pumped hydro storage, the investment costs should not be an obstacle for energy suppliers since pumped hydro storage systems cost at least as much. Although further studies are necessary, it will largely depend on the regulatory conditions designed by political and administrative authorities whether compressed air storage systems can make a contribution to the Energy Strategy 2050. It is also unclear which laws and regulations could apply to the underground storage of air at high pressure and the construction of the relevant underground plants.[52]

3 Medium- to long-term storage

3.1.1 Seasonal storage of sensible heat

Profile

Advantages

- novel concepts suitable for new buildings and retrofitting
- straightforward control and combination with solar collectors
- storage temperatures suitable for end-use applications
- relief for the power grid when combined with heat pumps
- increased energy storage density through combination with latent heat storage
- long service life of more than 50 years
- safe and reliable

Disadvantages

- large volume required, reduction is necessary
- without adequate thermal insulation, heat losses of up to 50 percent
- higher investment costs compared to gas-fired systems or those without storage
- economic feasibility only for large storage volumes

Maturity of the technology

Technology readiness level (TRL):

- 6 to 7 for storage in unused cellars and other artificial cavities such as unused tunnels or bunkers
- 9 for storage inside houses or in the ground outside buildings

Milestones of SCCER

- new concepts for sensible heat storage for retrofitting buildings
- development and evaluation of new thermal insulation materials
- operation of a pilot-scale demonstrator with a water-filled cellar

Further research needs

- long-term experience with the demonstrator
- improvement of economic efficiency

Significance for the Energy Strategy 2050

Discussions about the contribution renewable energy can make to the energy transition and dealing with climate change usually focus on electricity. In Switzerland, however, around half of the final energy is used to generate heat; in private households, this figure is as high as 80 percent. Space heating alone accounts for around a third of the total annual energy requirement. Satisfying the heat demand in winter with renewable energy collected in summer (only possible in combination with seasonal storage) would save considerable amounts of CO_2 and fossil fuel.[53]

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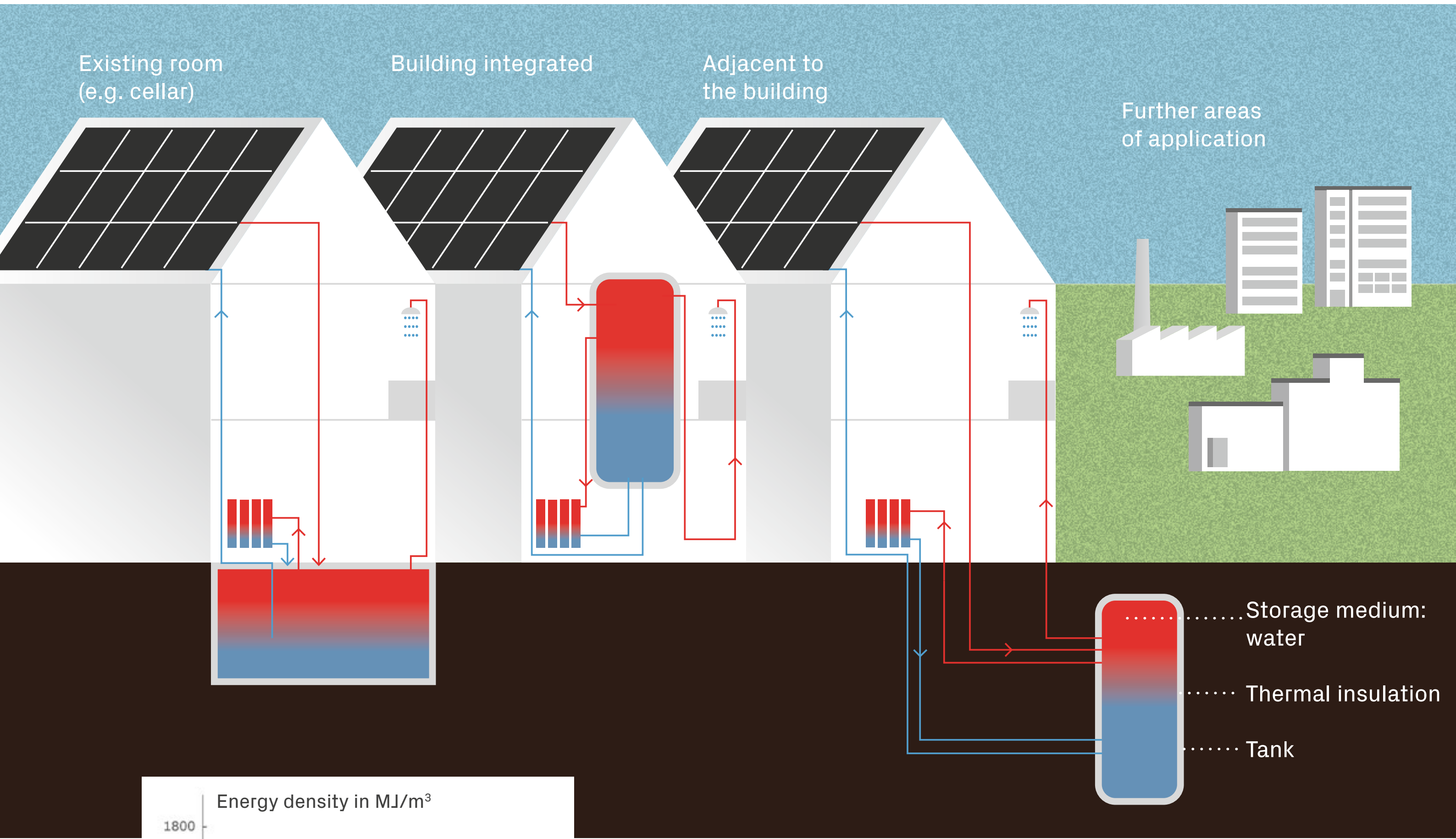
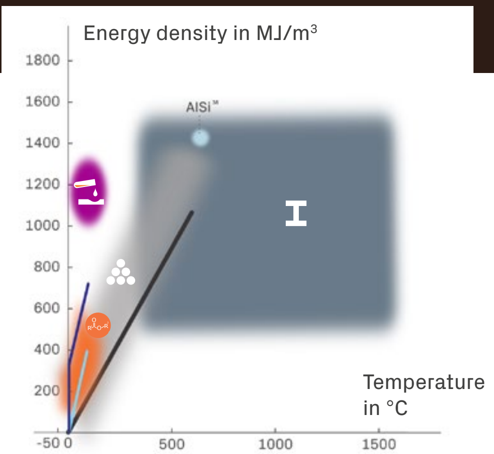
The integration of seasonal storage of sensible heat





Source: *Plot modified from Ding et al. [2013][99].*

Characteristics of heat storage materials (seasonal)

- Ice (seasonal)
- Water
- Pebbles[102]
- Molten salt[101] and grit[102]
- Metal alloys[99]
- Paraffin/ester[100]
- Caustic soda[103]

Sensible heat storage – operating principle

Today, sensible heat storage systems are in widespread use, often as borehole thermal energy storage or as hot-water storage units inside buildings. Compact hot water storage systems investigated by SCCER partners offer a valuable alternative for buildings where space is at a premium (e.g. residential buildings). When coupled with solar collectors or PV and heat pumps, they offer the potential to save large amounts of fossil fuel for heating. Like electricity, heat from renewable sources is often not available when it is needed. Moreover, while electricity consumption is nearly constant all year round, households require most of the heat in winter when solar energy sources are at a minimum. Storage systems are designed to bridge the seasonal gap by shifting the energy surplus of summer to the deficit experienced in winter.

As is the case for electricity generation, heat from renewable sources is often not available when it is needed.

Seasonal heat storage systems have been under development for decades, and some are already in use. SCCER partners have researched three available concepts:

- ***Latent heat storage systems*** use the phase change of a medium, for example from ice to water, to store heat. When the storage medium solidifies, it releases heat for heating. The materials used in such storage units are known as phase change materials.
- ***Thermochemical storage.*** Heat is released during chemical reactions or the absorption of water into a solid or liquid substance; the storage tank is charged in summer with solar heat via desorption.
- ***Sensible heat storage systems*** store heat in summer in a medium such as water, concrete or in the ground. They release the heat again via a heat exchanger during the heating period.

The sensible heat storage concept is the simplest and most widely used today. The principle is called «sensible» because the supply/removal of heat raises/lowers the temperature in the storage; the change can be felt directly as it can with a hot cup of tea.

In sensible seasonal storage, heat produced by solar collectors or heat pumps is collected and transferred to the storage medium to heat it in summer. In winter, heat is extracted from the storage medium again for the underfloor heating or to produce hot water for the bathtub.

One disadvantage of sensible storage systems is that the amount of energy stored is directly related to its temperature. This has a two-fold effect. Firstly, to satisfy all temperature requirements it must be ensured that the storage tank temperature does not fall below the minimum required (e.g. for heating tap water). This requires a good stratification of temperatures in the storage unit, which is achieved through optimisation of the control strategies applied to charge and discharge the storage. Secondly, sensible storage systems constantly lose heat to the surroundings and therefore require good thermal insulation to minimise heat loss. For this reason, seasonal storage systems built today are generally very large and can supply entire urban districts. They can also provide a buffer for district heating networks to some extent. In Switzerland, commercial solutions already exist for the storage of sensible heat, which are suitable for installation in low-energy houses.

For the market opportunities of sensible storage to increase for individual residential buildings, the energy losses and in particular the costs of small storage units must decrease. The research of the SCCER partners aims to optimise sensible storage systems in such a way that they can be operated economically in a compact design even in single residential buildings.

Research at the SCCER

In their research on sensible heat storage systems, SCCER partners concentrated on solutions that can be installed inside or near buildings. Ideally it would also be possible to retrofit them in existing buildings. The simplest and least expensive solution is a hot water tank. Such storage can be incorporated in three different ways: firstly, in an unused room in the basement; secondly, integrated over several floors inside new buildings; or thirdly, buried underground outside a building. The first and third configurations have the advantage that they can often be installed relatively easily in existing buildings. In all three cases, the heat loss must be as low as possible to ensure economic viability. Storage tanks integrated into buildings should also be as compact as possible so that they do not take up valuable living space.

For the first configuration, the Lucerne University of Applied Sciences and Arts (HSLU) and a business partner analysed existing thermal insulation concepts.[54] They also developed a new concept as part of an Innosuisse project in which available spaces in underground enclosures, such as unused cellars or redundant oil tank rooms, are thoroughly sealed and thermally insulated so they can be filled with water. The novel thermal insulation solution consists of a combination of extruded polystyrene and rigid polyurethane foam, materials normally used to insulate buildings. Around the outside of these materials is a cover, similar to a pond liner, which prevents water from penetrating the insulation and thereby reducing its insulating effect. Together with HSLU, the company involved in this development is already operating a pilot-scale demonstrator that consists of a 100 m³ tank in a formerly unused cellar.

> For economical operation, energy loss must be as low as possible.

The developed solution is designed for a maximum water column of six metres, a temperature up to 65 degrees Celsius and a service life of 50 years. The storage tank is charged with heat provided by a heat pump and solar collectors. In a follow-up project, the partners are now investigating how the temperature and pressure in the tank can be increased to achieve a higher energy density and improved economic performance.

The research group at the HSLU also investigated the optimisation potential of the other two options for the incorporation of water-based sensible heat storage in buildings. Simulation results have shown that the tank volume of the second configuration – integration inside new buildings – can be reduced by up to 30 percent solely through optimisation of the control strategies applied to charge and discharge the storage system. The study also revealed that in such a configuration, it is most economical to minimise the storage volume while maximising the surface area of the solar installation. This minimises the loss of valuable living space - an important consideration in expensive metropolitan areas. A private company has developed a concept with around 100 cubic metres of storage that can be integrated into the stairwells of new buildings. The advantage of this design is that the heat loss is tolerable in winter as it contributes to heating the building from the inside.

The third configuration (vacuum-insulated tank buried underground next to the building) represents a cost-effective option particularly for existing buildings, despite the high excavation costs and increased heat loss.

For efficient operation, the temperature stratification in the tank should be disturbed as little as possible: hot at the top for tap water, cooler at the bottom for underfloor heating.

Technical perspective

While storage tanks for installation indoors and in the ground outside the building are already commercially available, this is not yet the case for storage tanks in unused basements. The researchers are currently testing the long-term stability of the new insulation in the demonstration plant at their business partner's premises.

In a follow-up project, the research partners want to develop cost-effective insulation that can withstand temperatures up to 90 °C and pressures up to 1.2 bar. This would significantly increase the economic performance of the storage system both in residential buildings and industrial facilities.

For storage tanks that are installed inside buildings at the cost of valuable living space, hybrid systems that combine a water tank with phase change materials could provide a suitable alternative. This concept increases energy density and thereby reduces the required storage volume.

One challenge inherent in all these concepts is the turbulence that occurs when water flows into and out of the tank. For efficient operation, the temperature stratification in the tank should be disturbed as little as possible: hot at the top for tap water, cooler at the bottom for underfloor heating. The HSLU team has optimised this process so that the size of the tank can be reduced by up to 30 percent.

There are also alternative concepts for underground storage. In an Innosuisse project, the HSLU and a partner are investigating whether the ground itself could be used for storage. Although vertical boreholes are considered state-of-the-art, there are locations where this method is not feasible. This is the case, for example, if the land is already developed or if groundwater levels do not permit drilling deep into the earth. Instead of this conventional method, the project partners are using horizontal drilling technology to lay pipes parallel to, and under, the surface without having to disturb the earth above them.

Economic perspective

Studies undertaken by the SCCER partners show that seasonal sensible heat storage systems can be economical even with the use of more expensive insulation materials such as vacuum insulation panels or rigid polyurethane foams. These ensure minimal heat loss over several months and allow more compact storage units to be built, thus saving living space. The cost of the storage unit is determined primarily by the tank material and the insulation, followed by the heat exchange system.

The focus of this research project was on residential buildings where heat was generated entirely from solar energy. However, from an economic perspective, the optimum position is expected to be reached at a lower level of self-sufficiency in energy supply. This needs to be examined in more detail. Nonetheless, one thing is certain: the economic viability of big storage units increases when installed in large residential areas, as was the case with earlier concepts for sensible heat storage systems. A realistic evaluation of the economic efficiency of sensible heat storage should also take into account the benefits of sector coupling. Instead of «dumping» solar power in summer when electricity prices are low, it can be used to drive heat pumps. Electrical energy is thus converted into thermal energy that can be stored at a much lower cost than, for example, electrical energy in batteries. In this way, heat storage systems help to close a potential electricity gap in winter.

3.1.2 Ice storage for heating and cooling

Profile

Advantages

- energy storage in liquid water through controlled freezing
- low heat loss during storage
- high storage density up to 125 kilowatt-hours per cubic metre
- reverse heat loss: uninsulated storage tank can absorb heat from the environment
- CO_2 savings
- also suitable for cooling
- users already have experience with commercial plants
- long service life of up to 50 years
- simple construction and disposal
- very safe: storage medium can be untreated drinking water, for example
- can also be used in combination with a heat pump and low-temperature heat sources (solar thermal, waste heat, etc.) if geothermal probes or outdoor air heat pumps are not usable

Disadvantages

- economic efficiency often difficult to achieve at present
- high heat storage costs
- each individual unit must be planned separately
- promising new concepts are still in the research phase

Maturity of the technology

Technology readiness level (TRL):

- 9 for commercially available de-icing plants
- 4 for ice slurry technology with water sub-cooling in the heat pump evaporator

Milestones of SCCER

- low-cost ice storage heat exchangers with de-icing function designed and brought to market
- comprehensive analysis of the possible uses of solar-ice heating systems in residential buildings

Further research needs

- development and optimisation of ice slurry technology with water sub-cooling
- research and development of heat exchangers which can be de-iced with CO_2 as a refrigerant
- improvement of the economic efficiency of compact storage
- system integration and demonstration of ice storage for heating and cooling

Significance for the Energy Strategy 2050

Seasonal heat storage systems have a key role to play in the energy transition and in climate protection. In confined spaces such as cities and housing estates, the ground or outside air might not be usable as a heat source for heat pumps. Here, the ice storage systems can act as the heat source combined with solar heat and heat pumps. Ice storage systems can be used both for heating (as a heat source for heat pumps) and for cooling (as a heat sink for free cooling). They can thus make an important contribution if there is an increased need for cooling and air-conditioning as a result of climate change.

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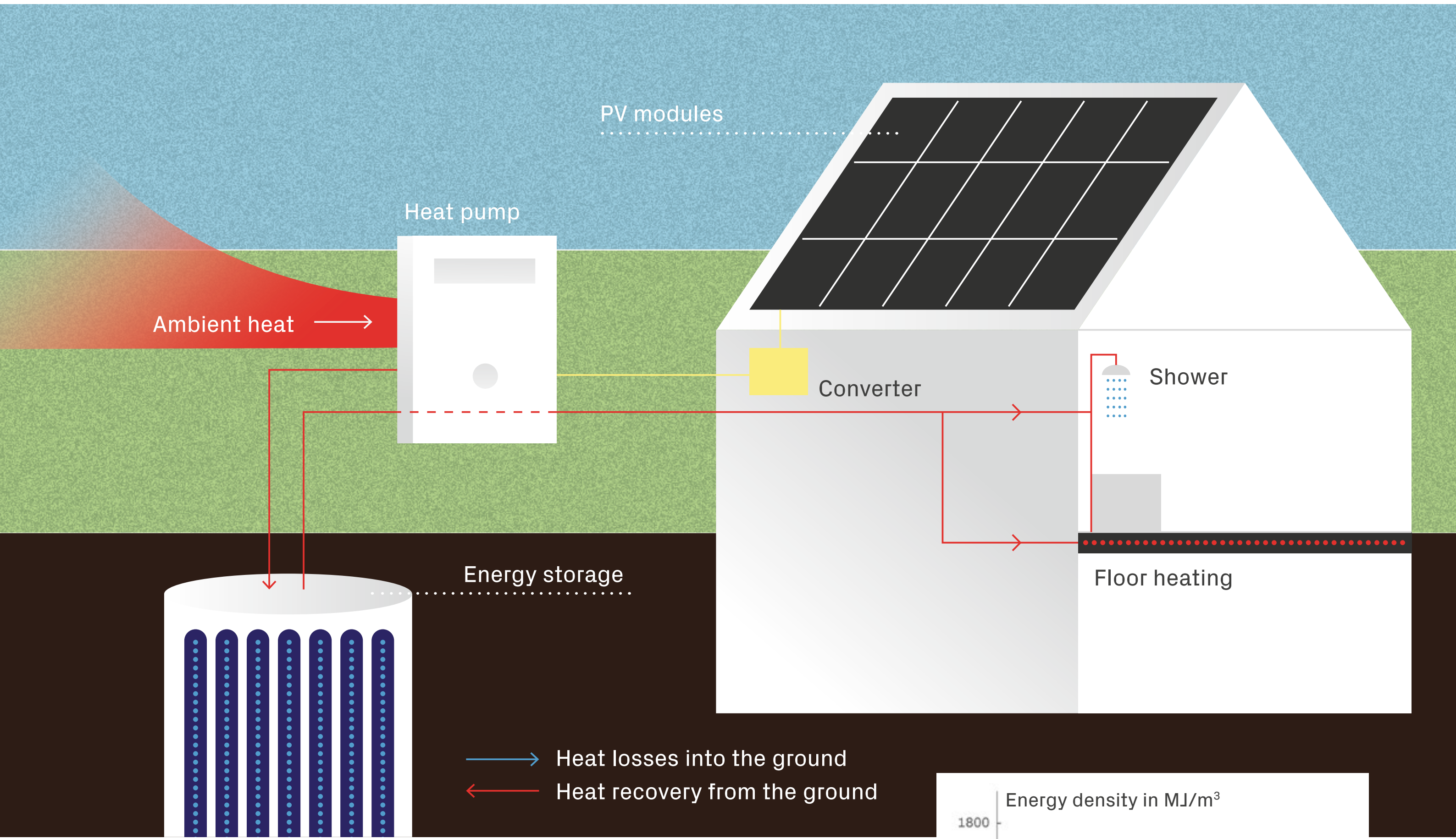
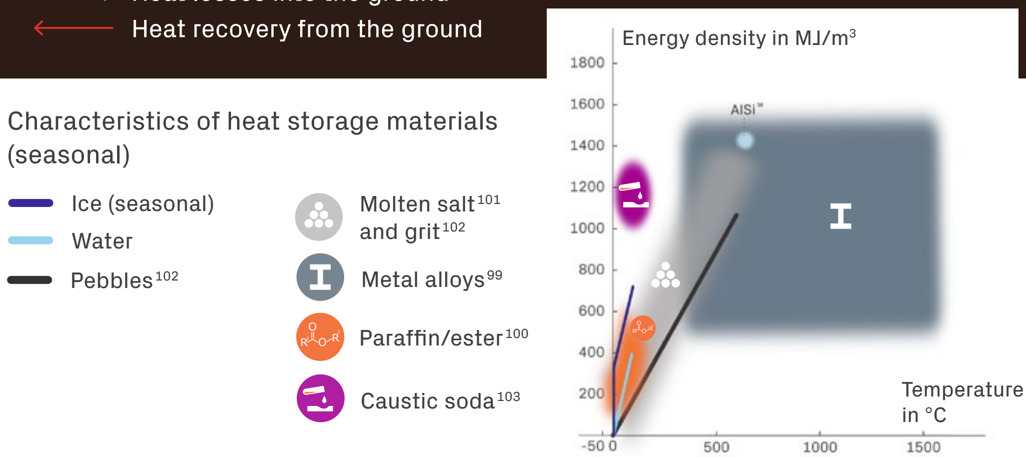
The integration of ice storage for heating and cooling





Source: Plot modified from Ding et al. [2013][99].

Ice storage – operating principle

At first, laypeople shake their heads: how can ice be used to store heat? In fact, ice storage is a serious option for storing heat for buildings or residential areas over a long period of time.

This works as follows. A heat pump, as is installed in many buildings today, extracts heat from the surroundings and uses it to heat up the rooms. In most cases, the heat comes from the ambient air or the ground. If the building has a large water tank, in effect a sensible heat storage tank (cf. «3.1.1 Seasonal storage of sensible heat», p. 52), it can be charged with solar heat in summer. In winter, the heat pump can draw heat from this tank until the water reaches the freezing point of 0 °C and solidifies. This phase change turns the sensible heat storage into latent heat storage, that is ice storage, which exploits the phase transition from liquid to solid.

Figure 5: *Glass container filled with water and floating ice crystals. Supercooled water flows into the container through a hose (top left) and turns into ice slurry as soon as it hits the floating ice crystals.*
Source: Daniel Philippen

The heat pump continues to work until the water is almost completely frozen. The storage tank temperature remains constant at 0 °C.

The solidification to ice releases large amounts of energy: 335 kilojoules or 93 watt-hours per kilogram of water. This corresponds to the amount of energy the heat pump can extract when it cools the same amount of water from 80 °C to 0 °C. Or to be even more specific, an ice storage unit with a volume of ten cubic metres supplies the same amount of energy as 110 litres of heating oil.

In summer, the ice melts due to the heat supply from solar collectors; in some concepts, also using heat from the ground or waste heat from the building. As a result, the same amount of energy flows back into the tank, where it is stored until the next winter. The seasonal performance factor, familiar to heat pump owners, has an excellent value of five for this process. In other words, the heat pump uses one kilowatt-hour of electricity to draw around five kilowatt-hours of heat from the storage tank.

Ice storage offers a good way to store heat compactly for months. Nevertheless, only about 40 such storage facilities are currently in operation in Switzerland. Researchers under the umbrella of the SCCER have further developed the technology in such a way that ice storage systems could become interesting for a larger group of customers.

Research at the SCCER

When the water cools down to the freezing point, a layer of ice forms on the heat exchanger. At first, it is thin and then gradually thickens. The ice acts as a growing insulating layer, and the heat pump uses more and more electricity for less and less heat, compromising efficiency. Researchers at the Eastern Switzerland University of Applied Sciences (OST) have found a way to deal with this. If the ice layer becomes too thick, their demonstration plant briefly pumps hot water from solar collectors through the heat exchanger. This «de-icing» loosens the ice layer which, due to its lower specific weight, floats to the surface of the water. This process is repeated until the tank above the heat exchanger is filled with sheets of ice and all the latent heat is removed. The following summer, during the recharging process, the ice melts, closing the cycle. Thus, the storage tank gets ready for the coming winter.

The concept of de-icing has proven successful in an ice storage facility which supplies a residential and office building in Rapperswil-Jona, Canton St. Gallen.[55] The container is made of concrete and has a capacity of 210 cubic metres. Solar collectors with a surface area of 120 square metres supply it with heat. The concept has also been implemented in a privately-owned detached house near St. Gallen.

Ice storage offers a good way to store heat compactly for months.

Technical perspective

The de-icing concept has proven its feasibility in tests. It also ensures a high level of economic efficiency for ice storage systems, including those serving residential buildings. This will not, however, be enough to encourage widespread adoption in competition with other storage concepts. The OST is therefore pursuing a new approach involving ice slurry technology.[56] With this concept, the water freezes, but, since the ice crystals are small, it remains in a free-flowing state and can be pumped back and forth. Because it forms directly after the heat pump, it also makes the large heat exchanger in the ice storage tank superfluous (cf. Fig. 5).

The heat pump's evaporator changes the water to a supercooled state; it does not freeze, even though it is cooled to a few degrees below freezing. When the water leaves the heat pump evaporator, then the sub-cooling stops and a «fluid» ice-water mixture is formed - the ice slurry.

A further idea for optimisation is to use carbon dioxide (CO_2) as a refrigerant in the heat exchanger instead of a water-glycol mixture. However, achieving higher efficiency comes at the cost of a more complex design, especially because the CO_2 has to function under a high pressure of 50 bar. The aim is to find an optimum between energy efficiency and design effort in the next few years.

In addition, OST researchers intend to devote more attention to the subject of cooling.[57] Ice storage systems have been used in industry for decades to cut peak demands for electricity in refrigeration plants. However, such systems are currently too uneconomical to be used for the air-conditioning of residential buildings. Further research and tests should show how ice storage can be integrated into combined heating and cooling systems in buildings in an economically efficient way.

Economic perspective

Ice storage systems as heat sources in combination with heat pumps and solar heat (solar-ice heating) are currently not economical under normal circumstances. They face competition from today's widespread, mostly fossil-fuel fired heating technologies. The investment costs of the ice storage unit are essentially determined by the construction of the container and the heat exchanger. However, ice storage systems are already economically interesting in locations where geothermal probes or ambient air units are not permitted or desired as the source of heat for heat pumps. Since ice storage units are operated at temperatures around the freezing point, they are clearly suitable for cooling buildings or cold storages.

> Only if fossil fuels are priced realistically can alternative storage systems achieve widespread usage and thus reduce electricity demand in winter.

Ice storage systems will only achieve a breakthrough if it is possible to increase their efficiency and reduce costs, for example by eliminating the heat exchanger through the successful development of ice slurry technology. There is reason to hope that this will be achieved in the next few years thanks to the work at the OST. However, the same caveats apply to ice storage as to other concepts for heat storage. Only if fossil fuels are priced realistically, that is, CO_2 emissions become more expensive, and if energy costs vary according to the season, can alternative systems such as ice storage achieve widespread usage and thus reduce electricity demand in winter.

3.1.3 Seasonal heat storage with liquid sorbents

Profile

Advantages

- storage for months without loss of heat
- high storage density and therefore compact storage units
- liquid media can be easily pumped into tanks and stored
- modular and easily scalable – storage capacity can be expanded as required by adding additional tanks
- improved integration of renewable energy sources
- increase in self-consumption and relief for the electricity grid through seasonal load shifting

Disadvantages

- comparatively high material costs
- higher complexity compared to water storage
- further optimisation necessary
- open research questions
- seasonal heat storage in the absence of a regulatory framework is not yet economically viable

Maturity of the technology

Technology readiness level (TRL): 6–7

Milestones of SCCER

- new process engineering design for liquid sorption storage to improve storage density and charge/discharge performance
- detailed understanding of the de-/absorption processes

Further research needs

- further optimisation of process management, especially during discharging
- evaluation of options for building integration
- demonstration under real operating conditions
- improvement of cost-effectiveness
- industry involvement for joint development and optimisation

Significance for the Energy Strategy 2050

Seasonal heat storage systems will play a key role in the energy transition and the mitigation of climate change. Only in this way is it possible to save large amounts of fossil fuels for heating and replace them with renewable energy. Which technology will prevail is an open question. It is likely that sorption storage systems in smaller residential units will gain a relevant market share.

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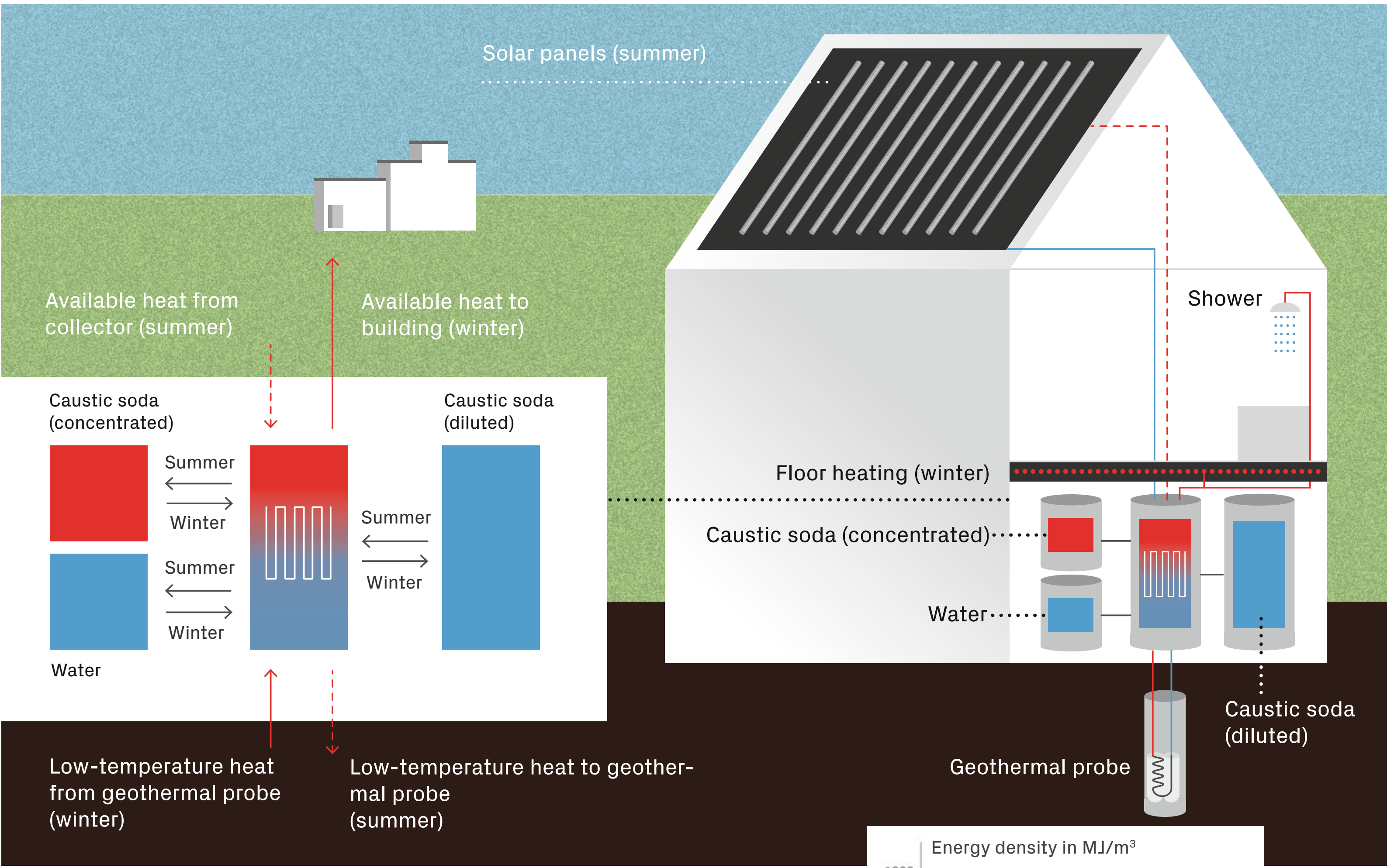
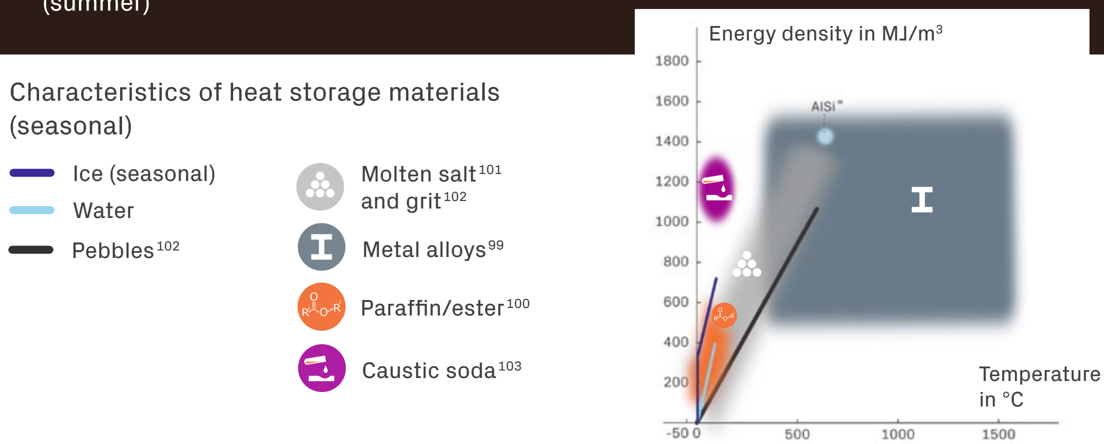
The principle of seasonal heat storage with liquid sorbents





Source: *Plot modified from Ding et al. (2013)*[99].

Heat storage with liquid sorbents – operating principle

Besides sensible and latent heat storage, there are also thermochemical heat storage systems. In contrast to the first two, thermochemical systems do not store heat directly but in a chemical compound.

The basis is a reversible reaction, which in one direction absorbs heat and in the other releases heat. Since only the chemical potential is stored and not the heat itself, thermochemical storage systems operate almost loss-free.

With sensible and latent heat storage, there is a continuous loss of heat (cf. 3.1.1, p. 52) and, as a result, the storage temperature and charge level fall. In the case of latent heat storage, this can lead to the tank discharging completely if the storage temperature falls below the melting point of the storage material and it solidifies.

Because of these continuous losses, sensible and latent storage systems are only practicable for long-term seasonal storage when the heat supply is intended for large districts. In such cases, big storage tanks with a small surface to volume ratio can be installed. In addition, the energy is usually stored at low temperatures, so heat losses are low. To ensure sufficient heat is available in this situation, an additional heat pump is required.

> Theoretically, a sorption storage unit can retain its heat without loss for years. The storage density is also higher than that of sensible heat water storage units.

In contrast, sorption storage systems, a special class of thermochemical storage, which has attracted increasing interest in recent years, are suitable for use in separate residential buildings or single-family homes. Sorption storage systems consist of a «sorbent», a granular or porous material such as zeolite, silica gel or metal hydride (or even salt solutions) that contain, or can absorb, a lot of water. In the charging process, water, the «sorbate», is extracted from the solution as vapour using solar heat. In winter, water vapour is fed back into the sorption medium and reacts with the sorption medium (the so-called sorption process), releasing heat. This concept of «chemical heat pumps» has a great advantage. The charged storage tank is not warm and therefore does not need to be insulated. Theoretically, a sorption storage unit can retain its heat without loss for years. The storage density is also higher than that of sensible water storage units. This makes it well suited for bridging the gap between seasonal heat production and consumption. The sorption technology is not yet established on the market as the chemical engineering processes in particular have not been sufficiently optimised.

Research at the SCCER

The aim of research in recent years has been to develop a compact sorption storage unit based on caustic soda and to test it in a demonstration plant with a discharge capacity of 5 kilowatts and suitable for a detached house. Previous experiments at the SCCER had shown that the operation of a sorption storage unit still raises a number of questions that stand in the way of commercialisation. In recent years, Empa and the Eastern Switzerland University of Applied Sciences (OST) have therefore further developed or redesigned various concepts for existing storage facilities. Two approaches have been examined more closely.

- The researchers have optimised an existing storage system with a discharge capacity of 1 kilowatt in such a way that the exchange of water vapour with the caustic solution takes place more effectively and thus increases the power density.
- The team has designed and tested a new storage system with a particularly high storage density. It was possible to increase the initially low discharge capacity gradually. A demonstration unit with a discharge capacity of 5 kilowatts will be brought into operation in 2021.

The two teams at Empa and OST decided to use a liquid sorbent (sodium hydroxide solution) and not the conventional solid materials, such as zeolite or silica gel, which had previously been used. The major advantage of this approach is that the sorbent storage tank does not have to be permanently installed in one place. Since only liquids are involved in the process, they can be pumped into tanks located in convenient places where they take up as little space as possible. Power output and the quantity of energy used can also be scaled independently of each other.

Moreover, sodium hydroxide is a readily available and therefore inexpensive chemical.[58]

In the first project with the 1-kilowatt demonstration plant, the research team at OST used a horizontal tube bundle falling film heat and mass exchanger and an aqueous solution of sodium hydroxide (NaOH) as sorbent. Other liquid compounds can also be tested in the demonstration plant.

One challenge is to ensure the thorough mixing of water and lye since this determines the speed of charging and discharging. The researchers set up a test where, at a lower process pressure, the lye runs down the outside of tubes, where it mixes with and absorbs the water vapour. On the inside of the tubes, a water-glycol mixture flows, which absorbs or releases heat. The team tested many different variants of tubes and found that the lye absorbed more water vapour in tubes with coated and finely structured surfaces.[59] Concerning sorbents, the case is clear: aqueous sodium hydroxide lye has achieved the best results so far and is very inexpensive.

The second concept investigated at Empa also employs sodium hydroxide as a sorbent but uses a different type of absorber/desorber. In this case, the liquid caustic soda runs slowly down a vertically mounted spiral tube heat exchanger and has plenty of time to absorb water vapour. The heat released in the process is transferred directly to the water that flows through the inside of the heat exchanger. To increase the power density of the reactor, the Empa team carried out in-depth investigations into the water uptake and release of the lye.

They used various analytical methods such as Raman spectroscopy[60] and also tapped into the analytical capabilities of the Paul Scherrer Institute, including neutron imaging at the Swiss Spallation Neutron Source SINQ. These studies have not yet been completed but have already led to optimisation of the absorber/desorber design. The insights gained will also be used to build a storage facility with a discharge capacity of 5 kilowatts.

This is an important step towards both implementation in buildings and eventual commercialisation.

Technical perspective

The forms of sorption storage optimised within the framework of the SCCER have proven that this type of storage is suitable for use in smaller residential buildings. From a technical point of view, however, there is still a need for further optimisation, especially with regard to power density: the heat exchange and absorption should take place more rapidly in order to increase the performance of the system. To this end, the researchers will continue to investigate the sorption process and optimise the reactors accordingly.

> Adjustments to regulatory conditions through CO_2 pricing could enable compact sorption storage systems to enter the market.

Economic perspective

Companies have already expressed interest in liquid sorption storage. However, there are still doubts as to whether such systems can be operated economically. Adjustments to regulatory conditions through CO_2 pricing could enable compact sorption storage systems to enter the market. Appropriate regulatory intervention is justified because these seasonal heat storage facilities would, through closer sector coupling, also reduce the load on the power grid. In summer, when solar electricity is plentiful, it could generate heat with heat pumps to be stored until the cold season. In winter, when the demand for heating is greatest but the yield from solar cells is low, less electricity would be consumed by electric heat pumps.

3.2.1 New materials for hydrogen storage

Profile

Advantages

- high energy density at low pressure
- can replace pressure tanks
- hydrogen compressor with no moving parts
- great potential to find new materials with high storage density

Disadvantages

- gravimetric hydrogen density
- costs of storage materials

Maturity of the technology

Technology readiness level (TRL):

- 8 for metal hydride
- 3 for complex hydrides
- 2 for new materials such as graphene oxide

Milestones of SCCER

- reversibility of nano-structured complex hydrides on graphene carriers
- high storage density in graphene oxide with nanotubes
- founding a start-up for hydrogen storage and metal hydride compressors

Further research needs

- stability and reversibility of complex hydrides
- new materials with higher storage density and/or lower costs
- long-term operating experience

Significance for the Energy Strategy 2050

Hydrogen can be produced in an environmentally friendly way from electricity or biomass. Due to its high energy density, it enables the de-fossilisation of the sectors in the energy system that are currently dependent on fossil fuels, like transportation. Long-distance transport or aviation have hardly any alternative in a climate-friendly future.

Hydrogen is the energy carrier of the future. The hydrogen economy requires storage facilities that can safely store large quantities of hydrogen more compactly. Hydrogen storage systems with metal hydrides are already mature. But new materials with a higher gravimetric hydrogen density such as complex hydrides or carbon graphene in combination with carbon nanotubes offer many advantages. From the next decade onwards, they could be the prevailing form of energy storage.

Using renewable energy, hydrogen can be produced through the electrolysis of water both efficiently (with an efficiency of up to 80%) and in a climate-neutral manner. Hydrogen is versatile and can be used, for example, to generate electricity in a fuel cell, to produce heat in catalytic combustion or as a precursor for chemical compounds such as methane, methanol or formic acid. Technology research for the production and use of hydrogen has been carried out successfully for decades. In the years to come, many of these technologies will be able to contribute to the energy transition.

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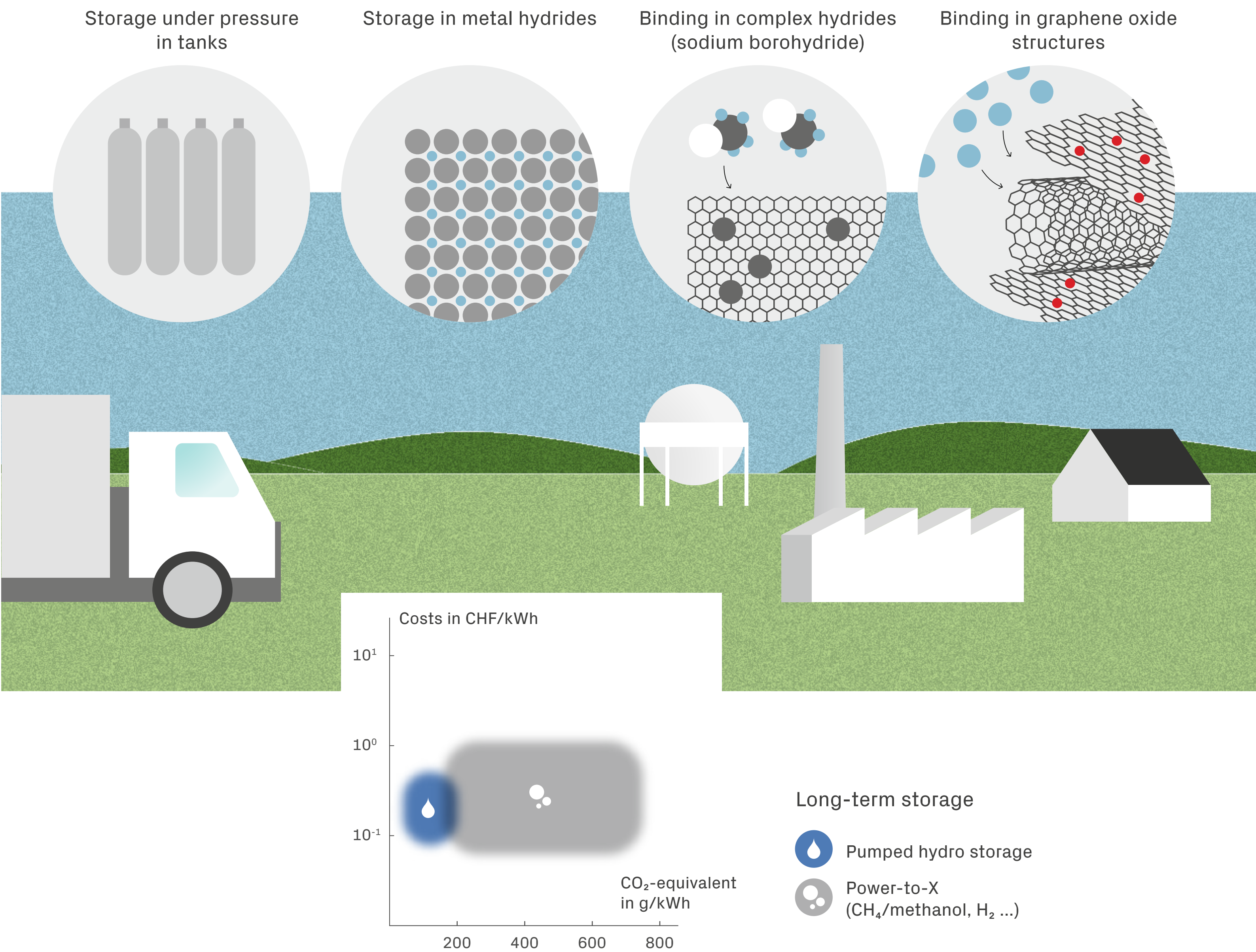
Storage methods for hydrogen



Source: Modified from Abdon et al. [2017][5].

Hydrogen storage with new materials – operating principle

The main focus here is on the question of how hydrogen can be stored compactly and safely. At 39.2 kWh/kg, hydrogen has the highest energy density of all energy carriers, three times higher than petrol. However, one kilogram of hydrogen at room temperature and atmospheric pressure, requires a volume of 11 cubic metres – 3000 times more than petrol. In order to store hydrogen in manageable volumes, the gas must be stored under high pressure in tanks; at up to 200 bar in stationary steel tanks or up to 700 bar in carbon fibre composite tanks on vehicles with fuel cells and electric drives. These solutions work and have been proven. Nonetheless, they are not ideal since high pressures mean high energy consumption and require technically sophisticated solutions to prevent unwanted leakage.

Hydrogen storage systems with metal hydrides are mature and already being launched on the market. Storage tanks with complex hydrides still require further development.

Researchers are therefore investigating and developing alternative methods to store hydrogen safely at high density. To do this, they are exploring the possibility of binding hydrogen in solids, for example in metal hydrides based on lanthanum and nickel or on magnesium and aluminium. *GRZ Technologies,* an EPFL start-up, is using this approach to build storage facilities with an energy content of more than one megawatt-hour. The metal hydride in the tank stores two percent of its weight with twice the density of liquid hydrogen and thus, in comparison to batteries, around five times as much energy by weight and 20 times as much by volume. Even greater gravimetric storage densities can be achieved with complex hydrides, which can absorb up to 20 percent of their weight in hydrogen.

Research at the SCCER

The compression of the large gas volume at room temperature to a small volume presents a challenge for storing hydrogen. To do this, the gas must either be put under high pressure or liquefied by cooling. The EPFL researchers have pursued a third option: they increase the density of the gas molecules by allowing them to interact with another material. Two approaches have been investigated.

- ***Chemical binding in complex hydrides:*** In sodium borohydride, the proportion of hydrogen to weight reaches 10.5 percent. The bond between hydrogen and sodium borohydride is, however, very stable. This presented an obstacle to its use for a long time since a hydrogen storage system should not only absorb and hold as much hydrogen as possible but also release it easily when it is needed. In addition, borohydride crystallises when hydrogen is released and prevents the hydrogen from being absorbed again in the next charging cycle. The researchers have found that these undesirable effects can be avoided if the sodium borohydride is brought into contact with an ionic liquid.[61] The researchers also prevent crystallisation by depositing small islands of sodium borohydride on graphene carbon.[62]
- ***Adsorption on GONT:*** The abbreviation «GONT» stands for graphene oxide-carbon nanotubes. This graphene oxide combined with carbon nanotubes stores five percent hydrogen at room temperature at a pressure of 50 bar. This corresponds to the storage capacity of a composite tank at 700 bar. More importantly, this type of storage can be easily discharged again.

The researchers have also developed a compressor for hydrogen that operates without any moving parts. To do this, they use a combination of lanthanum, cerium, nickel, cobalt and manganese. This substance absorbs hydrogen at a temperature of 20 °C and a pressure of 3 bar and releases it again at 100 °C at 25 bar, or at 225 °C at 200 bar. The pressure of the hydrogen can therefore be increased simply by raising the temperature. This compressor technology is already being commercialised by *GRZ Technologies SA,* an EPFL start-up, in collaboration with *Burckhardt Kompressoren* and *Messer Schweiz*.[63]

Overall, great progress has been made within the framework of the SCCER on the reversibility of complex hydrides, the development of new liquid hydrides and hydrogen storage in carbon nanostructures. The nanostructure approach allows storing the same amount of hydrogen at low pressure (<50 bar) as in composite tanks at 700 bar.

From 2035 onwards, the global energy market is expected to be based on renewable energy, dominated by hydrogen and synthetic hydrocarbons.

Technical perspective

Hydrogen storage systems with metal hydrides are mature and already being launched on the market. However, storage systems with complex hydrides, such as those investigated by EPFL researchers, still require further development. In the next few years, it will be important to:

- optimise the synthesis of these hydrides,
- simplify the reversible absorption and release of hydrogen in larger storage units and prevent undesirable reactions.

The newly discovered hydrogen storage systems using nanomaterials such as GONT are currently being investigated to understand their exact storage processes. Researchers believe that such nanomaterials could replace pressure storage systems in the near future. But to achieve this, it must also be possible to produce graphene oxide in large quantities.

EPFL researchers in Sion have built a demonstration plant to show that hydrogen can be the energy source of the future. The plant is designed to cover the energy consumption of a single person based on the global average. In addition to a photovoltaic system, the model includes two battery storage units, an electrolyser, a metal hydride hydrogen storage unit, a metal hydride compressor and two reactors that produce methane and methanol (cf. «3.3.4 Synthetic methane», p. 92). This plant is unique in Switzerland in that the entire path from solar energy to synthetic hydrocarbons is demonstrated at real scale in a single location.[64]

Economic perspective

Hydrogen can already be used economically as an energy carrier. One kilogram, produced with the latest technology and renewable energy, costs CHF 9. From 2035 onwards, the global energy market is expected to be based on renewable energy, dominated by hydrogen and synthetic hydrocarbons, which in turn will be produced from hydrogen and carbon dioxide from the air. More and more companies worldwide are betting on these technologies. In Switzerland, colleagues at the EPFL established a start-up company in Sion in 2017.

The company sells compressors that store hydrogen at low pressure in a metal hydride tank and release it when required at a pressure of up to 200 bar. The company is developing a large variant together with other Swiss companies. In addition, it has developed a large storage system consisting of an electrolyser, a metal hydride tank and a fuel cell, which is already being marketed. All components can be adapted according to the energy needs and performance requirements of the user. A successful financing round with well-known investors in 2020 shows how promising this technology is.

3.2.2 Alkaline electrolysis for hydrogen production

Profile

Advantages
- proven, durable technology
- available up to several megawatts

Disadvantages
- low flexibility with fluctuating electricity supply
- hydrogen technology is not yet competitive with other storage technologies
- new materials required for greater purity of the gas

Maturity of the technology
Technology readiness level (TRL):
- 9 for commercially available systems
- 3 to 4 for systems with new electrodes and membranes

Milestones of SCCER
- development of new materials for electrodes and membranes
- advances in power density, gas purity, load flexibility and cost

Further research needs
- development of new materials for electrodes and membranes

Significance for the Energy Strategy 2050
Hydrogen is one of the energy carriers of the future. Worldwide, 96 percent of the gas is obtained today via steam reforming or via conversion of coal or natural gas. This predominant use of fossil materials means «dirty» hydrogen, which is not contributing to a climate-neutral energy transition. If hydrogen is to demonstrate the advantages it can bring, it must be produced from renewable resources, on a large scale, in a climate-neutral way.

Alkaline electrolysers can produce hydrogen in this way when operated with renewable electricity, making them an essential building block of a hydrogen-based economy. Hydrogen can be used in many ways, for example, to generate electricity in a fuel cell or as a base material for chemical compounds such as ammonia, methane, methanol, formic acid or other hydrocarbons. It can be produced without the emission of climate-damaging carbon dioxide, provided this takes place in an electrolyser supplied with electricity from renewable sources such as solar, wind or water power.

The role of hydrogen in a future energy system consists, on the one hand, of enabling independence from fossil fuels in sectors which cannot operate with electricity alone, such as heavy-goods, long-distance and air transport, or the chemicals industry. On the other hand, hydrogen enables seasonal compensation by storing renewable energy generated in summer for use in the winter months by the electricity or transportation sector.

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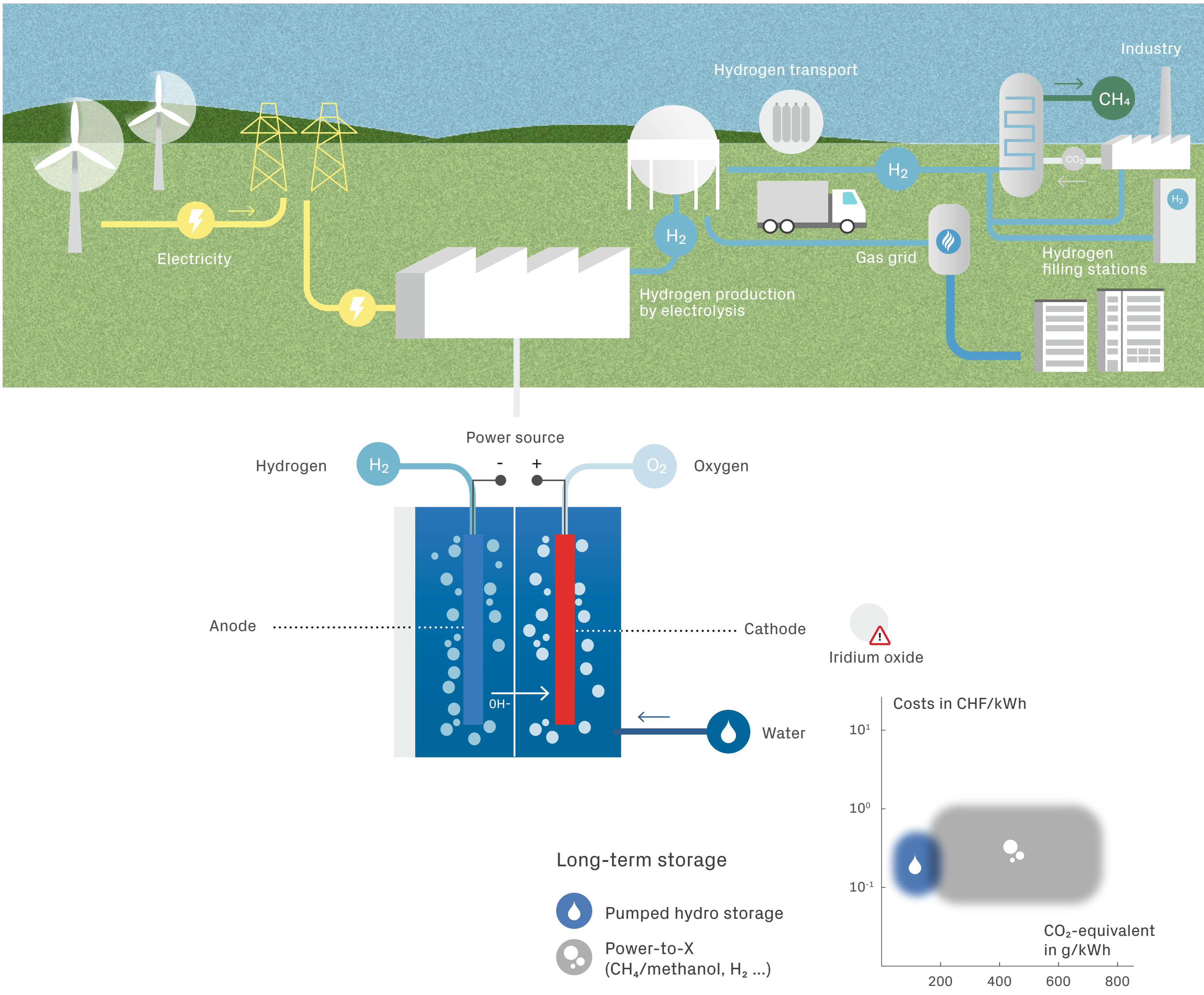
The principle of alkaline electrolysis for hydrogen production



Source: Modified from Abdon et al. [2017][5].

Alkaline electrolysis for hydrogen production – operating principle

In 1789, the Dutch chemist Adriaan Paets van Troostwijk and physician Johann Rudolf Deiman were the first to split water. Around 1800, the German chemist Johann Wilhelm Ritter proved that the components were hydrogen and oxygen. In 1879, the Frenchman Augustin Muchot tried to run electrolysis with electricity that he wanted to generate by concentrating sunlight. Around 1900, companies began to manufacture the relevant equipment, electrolysers, in large numbers.

Today, this technology is used worldwide. It is robust, works even at high pressures and is inexpensive. The most common approach is alkaline water electrolysis, in which two electrodes are immersed in a liquid electrolyte made from potash or caustic soda lye.

A thin membrane, permeable to hydroxide ions (OH^-), separates the two electrodes and the product gases (hydrogen and oxygen).

There are technical reasons behind the fact that hydrogen is still produced mainly from fossil materials. The simplest and most widespread variant of alkaline water electrolysis has significant limitations. The hydrogen purity in this process is only 99.5 to 99.9 percent because a certain amount of oxygen always penetrates the membrane barrier (separator). Subsequent purification of the hydrogen is necessary, upsetting the overall energy balance. Furthermore, available technical catalysts for the oxygen evolution reaction (OER) have a considerable voltage loss. Together with the ionical resistance in the electrolyte, this results in a lower current density. Alkaline electrolysers are therefore quite large and sluggish.

With the expansion of wind and solar energy, electricity generation will fluctuate even more in the future. This will result in an increasing number of electricity production peaks. Those peaks are welcome as a source of low-cost surplus energy capacity, which can be stored or shifted to other areas such as transportation. For an electrolyser to fulfil its transformative role in the future energy system, however, it must be capable of responding quickly to these fluctuations and making use of local excess electricity capacity. In other words, it must be able to operate dynamically.

Research at the SCCER

Water electrolysis currently accounts for only four percent of global hydrogen production. Moreover, hydrogen electrolysis is mostly limited to small plants, set up for situations where access to large-scale fossil fuel-based production facilities is not possible or not economical. As already discussed, the main reasons for the low representation of hydrogen electrolysis are the low current density and low degree of purity. The research activities at the SCCER focused primarily on the development of more cost-effective electrodes with improved oxygen evolution reaction (OER) properties.

The second research topic was the improvement of separators for alkaline electrolysers.

One measure for the OER properties is the electrical voltage at which electrolysis takes place. The difference between the actual and the theoretical voltage (overpotential) should be as small as possible since it limits the efficiency of alkaline electrolysers. Researchers at the EPFL examined a number of materials for their overpotential, including phosphates, borates and oxides. All of them showed a sufficiently low overpotential and satisfactory OER performance.[65] Recent experiments are concerned with low-cost materials, such as nickel steel, which has even better properties.[66]

Indeed, metallic electrodes based on iron, nickel and/or cobalt have re-emerged as promising and cost-effective anodes for the alkaline OER. Their simplicity and in-situ formation of a highly active oxy-hydroxide surface catalyst layer make this electrode composition attractive. It exhibits state-of-the-art overpotentials for the OER. Researchers at the EPFL have recently reported the relationship between the initial alloy composition, the OER performance and the emergent active catalyst composition using metallic anodes with defined Fe-Ni-Co atomic ratios prepared via arc melting. These investigations made it possible to find the ideal composition of the anode which provided both good stability at low overvoltage. This result will help to optimise commercial electrodes.[67]

Another possibility for reducing overpotential is to run the electrolysis at high temperatures or pressures. The research team has also found suitable materials for these applications.[68]

Technical perspective

Alkaline electrolysers are technically mature. Nonetheless, if the goal is widespread adoption of CO_2-neutral storage of electrical energy with hydrogen, the efficiency, dynamics, purity of the gas and overall costs must improve.

Further attention is being paid to the development of separators, which consisted of asbestos in the first commercial electrolysers. Today, the trend is towards material compounds made of porous polymers and inorganic substances. Further research aims to reduce the voltage drop and the gas transfer through the separator. Non-porous, OH-conductive membranes should solve the challenges of gas transfer and reduce electrode corrosion when the electrolyser is fed with pure water.

In the coming years, science will pursue the following goals through the use of new or improved materials for electrodes or membranes:

- increased efficiency by means of higher current densities and lower voltage losses
- cost reduction due to cheaper materials and longer component service life in part due to reduced corrosion
- improved load flexibility with minimal transfer of hydrogen or oxygen to the other side
- increase in gas purity, especially when operating under high pressure

Economic perspective

In Switzerland, hydrogen production with electrolysis has a long tradition. Switzerland is home to one of the leading manufacturers of alkaline electrolysers, with 50 years' experience. It has one of the largest production capacities for electrolysers worldwide.[69]

Storing energy through the production of hydrogen using alkaline electrolysis is currently not competitive compared to pumped hydro storage power plants. The reason is primarily the low efficiency of the entire system. The efficiency is less than 40 percent when hydrogen is converted back into electricity in a fuel cell.

However, if investment and maintenance costs continue to fall, alkaline electrolysis for hydrogen production could keep pace and become a substitute for fossil fuels. Under market conditions prevailing today, this is only possible with subsidies, as, for example, in Germany with 0.06 euros per kilowatt-hour and in the USA with 0.02 dollars per kilowatt-hour.[70]

Potential markets for the use of alkaline electrolysis already exist and are growing strongly. Small electrolysers, producing less than one standard cubic metre of hydrogen per hour, can fill gas cylinders. Medium-sized plants produce hydrogen for industry. Plants with an output of more than ten standard cubic metres per hour are suitable for ammonia production and the mobility sector, potentially serving hydrogen trucks. For small systems, the highest cost is the purchase of the electrolyser. For large systems, it is primarily the cost of electricity for operation. The investment costs are between 800 and 1500 euros per kilowatt, and maintenance costs amount to two to three percent of investment costs per year. During those periods outside of peak electricity demand, namely from April to September when Switzerland exports electricity, large electrolysis plants could benefit from cheap electricity.

Potential markets for the use of alkaline electrolysis already exist and are growing strongly.

3.2.3 Hydrogen production with redox flow batteries

Profile

Advantages

- power/output and energy content can be scaled independently of one another
- liquid energy storage; can be transported, refuelled and stored indefinitely
- large power range up to megawatts
- flexible use with the option of additional hydrogen production

Disadvantages

- up to now, only economical for large storage volumes
- use of precious metal catalysts

Maturity of the technology

Technology readiness level (TRL):

- 9 for the redox flow battery
- 6 in combination with hydrogen production

Milestones of SCCER

- extension of the concept with hydrogen production
- operation of a demonstration system at the Electromobilis plant in Martigny
- development of new catalyst and electrolyte materials

Significance for the Energy Strategy 2050

Redox flow batteries with hydrogen production are true all-rounders that can be used flexibly for the storage of renewable electricity and the production of hydrogen. This flexibility, as well as the possibility of scaling them according to requirements, should ensure they achieve a significant position in the mix of energy storage systems in Switzerland. The hydrogen-producing redox flow battery system is most suited in situations where
(i) medium-range power output,
(ii) decentralised storage and
(iii) hydrogen supply are required, while at the same time batteries are too small and expensive or pumped hydro and compressed air storage units are too large. One advantage of this technology is the parallel supply of hydrogen and electricity at filling stations for electric mobility.

Further research needs

- development of more cost-effective catalysts
- experience in operations management

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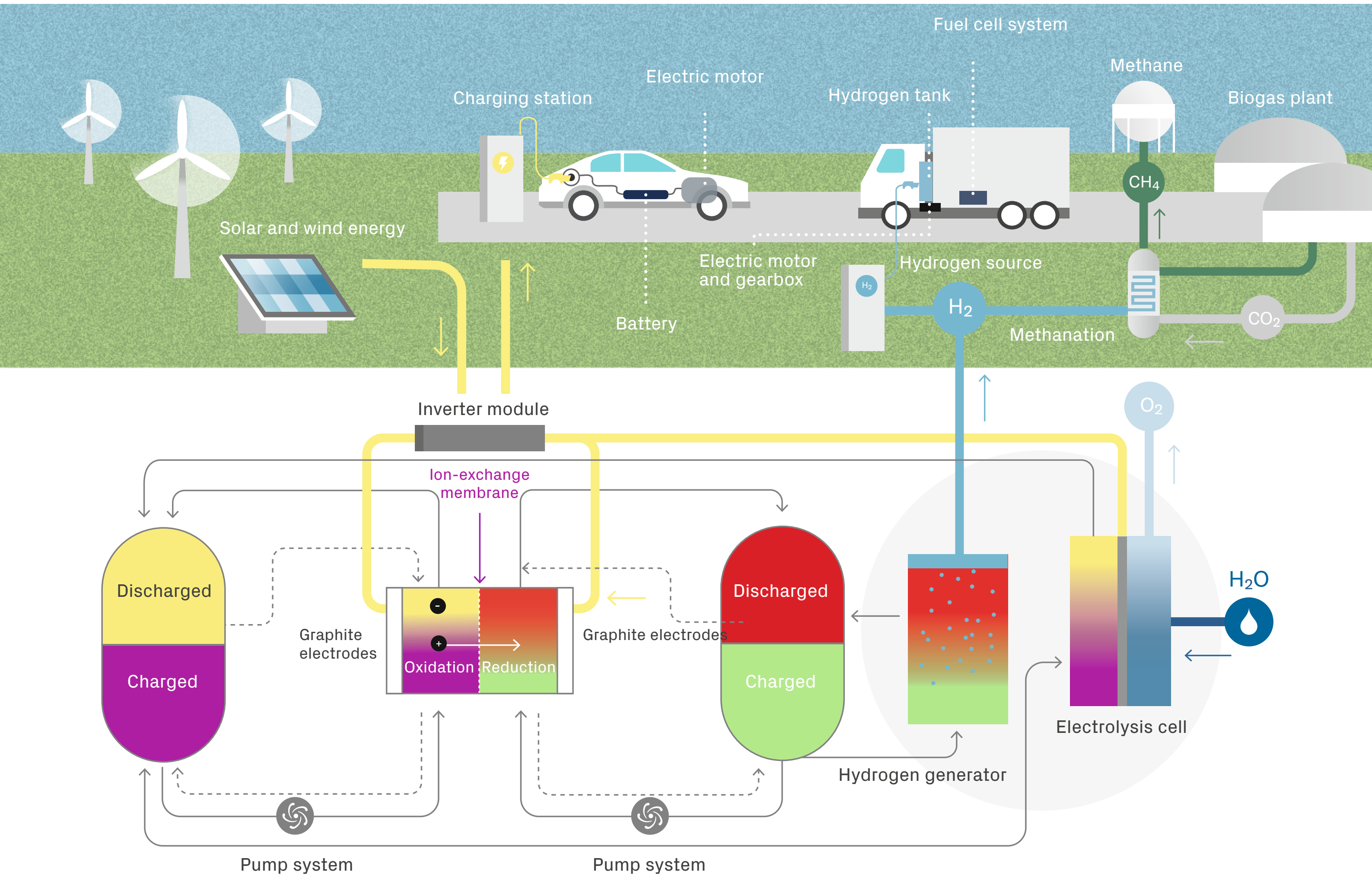
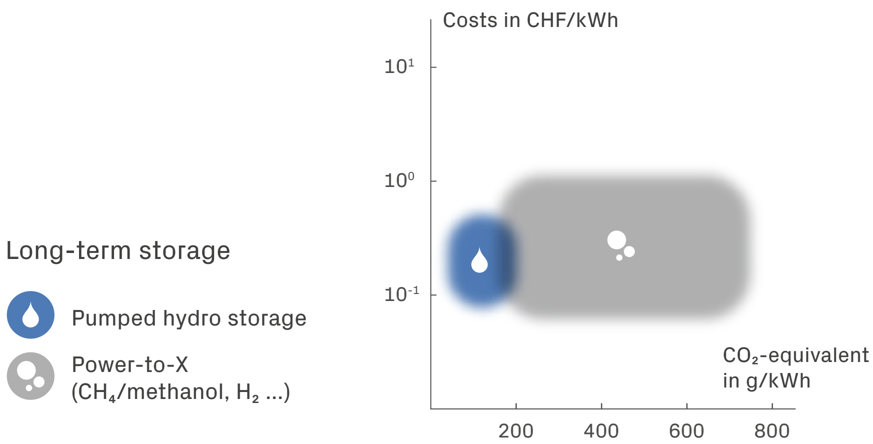
The principle of hydrogen production with redox flow batteries





Source: Modified from Abdon et al. (2017)[5].

Redox flow battery with hydrogen production – operating principle

In a car powered by an internal combustion engine, the power of the engine determines how fast it can go. The size of the fuel tank determines how far it can travel. If you want to drive 1000 kilometres instead of 500, you need a tank twice as big. This does not change the engine power. This decoupling of power and energy content is very practical; the two can be dimensioned separately from each other. This property also applies to the redox flow battery.

The redox flow battery consists of several components:

- an electrochemical cell, with two electrodes and a membrane, which derives energy from the electrolyte. The reduction and oxidation of the electrolyte take place on the surface of the electrode.
- two storage tanks, between which the electrolyte can be pumped back and forth
- peristaltic pumps that pump the electrolyte to the cell

The electrical power is determined by the size of the electrode-membrane unit (electrochemical cell). By adjusting the volume of the electrolyte, the capacity of the battery can be scaled as required. The battery is fully charged when the electrolyte on the positive side is completely oxidised and, simultaneously, the electrolyte on the negative side is completely reduced. When the stored energy is put to use, the direction of flow and the electrochemical processes in the cell are reversed. This charge/discharge cycle can be repeated almost indefinitely and the life span of such a system is estimated to be several decades.

These characteristics mean that the redox flow battery is employed time and again as a cost-effective alternative form of energy storage for use in stationary situations. It was developed by NASA in the late 1970s and patented by an Australian university in 1989. Over the last ten years there has been an increase in research efforts and in practical applications.

In the best systems currently available, the redox flow battery achieves a maximum energy density of 35 watt-hours per litre, 14 times lower than a Li-ion battery (500 watt-hours per litre). As a consequence, this technology has not become established in mobile applications.

In stationary use, on the other hand, some systems are already in operation, such as the 20 megawatt-hour redox flow battery at the Fraunhofer Institute for Chemical Technology (ICT) in Pfinztal, Germany. This serves as a buffer for a two megawatt wind turbine. The complex redox flow technology is particularly interesting for power outputs in the lower megawatt range because it is competitive with expensive battery storage systems as well as with pumped hydro and compressed air storage systems, which are only economical for significantly higher levels of power output.

In a future energy system in which hydrogen plays a central role, redox flow technology can also make a significant contribution.

Over the last seven years, the EPFL, in line with the SCCER, has developed the concept of a redox flow battery with an additional circuit for the production of hydrogen and oxygen.

Research at the SCCER

With the establishment of the SCCER in 2013, EPFL researchers proposed the concept of the dual-circuit redox flow battery and have since developed it into a demonstration system. The system is based on the following idea.

- On the positive side of the electrochemical cell, there is an electrolyte with cerium(III) ions which is oxidised to cerium(IV) during charging. If required, the charged electrolyte can be diverted via a valve into a catalytic converter, where it is reduced again to cerium(III) with a catalyst consisting of ruthenium or iridium oxides. The gaseous oxygen produced during this process is collected in a tank or escapes into the air.

- The research team has demonstrated the evolution of oxygen from the cerium electrolyte at laboratory level.
- On the negative side of the electrochemical cell, an electrolyte with vanadium(III) ions is reduced to vanadium(II). This electrolyte can also be diverted into a catalytic reactor. There the vanadium(II) is oxidised to vanadium(III) on a molybdenum catalyst. Hydrogen is released in the process, which in turn is captured. The efficiency of this process is almost one hundred percent.

Redox flow batteries are already in use today, for example as buffer storage for electricity from wind turbines. The work in the SCCER forms a bridge to the hydrogen economy and extends the range of applications.

The production of hydrogen is not mandatory. It can be included as part of the process when required. The electrolytes can also simply remain in their tanks in the first circuit. If there is a demand for electricity from the grid, the electrolytes can be converted to electricity in the redox flow cell. If the demand for hydrogen is high, the charged electrolytes can also flow straight into the second circuit. This can even take place simultaneously with the charging of the redox flow battery.

The EPFL research team has meanwhile developed the concept into a demonstration system to study hydrogen production on the negative side of the cell. The system is operated at the Electromobilis facility in Martigny. The vanadium redox flow battery which was supplied by Gildemeister Energy Solutions has an output of 10 kilowatts with an energy capacity of 40 kilowatt-hours.[71]

The cell is capable of producing vanadium(II). It was not possible to realise the original idea of producing oxygen on the positive side with the redox pair vanadium(V)/(IV) due to the low redox potential of 0.991 V; achieving this would have required 1.23 V. An electrolyte based on cerium, which has a sufficient redox potential, was not tested on a large scale because it would have corroded the cell electrodes. Furthermore, the cerium salts have poor solubility under acidic conditions. The Gildemeister system could not be modified within the scope of this project.

The team has optimised the catalysts to ensure the hydrogen production process runs efficiently. On the negative side of the cell, they consist of ceramic beads coated with molybdenum catalyst materials, which provide a large surface area for the catalyst-electrolyte interface. The liquid electrolyte enters a vertically mounted cylinder, filled with the beads, from below. The released hydrogen escapes upwards where it is collected. To achieve a higher yield, several of these chambers are connected and stacked on top of one another.

The prototype in Martigny is capable of completely converting up to one litre of electrolyte per minute into hydrogen or oxygen. This corresponds to a discharge capacity of 2.4 kilowatts, with the electrolytes being discharged after 16.7 hours.

In order to replace the expensive iridium oxide catalyst for the release of oxygen on the positive side of the cell, the research team investigated various alternatives:

- a process to oxidise toxic compounds such as hydrazine, sulphur dioxide or hydrogen sulphide to nitrogen (hydrazine) or sulphate (sulphur dioxide) and render them harmless. Industrial waste water could, for example, be treated in this manner.[72]
- the use of a hybrid vanadium/air electrolysis cell, in which oxygen is produced from aqueous electrolytes. This cell currently achieves an efficiency of 42 to 62 percent over 120 hours.[73]

Technical perspective

The dual-circuit redox flow battery offers a number of advantages: even when the electrolyte in the redox flow circuit is fully charged, hydrogen can still be produced using excess electricity from the mains. The combination of two different chemical energy sources makes the concept very flexible. If the redox flow circuit functions as a classic battery that generates electricity, the hydrogen can be used as fuel in vehicles or processed into hydrocarbons such as methane (cf. 3.3.4, p. 92) or formic acid (cf. 3.3.3, p. 88).

The research team did not develop the original idea of the cerium/vanadium cell to the point of a demonstration system because the stability of the positive electrolyte was insufficient. However, within the framework of the SCCER, it was possible to get around some of the technological hurdles of classical electrolysis. For example, gas purification, compression and the use of precious metal catalysts were largely eliminated as cost factors.

This approach could overcome the cost disadvantage of catalysts made of precious metal required by many chemical processes. In the originally designed dual-circuit redox flow battery with the cerium electrolyte, ruthenium oxide would be used on the positive side of the cell, or in the case of the vanadium electrolyte, molybdenum carbide would be used.

The goal of the research team is, however, to find alternative, cheaper substances. To this end, the team is currently experimenting with an electrolyte based on manganese[74] which should make it possible to increase energy density and make the entire system safer.

Economic perspective

Redox flow batteries are already in use today, for example as buffer storage for electricity from wind turbines. The work in the SCCER forms a bridge to the hydrogen economy and significantly extends the range of applications for such batteries, for example for wastewater treatment. This technology makes it possible to store fluctuating energy from renewable sources more flexibly. Intense research efforts and numerous start-ups worldwide promise to develop a lucrative market in the coming years.

3.3.1 CO_2 electrolysis

Advantages
- produces a variety of hydrocarbons «at the touch of a button»
- replaces fossil fuels with climate-neutral synthetic substances
- is suitable for storing electrical energy

Disadvantages
- development is still in its infancy
- not yet economical

Maturity of the technology
Technology readiness level (TRL): 3–4

Milestones of SCCER
- development of new catalysts with little or no precious metal content
- patented technical implementation

Further research needs
- optimisation of catalytic converters and process technology
- construction of larger demonstration models

Significance for the Energy Strategy 2050
Fossil hydrocarbons are an important raw material for Switzerland as well as other nations. They are used in many areas - for heating, for transportation and in industry. Their use generates CO_2 emissions which must be eliminated by 2050. Synthetic hydrocarbons can replace fossil fuels, are climate-neutral and are suitable for storing electrical energy. CO_2 electrolysis can make an important contribution in this field without taking a detour via hydrogen.

The energy sources of today's civilisation are hydrocarbons such as methane (natural gas), methanol, petrol, diesel, paraffin, coal and many others, all of which come from fossil sources. When burned, they release large quantities of CO_2 within a short space of time. This was bound up millions of years ago and is now being released into the atmosphere. Fossil hydrocarbons are therefore a major cause of the greenhouse effect. An energy industry that manages completely without hydrocarbons is unlikely in the coming decades, and a chemical industry without hydrocarbons is completely unrealistic. Many researchers and companies are therefore working on processes to manufacture these compounds synthetically. The raw materials for this, water and CO_2 from the air, are available in abundance. In order to combine these two raw materials electrochemically and climate-neutrally, electricity from renewable sources such as photovoltaic, wind or water power is required. Although CO_2 is released during combustion, it is the same quantity as is consumed during production. Synthetic hydrocarbons such as methane or methanol are also suitable for storing electrical energy. For this purpose, synthesis is always carried out when a substantial amount of electricity from renewable sources is available and at low cost, for example on sunny days in summer. When electricity becomes scarce, for example in winter, methane can be used to generate electricity in gas turbines or gas engines.

Profile

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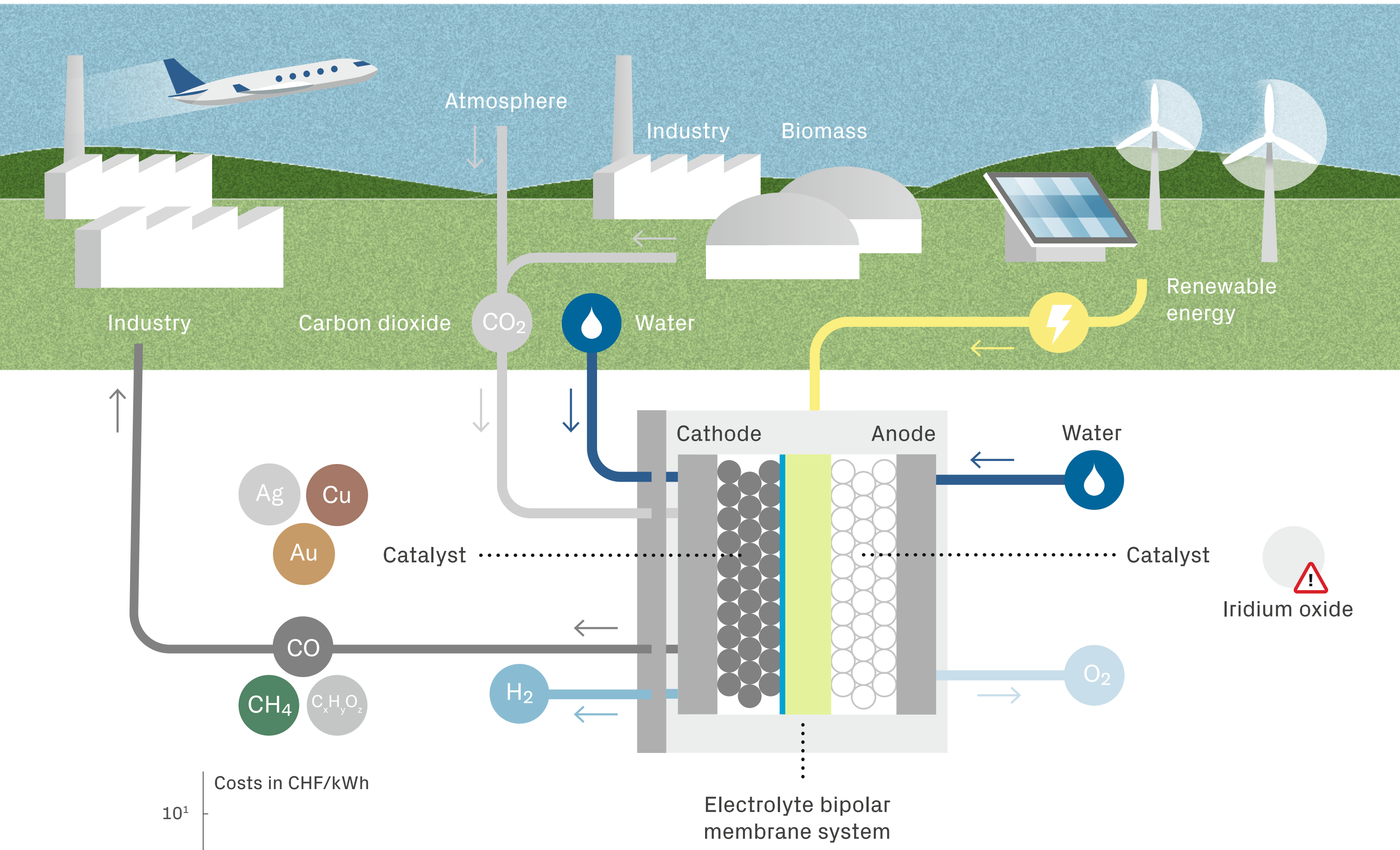
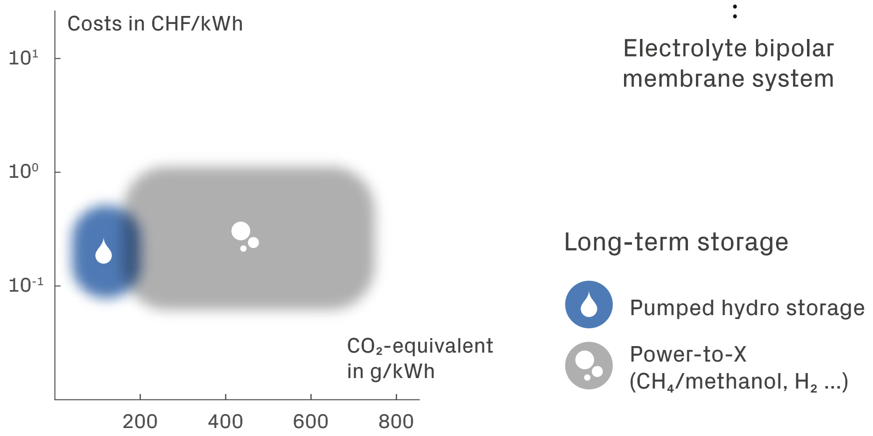
The principle of CO_2 electrolysis





Source: Modified from Abdon et al. [2017][5].

CO_2 electrolysis – operating principle

Various processes enable the production of higher quality hydrocarbons from water and CO_2. Teams from the SCCER and its partners have conducted research on some of these methods (cf. «3.3.2 Methanol from CO_2», «3.3.3 Hydrogen storage with formic acid» and «3.3.4 Synthetic methane»). All conventional processes are based on combining hydrogen with CO_2. But to do this, the hydrogen must first be obtained from water by electrolysis.

It would be ideal to have a single-step process that releases hydrogen from water and simultaneously converts CO_2 to carbon monoxide (CO), which then reacts with the hydrogen to form various hydrocarbons.

In order to make CO_2 electrolysis more economical, new electrodes containing less iridium are needed for operation in an acidic environment, or no precious metals at all for an alkaline environment.

The simultaneous decomposition of water and CO_2 is called co-electrolysis. The products are methane and oxygen. The SCCER research teams have proven that CO_2 electrolysis is possible and have successfully carried out the process in the laboratory. This concept has a special charm because the end product can be determined by using a specific catalyst. With gold, such a co-electrolyser produces carbon monoxide, an important starting material for chemical syntheses; with copper, methane is obtained. Different hydrocarbons can also be produced by varying the current density. By simply turning a control knob, the operator could change the product composition and set whether more hydrogen, methane or formic acid should be produced. It is still far from being that simple; the technology is at an early stage of development. Further research must prove whether the concept can be developed into a system that is ready for mass production.

Based on the cell design developed and patented by PSI, the research team is currently building a test system for CO_2 electrolysis with a capacity of one kilowatt.

Research at the SCCER

A key component for this technology is the catalyst. It determines which end product is created and how energy-efficient the process is. At the beginning of the project, there was hardly any reliable knowledge about this, only considerable speculation about why a copper oxide catalyst, for example, enhances the reaction leading to the production of ethylene or methanol.

The researchers were divided. Some saw the reason in the oxide surface, others in its roughness. SCCER research efforts at the University of Bern and at PSI showed for the first time that a copper oxide catalyst selectively produces ethylene due to its roughness. Based on these findings, researchers are currently concentrating on various catalytic materials with different compositions and structures such as aerogels, which have extremely porous mono- and bimetallic structures.

A further focus was the technical implementation of electrochemical co-electrolysis. Here, two processes have to be coupled: the reduction of CO_2 on the cathode side and the oxidation of water on the anode side. These are separated by an electrically insulating, ion-conducting layer, the electrolyte. In recent years, PSI has succeeded in developing a completely new cell design for CO_2 electrolysis with CO_2 in the gas phase. The researchers were the first to solve the problem that the cell inadvertently pumps CO_2 to the anode side. The solution consists of a bipolar membrane system (electrolyte) with a newly developed cell design.[75] This system not only suppresses the pumping of CO_2 to the anode side, it also significantly improves the overall efficiency. The concept has been patented. The group is currently working on further improvements, for example to increase the selectivity for specific hydrocarbons or to refine the water management.

The group at EPFL is exploring a fundamentally new concept. It is investigating ionic liquids that are suitable as electrolytes. These support the electrocatalytic reaction of CO_2 decomposition. However, it will take some time before such an electrolyte can be used in a technical cell.

Further efficiency losses in CO_2 electrolysis are caused by the reaction at the anode – the oxygen evolution reaction – which produces oxygen from water. The precious metal catalysts typically used to accelerate this reaction contain iridium dioxide. This is the most powerful catalyst for this reaction and the only one that is stable in an acidic environment. However, iridium is expensive and rare. In order to make CO_2 electrolysis more economical, new electrodes containing less iridium are needed for operation in an acidic environment, or no precious metals at all for an alkaline environment.

For operation in acidic environments, the team at PSI, together with researchers from ETH Zurich, has developed nanoparticles of iridium dioxide with an average diameter of 1.5 nanometres and a reduced iridium content. The reaction is very effective when using these particles because the smaller the catalyst particles, the larger the surface area of the catalyst. An alternative is offered by new types of catalysts, so-called pyrochlores, which incorporate not only iridium but also base metals into the structure. Such pyrochlore catalysts behave actively and stably during the oxygen evolution reaction even with a reduced amount of iridium. The team is currently testing the newly developed catalysts on a laboratory scale.

There are more catalysts to choose from for co-electrolysers at the anode in an alkaline environment. A well-known family of catalysts with metal oxides in a perovskite structure shows great promise. The team has also produced nanoparticles with these materials for the first time - with the help of Empa's flame spray synthesis plant, which can produce perovskite catalyst nanopowder in large quantities in a short time. Some perovskite nanocatalysts showed excellent performance in terms of stability and electrochemical activity, not only in laboratory tests but also in practical facilities. When tested in a commercial electrolyser, the perovskite nanocatalysts performed more reliably than a conventional iridium oxide catalyst.[76]

The huge potential of CO_2 electrolysis is confirmed by the great interest shown by various industrial companies.

Technical perspective

Based on the cell design developed and patented by PSI, the research team is currently building a test system for CO_2 electrolysis with a capacity of one kilowatt. With that they have succeeded in developing the new technology from zero to a technology readiness level of 3 to 4. The aim is to build a larger prototype with which the basic feasibility of a large-scale plant can be demonstrated. The huge potential of this technology is confirmed by the great interest shown by various industrial companies.

Economic perspective

The interest from a number of companies in further pilot projects suggests that the business community sees opportunities for commercialisation of CO_2 electrolysis. As things stand today, however, CO_2 electrolysis for the production of methane is not economical because fossil natural gas is far too cheap. On the other hand, the economic viability of other co-electrolysis products, such as carbon monoxide, methanol or formic acid, can already be foreseen.

In these instances, CO_2 electrolysis could be the missing link for an uninterrupted power supply (cf. 3.3.3, p. 88) that works with formic acid. Since formic acid is currently obtained from fossil raw materials, the technology is not climate-neutral. CO_2 electrolysis would overcome this disadvantage.

3.3.2 Methanol from CO_2

Advantages

- climate-friendly basic chemical for many applications
- complements the hydrogen economy
- suitable for storing electricity
- currently available technology

Disadvantages

- catalysts need to become more efficient and show long-term stability
- not yet economically viable

Maturity of the technology

Technology readiness level (TRL):

- 2–9 depending on the specific part of the project

Milestones of SCCER

- good detailed understanding of how the catalyst works
- development of catalysts with improved selectivity at low operating pressures

Further research needs

- further optimisation of the catalyst
- development of technical catalysts
- construction of larger demonstration plants

Significance for the Energy Strategy 2050

Methanol (CH_3OH) is an important basic chemical which today is mainly produced from coal or natural gas. Considering the need for climate-friendly production methods, the selective hydrogenation of CO_2 to methanol is a promising alternative. This technology could also be used to store renewable energy in liquid fuels, while at the same time reducing CO_2 emissions (methanol-economy). Further research is necessary if methanol is to become an economically feasible storage medium for various sectors from transportation to electricity. An important condition for achieving this is higher carbon taxation.

There is a huge focus on the «hydrogen economy» today. This light gas is considered key to a climate-neutral energy supply. Hydrogen can be produced from water and renewable electricity, stored in various ways and used in numerous applications, for example to generate electricity in fuel cells or as a fuel additive to power gas turbines. Chapter 3.2 (p. 66) explains more about hydrogen and the relevant research within the SCCER.

The energy density of hydrogen, however, is very low in relation to its volume. A possibility to overcome this problem would be to convert hydrogen, with CO_2 or CO, into a liquid hydrocarbon fuel such as methane (natural gas), methanol, petrol or paraffin. The hydrogenation of CO_2 is particularly appealing because binding it would reduce its impact on the climate change. The liquid fuels can be stored over long time periods and more easily than hydrogen. In addition, proven infrastructure exists for their storage and distribution, such as the natural gas network or filling stations.

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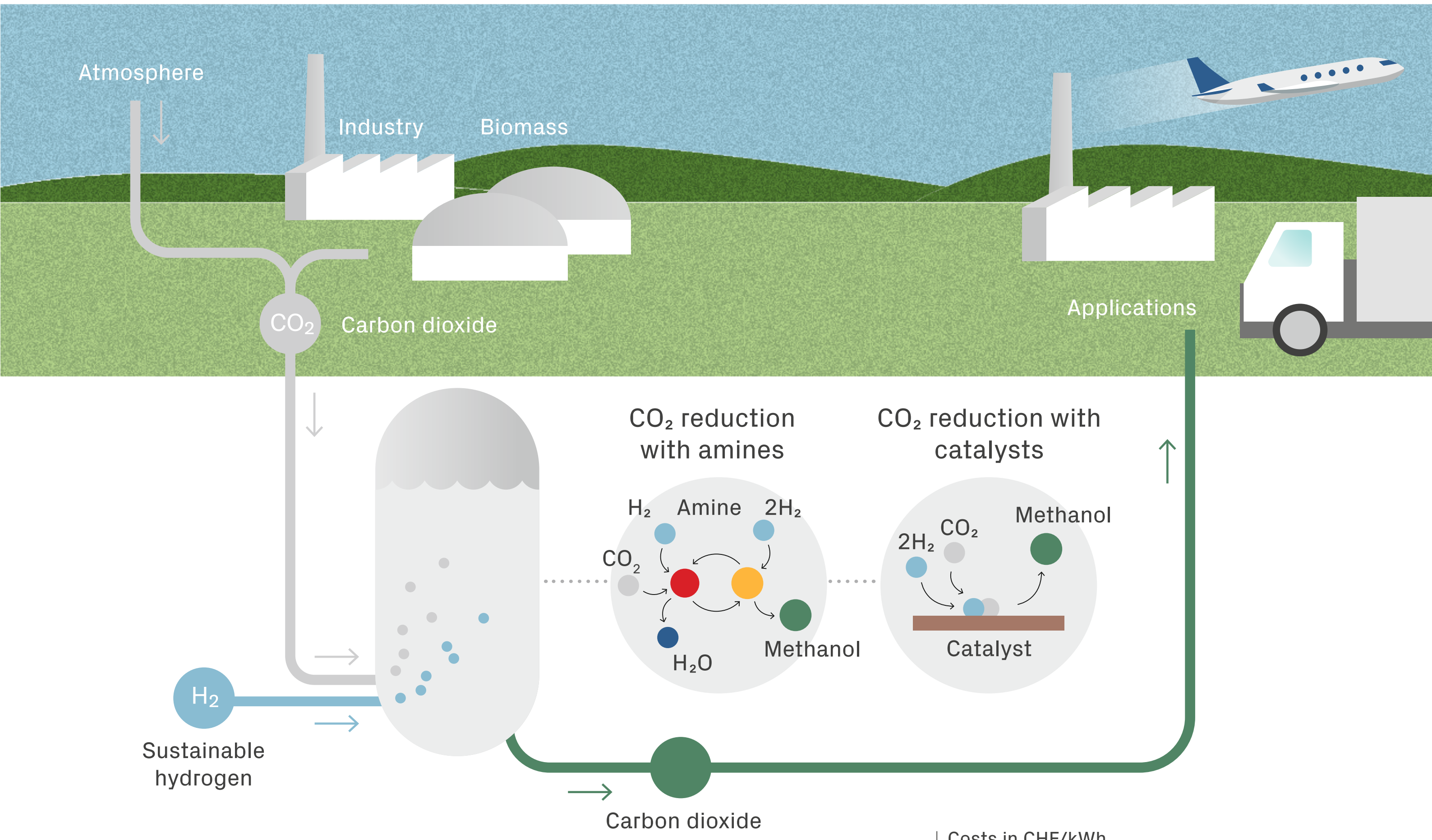
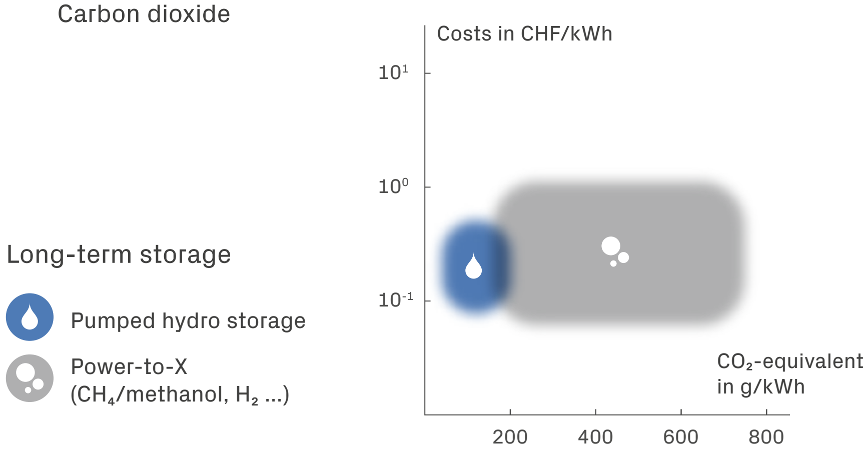
The principle of methanol from CO_2





Source: Modified from Abdon et al. [2017][5].

Methanol from CO_2 – operating principle

The SCCER has conducted research on a special case of hydrogen to liquid fuel conversion: methanol. With a production of 63 million tons per year (2013) and rising, methanol is one of the most heavily produced organic basic chemicals for many secondary products. Today, a first step in methanol production is to obtain synthesis gas, composed of carbon monoxide (CO) and hydrogen, by steam reforming or coal gasification. Since the synthesis gas is obtained from methane it contributes to climate change and, on top of this, its production process is highly energy intensive.

The production of climate-neutral methanol is possible and could replace the production of methanol from natural gas or coal.

As a result, between 0.7 and 1.1 kilograms of CO_2 are produced per kilogram of methanol giving a global warming index of 0.7–1.1.

Today, small amounts of CO_2 are already used in the process of methanol production. The aim is to increase this proportion to 100 percent so that it can completely replace the synthesis gas and there will be no further need for fossil materials. To achieve this, a completely new process must be devised because the catalysts used today for the production of methanol from CO are not optimised for the conversion of gas mixtures with a high CO_2 content.

In a sustainable methanol economy, CO_2 would be regarded as part of a closed energy cycle rather than a climate-damaging end or waste product as it is at present. If methanol were produced with «green» hydrogen from renewable energy sources and by the efficient CO_2 taken from the air or from CO_2-rich emissions (such as from power plants or the cement industry), it would have a negative global warming index of −1.1 to −1.3[77], thus reducing the amount of CO_2 in the atmosphere.

Process variants exist, which differ in their boundary conditions. One is the electrocatalytic approach (cf. 3.3.1, p. 80). In addition, heterogeneous catalysis at medium pressures and temperatures (25 bar, 230 °C) and catalytic processes in a liquid phase will be discussed in this chapter.

Methanol from CO_2 is interesting as a means of long-term storage of electricity from renewable energy.

There are many catalysts capable of converting CO_2 into methanol. However, they do not use hydrogen efficiently and produce CO instead of the desired methanol.

The processes described here are new and challenging for industry since it has used natural gas as a raw material in methanol production up to now and has had little incentive to consider alternatives. Within the SCCER, the focus is on better understanding and optimising the catalysts and processes required for the reaction.

Research at the SCCER

Starting from the idea of using CO_2 as a raw material, research teams at EPFL and ETHZ investigated the basic principles of the catalytic processes involved in homogeneous and heterogeneous CO_2 reduction. The aim was to gain insights at the molecular level in order to improve the CO_2 conversion processes for industrial use.

One of the processes the EPFL team studied took place in the liquid phase, during which CO_2 is dissolved and reacts with a molecule, such as an amine. Subsequently, with the gradual addition of hydrogen, the conversion into methanol occurs, and the original amine is again generated.[78] The binding of CO_2 and the separation of methanol via an intermediate product can also be carried out with the aid of a homogeneous catalyst.[79] In both cases, the challenge is to separate the methanol and reuse the catalyst and/or the amine. The research group is now focusing its efforts on industrial feasibility; it has successfully produced the catalytically active compound in the form of a solid that can be easily separated from the liquid.

The research group at the ETHZ has investigated the hydrogenation of CO_2 to methanol using heterogeneous Cu-based catalysts at medium pressures and temperatures (25 bar, 230 °C). At present, most CO_2 hydrogenation catalysts for industrial methanol synthesis are based on Cu – usually $Cu/ZnO/Al_2O_3$. Despite more than 50 years of research, the roles of the different components are still a mystery.

In particular, under CO_2-rich reaction conditions, these catalysts are neither very active nor very stable. Moreover, in these conditions, they mainly produce CO and not methanol. However, alternative Cu-based catalysts have shown promising catalytic activities, which vary greatly depending on the catalyst composition (support and promoters).

Pursuing these findings further, the research team investigated the origin of the increased activity and selectivity of copper-based catalysts for CO_2 hydrogenation. Detailed spectroscopic studies allowed the research group to understand the role of the individual promoters at the molecular level and to develop guiding principles.[80] The interface between copper nanoparticles and the support, as well as the processes of alloy formation and deformation[81], proved to be decisive for the selective conversion of CO_2 to methanol.

Based on these findings, the team has developed improved catalysts that consist of copper nanoparticles and tailor-made support. Compared to the industrial catalysts $Cu/ZnO/Al_2O_3$, they exhibit a selectivity for methanol under mild conditions that has never been observed before.

Technical perspective

The SCCER research programme has helped to obtain detailed information on the performance of catalysts for methanol synthesis and to improve the selectivity of this process. In recognition of these achievements, the research group at ETHZ was awarded the «Air Liquide Research Award». Currently the team is developing a catalyst for the industrial production of methanol on the basis of these concepts.

Economic perspective

The production of climate-neutral methanol is possible and could replace the production of methanol from natural gas or coal. CO_2 hydrogenation can play an important role here, alongside other concepts such as the production of methane from hydrogen. Methanol from CO_2 would be interesting for the long-term storage of electricity from renewable sources: it is easier to store than hydrogen, it can be kept for a long time and be transported anywhere in tanks. Moreover, methanol is a versatile raw material for the chemical industry. The demand is enormous: with 63 million tonnes per year (as of 2013), methanol is one of the most-manufactured organic basic chemicals.

> Methanol can be transported in tanks to any destination and stored for a long time. It is also a versatile raw material for the chemical industry.

Industrial processing of methanol is already in operation in pilot plants in Iceland and Germany. The project presented here is largely basic research that helps to achieve a better understanding of the function of catalysts for CO_2 hydrogenation and the improved efficiency of such plants. However, given the low pricing of CO_2 emissions and the high cost of hydrogen from water electrolysis, there is still a lack of economic incentive for its use in industry.

3.3.3 Hydrogen storage with formic acid

Profile

Advantages

- long-term storage without loss
- high energy and power density -> compact storage
- liquid media can be easily pumped into and stored in tanks
- commercial product available as an uninterruptible power supply

Disadvantages

- desorption of hydrogen with water vapour and CO
- high investment costs
- large system dimensions compared to performance
- sustainably produced formic acid is not available yet on an industrial scale

Maturity of the technology

Technology readiness level (TRL):

- 9 for uninterruptible power supply

Milestones of SCCER

- development of catalysts without rare and expensive raw materials or additives
- construction of a complete module for uninterruptible power supply

Further research needs

- reduction in the system size
- sustainable production of formic acid from CO_2 and hydrogen

Significance for the Energy Strategy 2050

Hydrogen is the energy carrier of the future. It can be stored in various ways, for example in the form of hydrocarbons. A promising option here is formic acid, which allows easy refuelling and can be stored for a long time. It is therefore well suited as an energy source for an uninterruptible power supply for remote locations.

The storage of hydrogen is considered a key technology for the energy transition. This lightest of all chemical elements can be obtained from water by electrolysis. If electricity from renewable sources such as solar or wind power is used for this purpose, hydrogen is a climate-neutral energy carrier. It can be stored in tanks and oxidised catalytically, that is without a flame, to generate heat or, in fuel cells, electricity. Hydrogen can also be processed with CO_2 to produce natural gas or other chemical substances and burned, for example, for gas heating. Even this use is completely climate-neutral, provided that the energy used to produce the fuel comes from renewable electricity. The technologies required for this already exist, but they still need to be optimised in terms of efficiency and economy.

One important aspect is the storage of hydrogen. The light gas is usually forced under high pressure into tanks. This is both technically complex and requires a substantial amount of space. An alternative is to bind the hydrogen chemically with other elements, in the best case to form a liquid, so that it can be stored in tanks without pressure.

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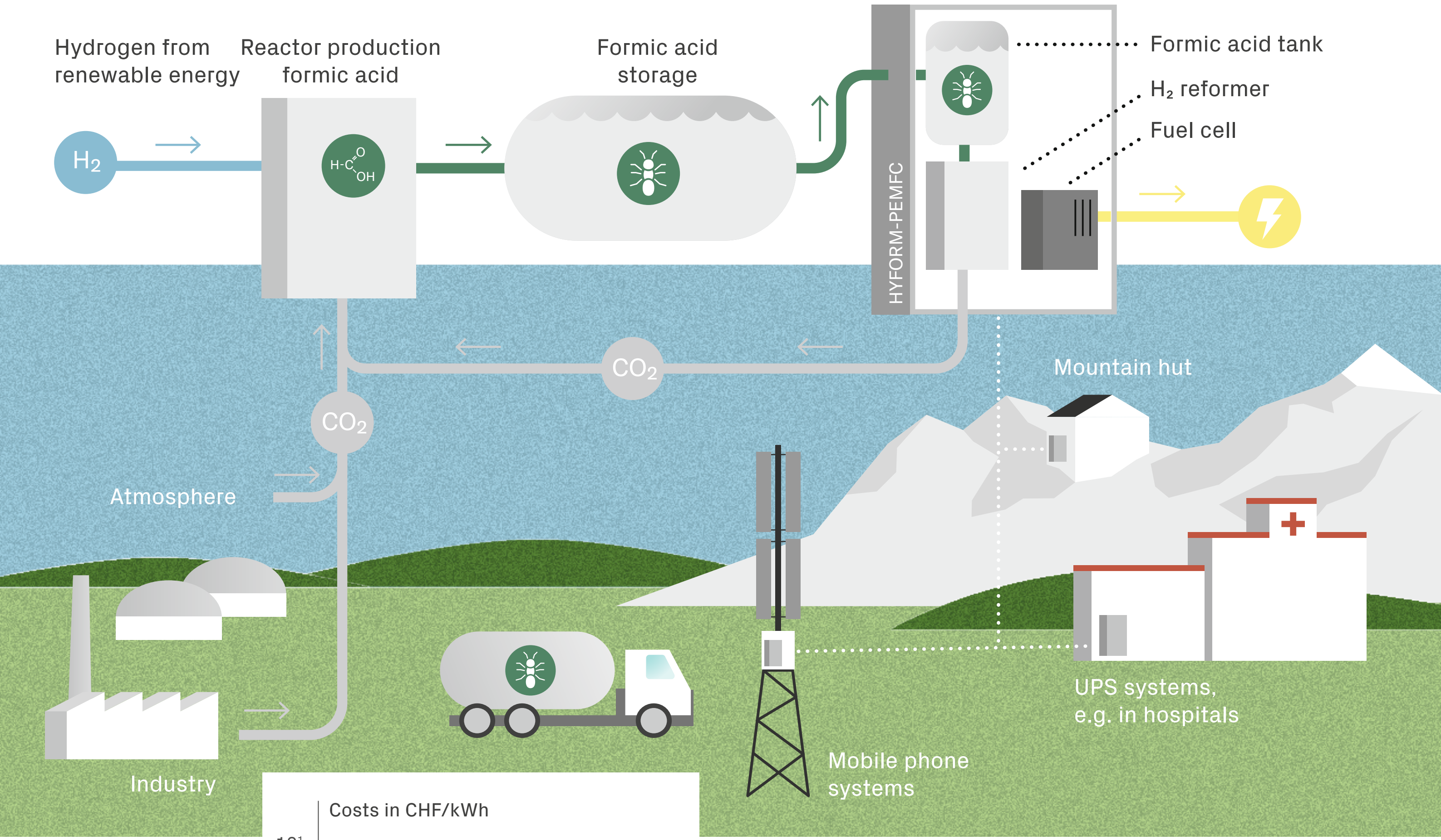
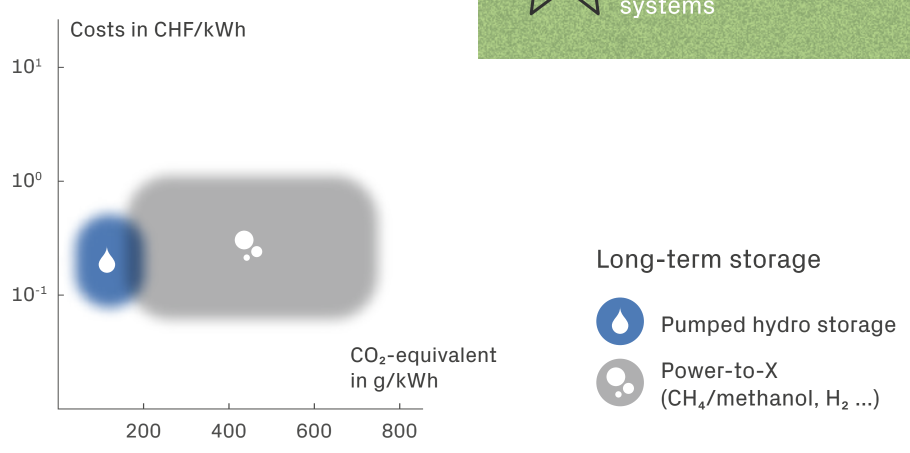
The principle of hydrogen storage with formic acid





Source: Modified from Abdon et al. (2017)[5].

Hydrogen storage with formic acid – operating principle

Since the late 1970s, researchers have considered formic acid for hydrogen storage.[82] This simplest of all carbon acids consists of one carbon atom, two oxygen and two hydrogen atoms (HCOOH). Formic acid, or methyl carboxylic acid, which is characterised by a pungent odour, is used in some cleaning agents for descaling and in various industrial processes. Every year around 720,000 tonnes (as of 2013) of formic acid are produced worldwide, mainly from methanol or as a by-product in other chemical processes.[83]

As a climate-neutral energy storage medium, formic acid is interesting because it can also be synthesised from carbon dioxide from the air and hydrogen. Formic acid contained in a stainless steel or plastic tank thus offers a good option for storing hydrogen. Whereas one litre of pure hydrogen, stored in a pressure tank at 200 bar, contains only 16 grams of hydrogen, one litre of formic acid contains, at four percent by weight, 53 grams, that is, more than three times as much. A relatively small container can therefore store large amounts of energy in liquid form at normal ambient temperatures, without pressure and without loss, over a period of years.[84]

In theory, formic acid is therefore an ideal hydrogen storage medium. After initial experiments the scientists were confronted with the following challenges:

- The yield of the chemical reaction which turns the two gases, carbon dioxide and hydrogen, into liquid formic acid, is low. A more successful approach is to bind the gases in a solvent and then convert them with the help of a catalyst. For a long time, it was unclear how a suitable process should be designed and, in addition, how this could be accomplished in an apparatus which was both compact and automated.
- If formic acid is broken down into carbon dioxide and hydrogen with a catalyst, some carbon monoxide (CO) and water are always released.[85] CO, however, inhibits the functioning of the fuel cell which is supposed to convert the hydrogen into electricity. Initially, no suitable catalysts were found to prevent the formation of CO.
- When researchers became increasingly interested in formic acid as a hydrogen storage medium, they initially used catalysts with rare and expensive metals such as ruthenium for the conversion. Since these were expensive, catalysts made from cheaper materials would be needed to make the process economically more interesting.

All these issues meant that formic acid was side-lined as a storage material for hydrogen. In 2008, however, formic acid experienced a renaissance.[86] Research groups around the world reported advances in catalysts made from low-cost materials, in process stability, in energy efficiency and in many other aspects such as additives that improve the formic acid production process. Nonetheless, these efforts did not bring the product any closer to mass production.

Research at the SCCER

In recent years, EPFL researchers have developed new and durable catalysts that do not require expensive rare raw materials or additives to separate hydrogen from formic acid. Together with an industrial partner (with funding from the SCCER and the Swiss Federal Office of Energy), they set up a system that is capable of converting formic acid into CO_2 and hydrogen with sufficient speed and purity. They presented the device called HYFORM-PEMFC to the public in 2018.[87]

This fridge-sized device contains everything it needs to generate electricity from formic acid. It has a tank for the formic acid and a compact reformer that produces enough hydrogen from the acid to power the 800-watt fuel cell, which in turn generates electricity from the hydrogen cleanly, safely and energy-efficiently. The patented apparatus is now in mass production[88] and serves as an uninterruptible power supply for remote locations where conventional alternatives are unsuitable.

Such a hydrogen storage system is only really sustainable, however, if the formic acid is also produced in a climate-neutral way. The research team has optimised catalysts and processes for this step as well. There is still a long way to go, but such systems could become commercially available in the course of this decade.

Apart from formic acid, the research team has long been working on methanol as a storage medium for hydrogen. This alcohol is also liquid and easy to store and has already been used as fuel for vehicles with fuel cells. Here, too, the researchers have developed more effective catalyst materials (cf. 3.3.4, p. 92).

Technical perspective

The HYFORM PEMFC represents a milestone on the way to achieving storage and power generation with hydrogen, but it is not the end of the road. The participating research groups and companies are working on further reducing the size of the apparatus needed for the chemical conversion of formic acid. One focus of future work will be to improve the production of formic acid from purely renewable sources using cost-effective catalyst materials that can be packed into a compact, automated apparatus. This would comprise an electrolyser to produce hydrogen using electricity from renewable sources and a reactor to produce formic acid from hydrogen and carbon dioxide.

Directly combining the production of formic acid with the above mentioned commercially available apparatus is, however, only practical in exceptional cases. For the short-term intermediate storage of electricity, the approach using formic acid is too costly. Alternatives such as batteries or the direct storage of pure hydrogen make more sense. Formic acid is of particular interest where an energy supply has to be kept ready for a long time - primarily in the case of uninterruptible power supplies. It is not necessary to produce formic acid on site. Rather, such systems can be supplied by tankers, as is currently the case with emergency power generators run on diesel. Future infrastructure will therefore provide for the production of formic acid with green electricity in large central plants with mobile supply of remote consumers.

Formic acid is interesting for long-term storage in remote locations.

Economic perspective

Whether and how quickly hydrogen technologies become established depends on many factors. In addition to the management of further technical improvements, the question of the economic viability of a hydrogen economy still remains.

If renewable energy is to gain a substantially increased share of energy supply, there will also be a greater need for storage facilities. Hydrogen is a promising option here, but not the only one. Other processes using hydrogen offer an alternative to the production and storage of formic acid. However, SCCER calculations regarding economic efficiency are encouraging. The business partner has calculated that electricity from the commercially available HYFORM-PEMFC is around 20 percent cheaper than from the battery of an electric vehicle; but the production costs of formic acid were not taken into account here.

For the storage of electrical energy with a rapid sequence of charging and discharging cycles, formic acid is uneconomical compared to battery storage.

However, formic acid is interesting for long-term storage in remote locations. There is great interest in this technology from telecommunications network operators. Some base stations in the German public safety radio communication systems are now equipped with uninterruptible power supplies which work with hydrogen-powered fuel cells.[89] For such applications, formic acid is the better alternative. It is cheaper than hydrogen, can be easily transported by truck and can be stored for as long as required.

3.3.4 Synthetic methane

Advantages
- climate-friendly compared to fossil natural gas if generated using renewable electricity no critical materials necessary for catalysts, etc.
- higher prices are accepted for renewable methane

Disadvantages
- further optimisation is necessary for catalysts and process management
- cost-effective sources of renewable CO_2 are limited renewable hydrogen from electrolysis is still expensive
- renewable electricity for electrolysis is essential if any advantage is to be achieved over fossil natural gas in terms of climate protection

Maturity of the technology
Technology readiness level (TRL):
- 5–9 for conventional methanation
- 6–7 for fluidised bed methanation
  for sub-processes:
- 9 for alkaline / PEM electrolysis
- 3–5 for high-temperature electrolysis

Milestones of SCCER
- new concepts for methanation with increased efficiency
- purification of methane
- optimised and automated control of entire plants
- development of new materials and measurement technology

Further research needs
- construction of 1 megawatt pilot plants
- coupling with high-temperature electrolysis on a large scale

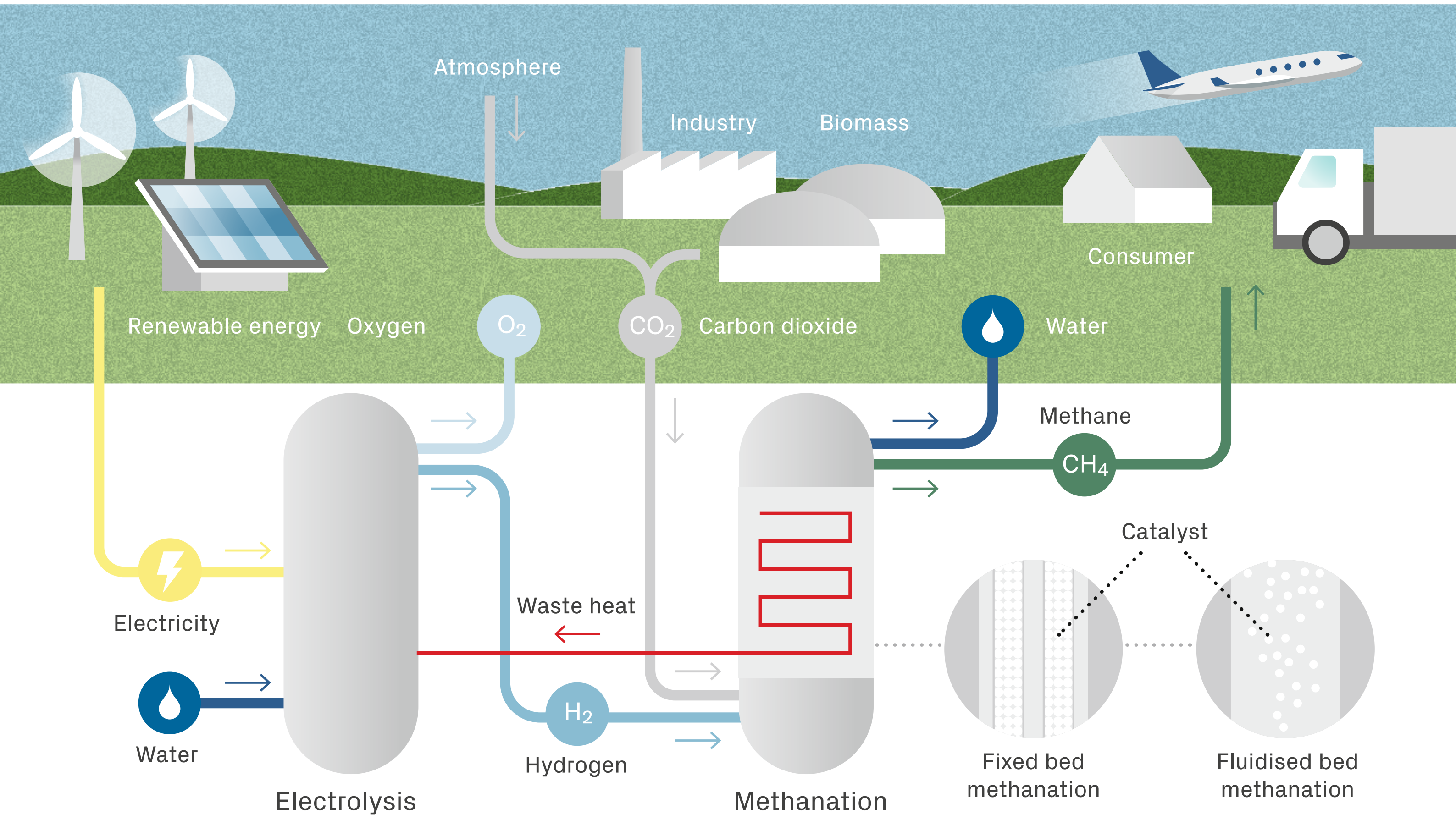
Significance for the Energy Strategy 2050
Fossil fuels have kept modern industry running for 200 years. They are used to heat buildings and run industrial processes, to generate electricity in thermal power stations, to produce combined heat and power in gas turbines, and, of course, for transport and mobility in vehicle engines. Since combustion produces a huge amount of CO_2, there is no future for such unrestrained consumption when taking climate change into consideration.
The demand from all consumers of fossil-fuel energy in Switzerland in 2018 was around 146 terawatt-hours. Transport accounted for the lion's share with 82 TWh, industry and services consumed 33 TWh, and households used 31.5 TWh.[90]

Methane (natural gas, biogas, CH_4) constitutes a large proportion of Switzerland's energy supply – equal to the proportion of Swiss hydropower in Switzerland's total energy consumption. Methane is used in many areas: for heating, to generate electricity, in vehicle engines and in industry.

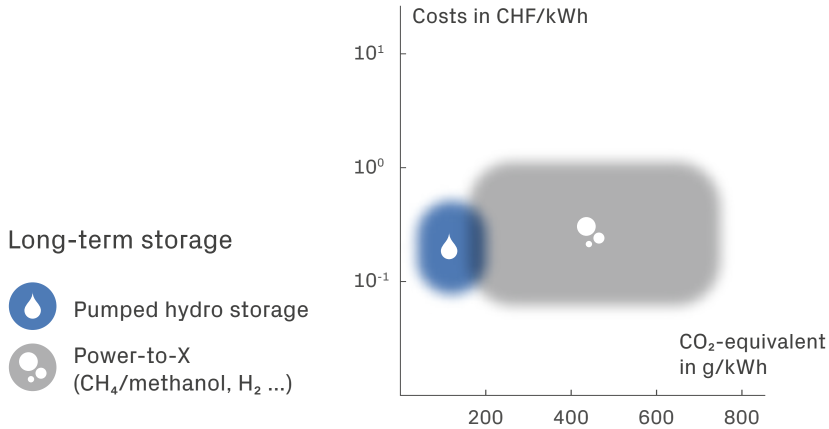
Predictions based on future modelling suggest that about 30 percent of road traffic mileage (7.4 TWh) could be covered by electromobility.[91] At the same time, the entire energy demand for heating and hot water in households, as well as for industry and services (46 TWh), could ideally be covered by electricity and seasonal heat storage. Even under these idealised assumptions, there still remains an energy requirement of about 93 TWh for applications such as heavy transport, air traffic or industry, which are still dependent on fuels such as methane, oil or hydrogen.

If renewable energy is used for methane production, synthetically produced methane makes possible the almost climate-neutral provision of energy for each of these applications. Additionally, synthetic methane can play a role in the storage and transfer of electrical energy in the short- and long-term, for example by making photovoltaic electricity generated in summer available in winter for heating or transport. Synthetic methane can therefore play a significant role in making Switzerland less dependent on imported natural gas.

The principle of methane from CO_2



Switzerland cannot do without methane in the medium term. But instead of extracting it from the earth's fossil fuel deposits, methane can also be produced artificially. The raw materials for this are water, CO_2 and electricity. If CO_2 is obtained from biomass, from the air or from industrial processes such as cement production, and if the electricity is generated from renewable energy sources, the methane produced is almost climate-neutral. If it is burned, the same amount of CO_2 is released as was previously used for its production. In the case of industrial processes, CO_2 emissions would be attributed to its main product, for example cement, and not to methane combustion.



Source: Modified from Abdon et al. [2017][5].

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Synthetic methane – operating principle

The various processes for producing synthetic methane have been known for decades. They could not become established, however, because fossil methane (natural gas) is so cheap. Methanation on a large scale only makes sense if a sufficient quantity of renewable electricity is available. This is increasingly the case, so the time has now come for synthetic methane to play a major role. It is an ideal storage medium for electricity harvested by volatile systems, in large quantities i. e. photovoltaic, on summer days. Instead of storing the electricity in batteries, it can be used to produce hydrogen and, in a further step, methane. This can be fed into the natural gas grid and, if required, can be used to generate electricity in combined heat and power plants and in gas turbines. Methane can also be used to refuel vehicles or provide heating for buildings. The production of methane using surplus electricity from renewable energy sources contributes significantly to reducing dependence on gas imports.

Instead of extracting methane from the earth's fossil fuel deposits, it can be produced artificially. The raw materials for this are water, CO_2 and electricity.

Research at the SCCER

Within the framework of the SCCER, researchers from the Eastern Switzerland University of Applied Sciences (OST), the Paul Scherrer Institute and the EPFL have investigated and improved numerous aspects of the production of synthetic methane with renewable electricity. Some of these are presented below.

Technical feasibility of methanation:
At the Werdhölzli sewage plant in Zurich, sewage sludge treatment produces, in addition to methane, large quantities of CO_2. At present, separating these two gases is costly. The PSI teams have been working at a mobile methanation plant on aspects such as gas purification, the activity and selectivity of the catalyst and also the catalyst's declining activity over time. The analysis shows a good potential for methanation.[92]

Increase in efficiency:
Waste heat recovery
Electricity-to-methane technologies have so far achieved an efficiency of just under 60 percent.[93] With a newly developed heat management system, the waste heat generated in the methanation process is used to support the steam supply, which assists the high-temperature electrolysis to produce the hydrogen required for methanation.

Multi-stage feeding of raw gases into the reactor
Conventional catalytic methanation requires water vapour in the reactor. Due to the multi-stage feed-in of raw gases, there is no need to supply steam, which reduces the energy demand of the process.

Together with the use of waste heat, the multistage process design increases the efficiency of the overall process by a fifth to around 75 percent. The process thus reduces the costs as well as the environmental impact of the methane produced.

Process improvement through new technologies:
Besides the main product of methane, methanation also produces water. To increase the methane yield, it makes sense to remove this water from the process. Together with ZHAW, OST has developed a catalyst system in which the catalyst's support material can directly absorb the produced water. Two catalyst beds are used in this process: while one is producing methane, the other is being dried with waste heat. The process control is then changed and the first bed is dried.

Extended service life of consumable materials
The nickel catalysts, which are used to generate methane gas from CO_2 and hydrogen, continuously lose activity because sulphur impurities present in the raw gas accumulate on them. In cooperation with the Zurich University of Applied Sciences (ZHAW), OST has developed sulphur-resistant catalysts with a longer service life.

The SCCER researchers achieved:
- complete automation of the demonstration plant in Rapperswil, deployed in an industrial environment
- development of smaller and cheaper gas sensors
- investigation of the hydrodynamic principles of fluidised bed methanation at PSI in a newly built pilot plant[94]
- investigation of the fundamentals of catalytic processes[95]

Technical perspective

The work carried out within the SCCER has shown that electricity-to-methane technology has the potential to replace fossil natural gas in the coming decades and thus make a significant contribution to the fight against climate change. As the demonstration plants at OST, PSI and EPFL in Sion show, all the necessary technologies are known. They must now be optimised and made ready for mass production. In the Sion demonstration plant, for example, methanation is run in combination with electricity generation from photovoltaics, batteries, hydrogen production and storage and the synthesis of methanol. The plant is designed to cover average energy consumption of a single person, based on the global average. The demonstration plant shows in particular how the components work together.[96]

To achieve market readiness, the SCCER researchers recommend the construction of a plant with a capacity of around one megawatt for each of the methanation technologies. In this way, the final hurdles to mass production can be overcome and full commercialisation achieved. New research questions will arise with each of the applications. It is therefore important to validate the findings from the demonstrators scientifically.

Electricity-to-methane technology has the potential to replace fossil natural gas in the coming decades and thus make a significant contribution to the fight against climate change.

A further research topic is the coupling of methanation with high-temperature electrolysis, in which the waste heat from methanation is used in the electrolyser. The electrolysis for the production of hydrogen remains the core issue for achieving higher efficiency and lower costs. Further efforts are needed in this area; they have been initiated within the SCCER and will be continued in future. Ultimately, companies will have to take on the task of scaling, automating and industrialising the SCCER technologies.

Economic perspective

The technology «electricity to methane» is not yet ready for the market. In Switzerland, synthetically produced gas is currently only available at a research facility in Rapperswil where a few interested parties can refuel their vehicles. The technical advances are primarily aimed at reducing costs.

The research teams have examined the costs of these technologies as part of their work within the SCCER. The cost price of synthetic methane is currently between CHF 170 and 250 per megawatt-hour, taking into account the higher calorific value of the gas.[97] In regions with low costs for natural gas/CO_2 and renewable electricity as well as proximity to the gas network, gas production costs of around 14 centimes per kilowatt-hour are possible in Switzerland. For the transport sector, this is already an economical price. Basically, however, the production costs for synthetic methane are two to three times higher than those for fossil natural gas. Since private customers in Switzerland are prepared to pay between 15 and 20 cents/kWh for biogas, they are the target customers for synthetic methane.

For further applications to become attractive, even greater cost reductions will be required. The most promising avenue is through lower costs for electrolysers used in the production of hydrogen. In the STORE&GO project, SCCER scientists have calculated the gas production costs for electricity-to-methane technology for the years 2019, 2030 and 2050. They assume that the cost price of synthetic gas will be more than halved by 2050[98], although they do not expect any major cost reductions in the methanation process itself. The greatest potential for cost reduction can be found in:

- lower costs of raw biogas/CO_2
- lower costs for renewable electricity without grid usage fees
- higher efficiency and lower costs for electrolysis
- proximity to the gas network

As with all other technologies for storing electricity, except for pumped hydro storage systems, all of the electricity consumed in electricity-to-methane plants is, according to current legislation, regarded as final consumption, meaning that grid usage fees have to be paid. This requirement is hindering the breakthrough of storage technology.

If such systems are used to support the grid, that is, to store electricity and generate it again later, the fees should be waived – provided they do not relate to conversion losses. If synthetic methane were also recognised as a climate-neutral fuel for road transport, this would give an additional boost to its economic viability. Automobile manufacturers could claim that by using synthetic methane, CO_2 emissions have been avoided and should be credited in the calculation of their fleet emissions.

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