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RESEARCH ARTICLE

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Possible role of power-to-heat and power-to-gas as flexible loads in German medium voltage networks

Abstract Germany's energy transition triggered a rapid and unilateral growth of renewable energy sources (RES) in the electricity sector. With increasing shares of intermittent RES, overcapacities during periods of strong wind and photovoltaic electricity generation occur. In the face of insufficient transmission capacities, due to an inhibited network extension, the electricity generation has to be curtailed. This curtailment of RES leads to economic losses and could be avoided through flexible loads. As an option to cope with those problems, the technologies of power-to-gas (PtG) and power-to-heat (PtH) are presented in this paper. First, the alkaline electrolyzer (AEL), polymer electrolyte membrane electrolyzer (PEMEL), and solid oxide electrolyzer cell (SOEC) are investigated regarding their operational parameters. Second, the electric boiler, electrode heating boiler, and heat pumps are considered. Ultimately, the network-supporting abilities and the potential to provide ancillary services, such as control power, load sequence operation, cold start and part load capability, are compared among one another.

Keywords power-to-gas, power-to-heat, flexible loads, ancillary services, coherent energy systems

1 Introduction

The German feed-in tariff system has triggered a rapid expansion of renewable energy sources (RES) in the energy system which, now, faces a delayed network extension. The insufficient network capacities cause increasing curtailment of RES electricity generation due to the periodically high solar and wind generation which comes along with insufficient storage and transmission options. Curtailment of capacities is conducted in case of transmission bottlenecks. In the event of transmission bottlenecks, the (*n*–1)-criterion is endangered according to the current generation schedule [1]. In 2014, the curtailment of RES excess generation in Germany, which was fully remunerated within the framework of a feed-in management measure, accumulated to 1581 GWh. In 2015, the curtailed excess generation, the so called "phantom power", exceeded 4722 GWh and, thus, almost tripled. The estimated costs for the curtailment of excess power in 2015 amounted to €478 million. Almost 93% of the total curtailment occurred on the distribution network level [2]. In 2016, the curtailed excess generation reached 1511 GWh, only during the first quarter of the year [3].

In this regard, the discussion about sector coupling and convergent energy systems is an in vogue topic among actors involved in the design of future energy systems. Indeed, it seems rational to leverage synergies between the sectors power, heat, mobility, and gas. In the face of increasing shares of intermittent RES, the issues of flexibility, reliability, and long-term storage capacity become of greater importance. Hence, new technologies such as power-to-gas (PtG) and power-to-heat (PtH) might be the only sound solution to secure energy security and reliability in energy systems with intermittent electricity generation. From the point of view of a transmission system operator, both technologies equally serve as flexible loads that are able to provide network services and to stabilize the system. However, the technical set-up is fundamentally different and the output of the technologies differs significantly. The products of the PtG process are gaseous which makes them easy to convert, store, and transport, whereas PtH produces heat that can be utilized in the heat sector.

To provide a secure and reliable power supply in future energy systems with shares of 80% RES and more, seasonal storage capacities become necessary to secure the reliable electricity supply over long periods of low RES generation. In Germany, those periods of low wind and solar radiation occur especially during the winter season

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when low wind speeds encounter low stratus. The so called “dark doldrums” may last for two weeks or even longer. The resulting lack of energy generation must be compensated by the seasonal storage capacity. The eligible large scale storage technologies are pumped-storage hydroelectricity (PSH) and PtG. Since PSH is limited by its technical potentials, PtG is the only technology to provide seasonal storage capacity in Germany.

In regard to the intermittent and non-dispatchable RES generation, flexibility represents the key factor in future energy systems with high shares of RES. In contrary to the traditional energy systems, where energy generation followed the demand side, now, load must be able to react to changes of the supply side. PtG and PtH are able to increase the electrical load of a system by increasing their operations during periods of high RES generation or to decrease the electrical load by decreasing their operation (assuming a permanent part load operation). According to the *German Energy Act* (EEG), the excess generation is curtailed, but simultaneously remunerated by the transmission system operators (TSO). Thus, enabling flexible loads to transform electricity into other energy forms, such as heat or gas, contributes to the performance of the entire energy system. Additionally, flexible loads can provide ancillary services to guarantee the operational reliability of the electricity network. According to the German distribution network operators, those ancillary services comprise the maintenance of the frequency stability, voltage stability, black start capability, and operations management. Therefore, the provisioning of control power as well as reactive power belongs to the ancillary services [4].

The German electricity system provides several marketing options and cost optimization potentials for flexible loads. Among the marketing options are the participation at the reserve market, the optimization at the spot market, and the marketing according to the ordinance on agreements concerning interruptible loads (AbLaV). Cost optimization potentials can be found in the minimization of network fees through atypical utilization and peak load reduction as well as in the balance group settlement through avoidance of balancing energy utilization [5].

2 Power-to-gas (PtG)

The PtG process links the power sector with the gas sector by converting excess electricity generation into gas via a two-step process. First, hydrogen (H_2) is produced by water electrolysis. Second, H_2 is converted with an external carbon-monoxide (CO) or carbon-dioxide (CO_2) source to methane (CH_4) via methanation. The resulting CH_4, known as substitute or synthetic natural gas (SNG), can be injected into the existing natural gas networks, used as compressed natural gas (CNG) motor fuel, or utilized in other natural gas applications, such as in the private households and the chemical industry. Alternatively, H_2 could be injected into the gas network or utilized in the sectors directly (see Fig. 1). However, the proportioning rate of H_2 is limited by the technical specifications of the facilities that are originally made for the utilization of natural gas and a separate hydrogen infrastructure had to be established [6]. In regard to the role of flexible loads in the electricity network, hereinafter the water electrolysis and its technical applications in the electricity network will be discussed. However, the understanding of the entire PtG cycle is important in order to comprehend the complexity of the technology.

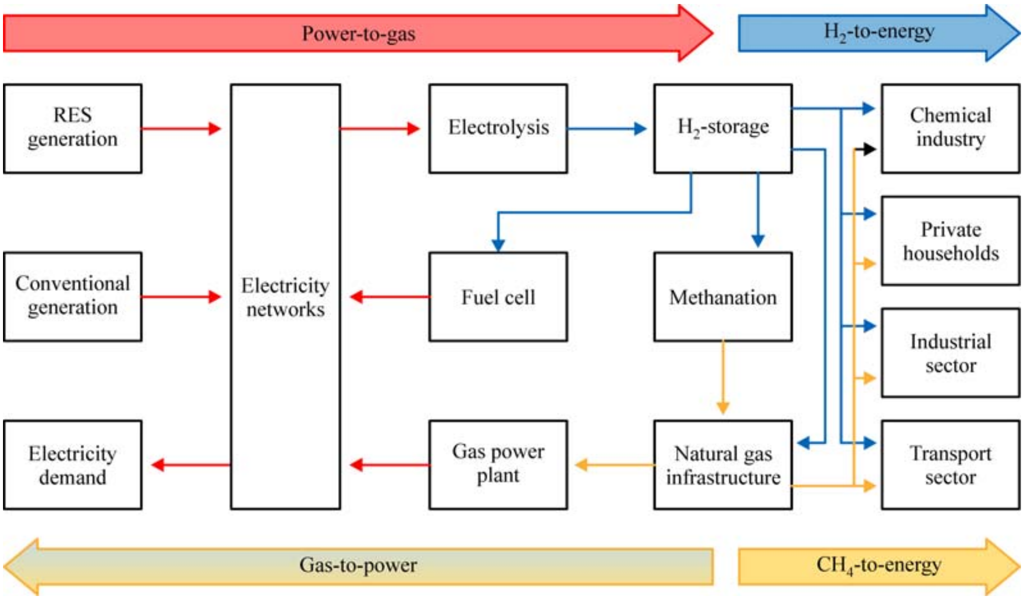

Fig. 1 Power-to-gas cycle

2.1 Water electrolysis

Electrolysis is an electro-chemical process that refers to the degradation of a liquid ion conductor, the so-called electrolyte, through an induced electrical current between two electrodes. In the particular case of water electrolysis, this liquid ion conductor is an aqueous solution. Since plain water is not an ideal electrical conductor, acid, base, or salt has to be added in order to increase the conductivity. Generally, electrolyzers have the following components in common [7]:

1) Power supply unit: transformer and AC/DC converter.

2) Atmospheric circulation at the oxygen compartment: water tank, circulation pump, heat exchanger, ion exchanger, stack, gas separator, aerosol filter, and oxygen outlet.

3) Pressure circulation at the hydrogen compartment: stack, water tank, and downstream gas treatment (aerosol filter, heat exchanger, cold trap for electroosmotic transported water, deoxidizer, dryer, hydrogen tank).

4) Monitoring and security system: optical, pressure, and temperature sensors as well as pneumatic valves for the water and gas flow regulation.

An electrolyzer consists of a cathode, the negative pole which deposits hydrogen in a reduction reaction, and an anode, the positive pole which deposits oxygen and anions (e^-) in an oxidation reaction. Figure 2 illustrates the basic principles of the electrolysis process in regards to the Hofmann voltameter [8].

The positive charged ions that are close to the negative charged electrode, the cathode, are attracted by the negative charge of the cathode. At the cathode, the ions are discharged in a cathodic reduction reaction that releases hydrogen. Simultaneously, negative charged electrons are extracted from the aqueous solution in an anodic oxidation reaction at the positive charged anode. Those oxidized water particles are instable and decay with release of oxygen. The remaining oxonium ion does not flow to the cathode as they rather transport their positive charge to the anode by redirecting their hydrogen bridges in a so-called proton conduction. During those reactions, gaseous hydrogen and oxygen ascend in the ratio of 2:1. Thereby, the anode section becomes acidic and the cathode section becomes alkaline. Once the necessary decomposition voltage is reached, the continuous electrolysis commences. After a short period, the reaction reaches the electro-chemical equilibrium and a constant current flow. Thereby, the electrolytic current has to overcome the electrical resistance of the aqueous solution. In case the applied voltage is below the decomposition voltage, the electro-chemical process stops [8].

The electrical and chemical processes along the phase boundary between electrode and electrolyte determine the speed of the process. Regarding the velocity of the electrochemical-process, the speed of the oxygen separation is determinative for the electrolysis. In case of high currents, the substance conversion at the electrodes is faster than the substance transport in the electrolyte and the

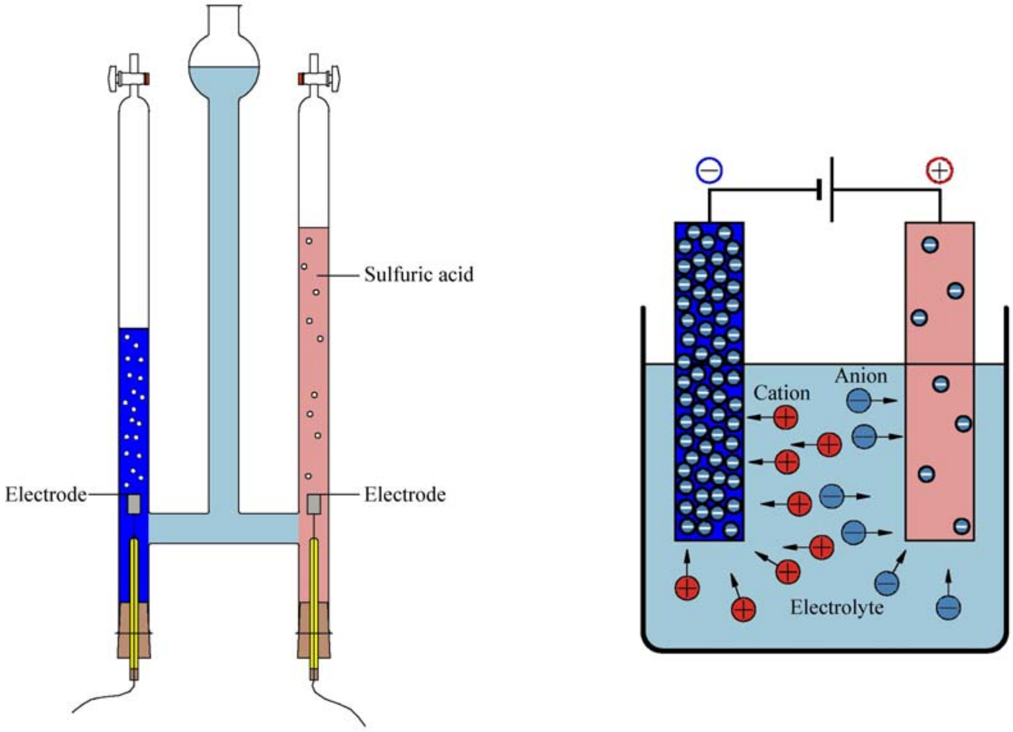

Fig. 2 Schematic drawing of a Hofmann voltameter and the electro-chemical reaction

diffusion-limited current is rising. Consequently, the diffusion-limited current restricts the maximum applied current [8]. Thus, the dimensioning, materials, and shaping as well as the properties of the electrolyte and the catalysts are of high interest for the operational behavior and power potential of such a device. A state of the art electrolyzer consists of a bipolar cell construction. The cell construction comprises the hydrogen compartment, anode, electrolyte matrix, cathode, oxygen compartment, and bipolar plate that form a repeatable unit (see Fig. 3) [7]. Advantages of this configuration are the vertical current flow induced by the large electrode cross-section. As a prevailing disadvantage, the weakest cell determines the performance of the entire stack [7].

The core component of a PtG unit is the water electrolyzer that can serve as a controllable and flexible load. Water electrolysis is a well understood technology with manifold applications. However, there are several different technologies for water electrolysis. The relevant technologies for PtG applications are the alkaline electrolyzer (AEL), polymer electrolyte membrane electrolyzer (PEMEL), and solid oxide electrolyzer cell (SOEC) [6].

2.2 AEL

Among the three types of PtG electrolysis technologies, the AEL is the most common and mature technology. AEL can be either operated atmospherically or under elevated pressure. Usually, an aqueous alkaline solution, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), is used as the electrolyte. A pressurized AEL possesses a lower efficiency and produces a product gas with a lower purity than the atmospheric AEL. Nevertheless, the efficiency loss of the pressurized electrolysis is lower than the efficiency loss caused by a downstream H_2 compression for further use or gas network injection [6]. An AEL possesses an operational range from 20% to 100% of its rated power. Additionally, it can overload up to 150% for a certain period [6]. An AEL with technical application operates at temperatures between 50°C and 80°C, pressures between 1 to 150 bar, current densities between 0.2 and 0.45 $A\cdot cm^{-2}$, and cell voltages between 1.8 and 2.4 V [7].

The broad operational window and the possible overload operation makes the AEL a good choice for the coupling with intermittent RES. Nonetheless, the restart times of 30–60 minutes after a shut-down are comparably long. Thus, continuous operation of the AEL is recommended. However, AEL cells and stacks can follow intermittent load changes instantaneously. Unfortunately, this ability does not apply for the gas processing and the peripheral components of the electrolyzer. Especially, the start-up, shut-down, and standby operations of the electrolyzer require temperature conditioning of the electrolyte as well as flushing of the system with nitrogen. In regard to network stabilizing measures, the reaction time of the AEL is significantly reduced. Moreover, frequent power interruptions enhance the degradation of the commonly utilized nickel anodes. Under industrial application circumstances, the AEL may reach a lifespan of 30 years, whereby the diaphragms, electrodes, and other cell components have to be overhauled after 5–10 years [7]. As a major drawback, those regular overhauls, due to the high corrosiveness of the electrolytes (e.g. alkaline solutions with 20%–30% KOH), increase the maintenance costs drastically [6].

2.3 PEMEL

A PEMEL is based on a solid polymer electrolyte that serves as electrolyte, catalyst carrier, and separator for the product gases. Typically, a PEMEL operates at current densities of 0.5–2.5 $A\cdot cm^{-2}$, cell voltages of 1.7–2.1 V, pressures of 1–200 bar, and temperatures of 50°C–79°C. The electro-chemical efficiency can reach 86%, whereby the ohmic voltage drop in the electrolyte remains comparably low. The performance limiting factors are rather found in the gas quality and the maximum power consumption of the auxiliary units [7]. At high pressures, a PEMEL can be operated at 5%–100% of the rated power with short overpower periods. The prevailing advantage over the AEL technology is the fast cold start, higher flexibility, and better interaction with dynamic and

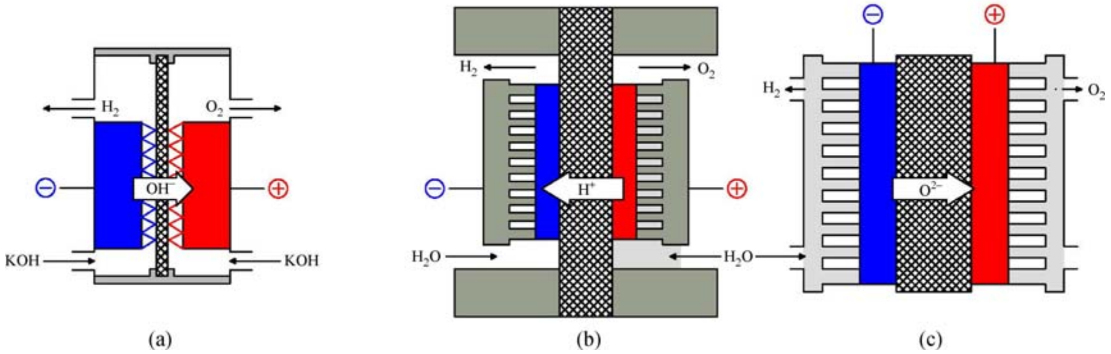

Fig. 3 AEL, PEMEL, and SOEC technologies
(a) Alkaline electrolysis; (b) polymer electrolyte membrane electrolysis; (c) high-temperature steam electrolysis

intermittent RES. Moreover, the product hydrogen has a high purity. Due to the costs for the membrane and noble metal catalysts, a PEMEL is more costly. Additionally, it has a reduced life expectancy [6].

Economically viable operations of the PEMEL are those at high pressures in order to facilitate the subsequent storage of hydrogen in combination with high production volumes due to the technical effort induced by the additional gas treatment and auxiliary units. The prevailing advantage of the PEMEL over the AEL technology is the high kinetic pace at the platinum catalysts that results in advantageous cell voltages and 4–10 times higher current densities. The PEMEL shows an excellent part load performance and is characterized by an instantaneous reaction on load fluctuations and good performances at low current densities. Moreover, the ramp-up times during a cold start and the cooling down times in the case of thermal overload are considerably low due to the low mass of the electrolyzer [7]. The reaction times of a state of the art PEMEL are quick enough to provide primary control power at the reserve market [9].

Proton exchange membranes are gas-permeable and can solubilize hydrogen as well as oxygen to a certain extent. At high current densities, the gas permeation to the other side increases drastically. Additionally, the mechanical stability decreases in combination with high system temperatures. The adjacent gas compartments and the electrically conductive but impermeable bipolar plates of the membrane-electrode-assembly (MEA) cells are separated from each other by the proton exchange membranes. Within the framework of the zero-gap technology, the catalysts are applied directly to the proton exchange membranes. The current collector and the supporter of the anode and cathode backsides between the MEA and the bipolar plate serve the electrical contacting, the evacuation of the product gases, and the resupply of water. As hydrogen and oxygen are not supposed to amalgamate, the bipolar plates have to be made of temperature, pressure, and chemical resistant as well as refractory metals, such as titan, tantalum, and niobium. Those metals are costly and prone to the formation of oxide layers that inhibit the current flow [7].

2.4 SOEC

The SOEC, also referred to as high-temperature electrolysis (HTE), is based on ceramic solid electrolytes that are able to resist the operation temperatures of about 800°C. At high temperatures, the solid electrolyte becomes an oxide-ion conductor. As a major distinction to the other electrolysis technologies, the electrolyzer is fed with overheated steam. The steam has to be purified (filtration, degasification, desalination) before entering the electrolyzer. Geothermal, solar, and nuclear waste heat may serve as the source for the SOEC. In contrast to the AEL and PEMEL, the SOEC technology consists of a power supply unit with a transformer and an AC/DC converter, an outlet at the oxygen compartment, and pressure circulation at the hydrogen compartment (water supply, heat exchanger, stack, and gas separator membrane) [7].

The design of the SOEC can be either planar or tube-like. Either way, the cathode gas consists of hydrogen and the remainder of water vapor, whereas the anode gas is made of plain oxygen that can be utilized without any separation and purification. The planar design has advantageous current densities but may cause sealing problems, whereas the tube-like design is easily sealable but does not reach as high current densities in comparison to the planar design. The thermal expansion coefficients of the electrode material and the electrolyte should be similar in order to avoid mechanical strain during temperature changes. Over the course of the operation time, the performance of the SOEC reduces drastically due to material wear-off. Thereby, the electrodes dissolve from the solid electrolyte and degrade due to the migration of chrome, manganese, and silicon. Simultaneously, the electrolyte changes its structure and conductivity. Moreover, the reaction on load changes of the SOEC is only limited and it has long heat-up phases. Especially quick load changes and repeated on/off changes are critical for the operation of the SOEC in combination with intermittent RES. The resulting current heat causes temperature gradients and thermal stresses that may lead to micro cracks in the electrolyzer materials. Thus, the temperature conditioning during the switch-on and shut-down phases has to take place with moderate pace. Additionally, the temperature should not fall less than 600°C during stand-by phases as the ramp up time will increase disproportionately. Consequently, the SOEC technology has only restricted application for the compensation of load changes of intermittent RES [7].

The high temperature of the SOEC process reduces the equilibrium cell voltage and, therefore, the electricity demand. The comparably low electricity demand is the prevailing advantage of the SOEC technology. Theoretically, efficiencies above 100% could be reached in an endothermic mode. The prevailing disadvantages of the SOEC technology are the fast material degradation and the restricted long term stability due to the high operation temperatures. The instability against fluctuating and intermittent power sources makes the technology unsuitable for power systems with high shares of intermittent RES [6].

3 PtH

PtH refers to the conversion of electricity to heat. In order to be able to satisfy the heat demand of a system with high flexibility and independency of the situation at the electricity exchange, PtH units are usually integrated into a bivalent heat generator system. Thus, the PtH unit is not the only heat source in a system. It rather serves as an additional electricity consumer to utilize excess electricity of the RES that, otherwise, could not be consumed or has to be curtailed [10].

PtH units can be distinguished between heating rods and cartridges on the decentralized low temperature level and electric boiler and electrode heating boiler on the large-scale industrial level. On the industrial level, process steam with 30 bar and 230°C can be produced through electrode heating boilers. Subsequent electric flow heaters are able to increase the temperature further to, theoretically, serve the entire spectrum of industrial process steam applications. On the low temperature level, heat pumps are another technological option for PtH that come along with significant efficiency increases [10].

3.1 Electric boiler and electrode heating boiler

Similar to heating cartridges and rods, electric boiler systems are based on the heating of the storage and transport medium water through electricity and resistance heating in a heating element (see Fig. 4(a)) [11]. An electric boiler can be integrated into the hot water and steam production. The power classes of those systems usually range from 0.1 to 15 MW. The electrode heating boiler works according to the direct resistance heating principle. In this set-up, the water is passed through by a current flowing from the electrodes to the boiler housing and, thus, is heated up (see Fig. 4(b)) [11]. The technology requires treated water which has an electrical conductivity of 0.001–0.005 $S \cdot m^{-1}$. Typical power ranges can be found between 1 and 90 MW. The electrode heating boiler technology has already been integrated in the district heating systems of some German public utilities [11].

Basically, the availability of a PtH storage system is not necessary. However, a storage system can increase the economic efficiency and provide more flexibility which also supports the operation of the PtH units on the electricity network side. At this stage, the reaction times of the PtH allow a participation in the secondary and tertiary reserve markets. The participation in the primary reserve market is still limited due to technical restrictions [10].

The present PtH projects in Germany are largely conducted in the area of district heating. The combination of PtH with district heating systems has numerous advantages due to the connection power of the already existing heat generators and the reduced network charges of the superimposed network levels of the district heating generators. In combination with the integration into the optimized operation and marketing processes of the already existing district heating systems, economical and administrative potentials can be easily exploited. In many cases, heat storages are readily available [10].

The first pilot projects of PtH are implemented in the field of industrial applications. Due to the variety and individuality of industrial applications, such as temperature levels, heat load profiles, legal restrictions, electricity purchasing conditions, and special regulations, the technical design of industrial PtH units and their economic efficiencies are rather individual. However, the usually continuous heat demand of industrial processes serves as a positive condition for the integration of PtH units. On the

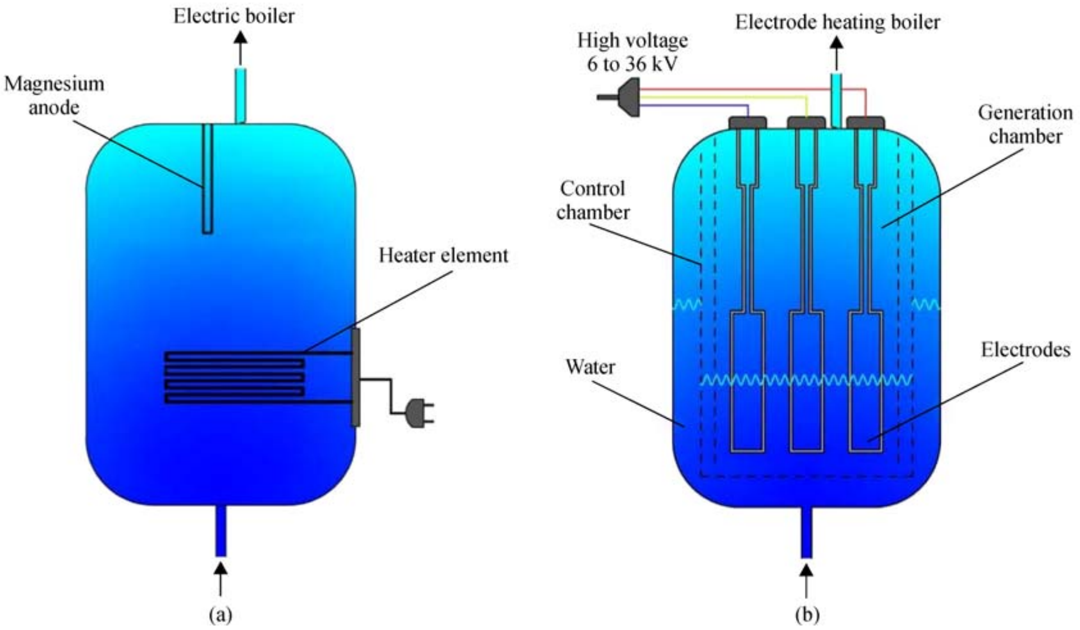

Fig. 4 Electric boiler (a) and electrode heating boiler (b)

other hand, the limited capacity and high prices of high temperature heat storages can be an inhibiting factor for the utilization of PtH in industrial processes. Regarding the potential of industrial PtH integration, it has to be distinguished between industries that generate process heat with combined heat and power (CHP) and those who generate process heat without CHP. Industries with CHP and relatively high electricity costs are less inclined to substitute CHP with PtH, whereas industries without CHP and low prices for the purchase of electricity have higher tendencies to integrate PtH [10].

PtH applications for small- and middle-scale power classes comprise heating cartridges for the heat storages of micro CHP units as well as to upgrade hot water and buffer storages with heating rods. Those upgrades come along with increased investment costs for the registered performance measurement as alternative for the standard load profile consumption measurement and costs for the information and communication technology, customer services as well as accounting and billing. Moreover, the integration of PtH on the subordinated network levels incorporates increased network charges [10].

3.2 Heat pumps

Heat pumps work according to the reverse Carnot cycle (see Fig. 5). Thereby, heat is extracted from the environment, elevated to a higher temperature level through compression, and, then, converted into useable heat. The reversal of this process can also be used for cooling purposes. The heat pump system consists of the heat source, the heat pump, and the heat distribution system (heat sink). First, the heat transfer medium in the probe is heated up by the heat source, such as air, ground water, or soil. Through a vaporizer, the collected heat is transferred to the refrigerant of the heat pump. Subsequently, the liquid refrigerant is heated up and vaporized. The resulting gas is compressed to increase the temperature level further. After the accumulated heat of the refrigerant passes the heat exchanger to the heat distribution system, the refrigerant condenses. The condensed refrigerant passes the expansion valve and the pressure is reduced to the initial level [12].

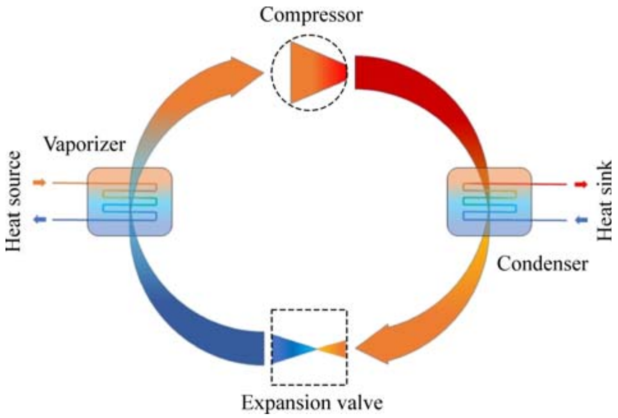

Fig. 5 Reverse Carnot cycle of a heat pump

Within certain time spans, heat pumps can be controlled according to the electricity network needs without any loss of comfort. In combination with area heating systems, which serve as heat storages, the heat pump can be shutdown for up to two hours. Due to this flexibility, heat pumps can operate at the reserve markets as well as in part load and load sequence operation. In most cases, the decentral and low-scale heat pumps of the housing sector can be pooled and organized in virtual power plants. Therefore, they are especially suitable to support the network control in subordinate network levels [13]. To achieve the highest efficiency, heat pumps are operated continuously are not coined by sudden load changes due to their operational scheme. Therefore, the negative load shifting potential is very stable around the clock [14]. Additionally, the ambient temperature can be increased by up to 0.5°C in the case of excess electricity generation. Consequently, electricity driven heat pumps with buffer storages can support the load shifting, optimize the unit commitment, and minimize the curtailment of RES [12].

4 Flexible loads and ancillary services

Currently, the reserve market, even though it possesses only a marginal market volume, is the most beneficial market for flexible loads. Here, prequalified PtG/PtH units can offer primary, secondary, and tertiary control power according to their technical specifications. The provision of secondary negative control power is more attractive than the provision of tertiary control power. However, the legal and technical barriers are higher and the access to the tertiary market is easier [10].

The German reserve market comprises primary, secondary, and tertiary control power. Primary control power is a symmetrical product and has to be offered simultaneously as positive and negative control power for prescribed time slices. Secondary and tertiary control power can be offered either as negative or as positive control power for the specific time slice [15]. Hence, flexible loads that are offered at the primary reserve market have to be operated at part load in order to be able to provide positive and negative primary control power at any time during the committed time slice.

At the spot market, the economic efficiency of flexible loads is very much correlated to the conditions of the individual electricity purchase of the market agents. Those conditions determine the due payment of the electricity price. Additionally, the electricity price components EEG surcharge, network charges, electricity tax, and other levies must be incorporated. In most cases, the participation of flexible loads at the spot market is only reasonable at strong negative spot market prices [10].

A cost-based redispatch system enables a relatively efficient handling of network bottlenecks on the transmission network level. As an alternative to the curtailment of wind energy converter, flexible loads could be activated and feed the excess electricity into other energy sectors. This effect is even stronger when electricity excess generation comes along with a high fuel demand in those sectors. In most cases, PtG/PtH can achieve higher efficiency gains during the winter months [10].

Excess electricity can have two different initial reasons. Either the electricity generation is superior to the demand or a local network insufficiency leads to a bottleneck. In case the increased RES generation is forecasted, the market will react with low or negative prices at the spot market. If the excess electricity is not anticipated, control power has to be called. A bottleneck in the transmission or distribution networks can be balanced by feed-in management measures. Feed-in management measures, such as curtailment and redispatch, are meant to avoid a destabilization of the electricity network. More than 95% of those feed-in management measures are aimed at electricity generators on the distribution network level. Therefore, the integration of flexible loads on the distribution network level can reduce the frequency of those measures and relieve strain on the transmission networks [16].

PtG and PtH units have the ability to support the electricity network operation. Depending on their technical specifications, they are also eligible to provide selected ancillary services (see Table 1). Those services comprise the provisioning of negative control power and the support of the operations management. Among the three presented electrolyzer technologies for PtG, the PEMEL seems to be the most appropriate for the provisioning of ancillary services as the technology is characterized by fast reaction times, a broad operational power range as well as quick start-up and shut-down times. Moreover, it has a stable standby operation. In regard to those characteristics, the PEMEL is technically qualified to provide primary, secondary, and tertiary control power.

Regarding the provisioning of ancillary services, the PtG and PtH technologies have the ability to provide control power in accordance to their individual technical specifications. Moreover, they are able to support the operation management by increasing the electricity demand in the role of a flexible load. Therefore, both technologies, if integrated in the distribution network levels, have the ability to decrease the electricity network extension or, at least, to compensate temporal and spatial gaps of the network extension. Thereby, the integration of those flexible loads with sufficient capacity near the electricity generation units facilitates the operation of all superimposed network levels. Since 95% of the RES generation units are integrated in the distribution network level, an increased market penetration of flexible loads can disburden the transmission network, especially during peak generation times. However, PtH and PtG (in the set-up of a stand-by load) cannot provide additional system services, such as reactive power, positive control power, and black start capability. In case the flexible loads are operated at part load, they can provide control power (some technologies even primary control) in both directions. However, such a set-up would increase the electricity base load.

4.1 PtG and ancillary services

The coupling of PtG units with storage systems and power plants capable of reconverting the PtG products hydrogen or methane assume greater importance in power systems with increasing shares of intermittent RES. Those combined systems are capable of storing electricity in chemical storages during times of peak generation and providing energy during times of generation scarcity. Moreover, the storages can be designed as mobile devices or the natural gas network itself might be utilized as a storage. Thus, such a system is able to decouple generation and demand temporally as well as spatially [7].

Table 1 Comparison of the PtG and PtH technologies

Performance	AEL	PEMEL	SOEC	Electric boiler	Heat pump
Primary control power	x[1)]	x[1)]	x[1)]		
Secondary control power	x	x	x	x	x
Tertiary control power	x	x	x	x	x
Cold start capability	Medium	High	Low	High	High
Part load capability	Low	High	Medium	High	High
Load sequence operation	Medium	High	Medium	High	High
Scaling up	High	Low	Medium	High	Medium
Efficiency	Medium	Medium	High	High	High
Costs	Low	High	Medium	Low	Medium
Life time	Medium	Medium	Low	High	High
Complexity	Medium	High	High	Low	Medium

Note: 1)–technically possible at permanent part load operation.

PtG has the ability to relieve the electricity network and to reduce the need for network extensions. PtG units can be dimensioned and scaled according to the individual and local needs of the network. Consequently, PtG can temporally delay network extension projects and avoid inefficiency due to demand driven single measures. Moreover, curtailment of excess generation due to forecasting errors can be avoided through the storage of the excess energy within a balancing group [17]. Hence, PtG has the capability of peak shaving and to reduce the demand for balancing energy.

AEL are able to follow load changes quickly but their operational flexibility is limited by the peripheral equipment. Also, the comparably long start-up times after a shutdown restrict the intermittent operation of AEL in systems with rapid load changes. The operational power range is not as flexible as that of the PEMEL technology.

Despite the favorable efficiency of the SOEC, the operational parameters do not ease the operation of those electrolyzers in power systems with intermittent RES. Due to material instability and the subsequent moderate temperature conditioning, the start-up and shut-down phases are rigid and, therefore, not eligible for quick operational changes. Moreover, the minimum temperature should not fall less than 600°C during stand-by phases as the ramp up time will increase disproportionately. Hence, the temperature has to be kept at high levels in order to enable a rapid respond time to load changes in the network.

Looking at PtG as a fully integrated system with reconversion of gas-to-power (GtP) (e.g. in combination with a conventional gas power plant), a PtG/GtP system can provide positive control power and all other system services necessary to stabilize the electricity network similar to the characteristics of a gas power plant. Especially, the transport and storage ability of PtG systems that is integrated into the natural gas networks, has system supporting abilities as it can temporally and spatially decouple intermittent generation and demand of electricity and transfer the energy from the electricity sector to other sectors. Similarly to the PtH systems, the PtG operation is also restricted by its storage capacity. Here it must be differentiated between power-to-hydrogen (PtH_2) and power-to-synthetic natural gas (PtSNG) systems. The PtH_2 systems are limited by the capacity of the storage tanks or the local proportioning rate of H_2 in the natural gas network (1%–12%). In case of a downstream methanation in a PtSNG process, the operation is theoretically only limited by the capacities of the natural gas networks. However, those networks have seasonal operation conditions and the capacities might be restricted during certain periods.

4.2 PtH and ancillary services

All technologies available for PtH applications possess quick start-up and shut-down times and, thus, are eligible to operate at the reserve markets. Moreover, excess electricity can be converted into heat by comparably cheap and easily available technologies. The ramp-up times and load change rates of PtH units are very low and the respond time to changes in the network is short. Hence, the PtH units are technically eligible to operate at the secondary reserve market. The provision of additional load by those units is, theoretically, unlimited as long as there is a corresponding heat sink. The general advantages of PtH units are the option to market capacity at the reserve market, the high efficiency of the conversion of electricity to heat, and the bivalent design of those heating systems that imposes some redundancy on the system. Industries that possess high process energy demand, such as the food, chemical, and pulp and paper industry, can especially profit from those advantages when they are able to procure electricity at low costs. The utilization of PtH can be reasonable to cope with regional bottlenecks in the electricity network.

The prevailing limiting factor for the application of PtH is the necessity of an appropriate heat sink, preferably in the vicinity of the RES generators. Unfortunately, the heat demand varies over the course of the year and some PtH capacities may not be available in summers due to reduced operating and recall times. Moreover, there is only little correlation between wind generation and heat demand. In middle Europe, low wind speeds occur mostly during very cold days (continental high pressure weather conditions) and during times of high wind speeds the temperatures are moderate (maritime low pressure weather conditions). Thus, the possible heat generation due to excess energy of RES does not always encounter an appropriate demand. In dependence on the outdoor temperature, usually only a limited amount of the maximum rated power is available. Moreover, the appropriate heat sink should be in direct vicinity of the electricity generation source [18]. Additional drawbacks are the unfavorable CO_2 balance if the electricity is not generated by RES, the comparably high costs in comparison to heat generation based on fossil fuels, and the additional investment costs [11].

5 Conclusions

One of the key challenges for future energy systems with high shares of RES is the balancing of periods with high and fluctuating RES generation that encounter comparably low load in the electricity network. Hereby, the networks have to be able to transport the excess electricity to the superimposed network level. Basically, the generation of minor amounts of electricity on the subsidiary network levels eases the network operation as the demand on those levels can be met by the local generation. In case the generation exceeds the local demand, the excess electricity has to be transported across all network levels to the transmission network and, thus, burdens the entire network. In those cases, flexible loads on the medium voltage level, such as PtG and PtH, are able to reduce the amount of excess electricity generation and to ease the network operation. According to the individual technical specifications and the operational mode of the PtG and PtH technologies, flexible loads are able to provide primary, secondary, and tertiary control power. Thus, they support the frequency stability. Moreover, flexible loads contribute to the voltage stability on the distribution network level through load sequence operation. Therefore, the additional flexibility in the network can avoid transmission bottlenecks and curtailment of RES generation during times of high generation and low load.

Regarding the PtG technologies, dimensioning, materials, and shaping as well as the properties of the electrolytes and the catalysts are the most influential factors for the operational behavior and power potential. Here, especially the chemical reaction speed is predominantly determining the potential of PtG units in the electricity network. Moreover, the wear-off and the costs of the utilized materials are critical factors for the performance of PtG units. Among the individual PtG technologies, the PEMEL seems to be the first choice regarding the optimization of the network operation, as it is coined by rapid start-up and shut-down times as well as a great part load range. Especially, the pressurized operation of the PEMEL supports its integration into the gas network as it can be operated without an additional compressor. In comparison, the AEL does not possess the flexibility range of the PEMEL technology and, therefore, is restricted in its ability to ease the network operation. Its prevailing advantage is the maturity and the low costs of the technology. The SOEC technology with its extraordinary efficiency might be a good solution for niche applications where high temperature steam sources are available. The rapid wear-off is still a cost intensive disadvantage. Both presented PtH technologies are technically mature and show similar features. However, the electrical boiler system is rather suited for industrial applications, whereas the heat pumps can be operated in decentralized, small-scale systems such as households. Here, they possess excellent efficiencies and can be pooled in a so-called virtual power plant to participate at the reserve market. PtH technologies are characterized by both, excellent part load behavior and rapid respond times. The inertia of the more or less rigid heat systems supports the flexible operation of PtH technologies.

Theoretically, a vast and fully integrated PtG and PtH system could reduce and postpone the network extension, but not make the extension redundant. However, such a system requires a significant amount of heat and gas sinks that are readily available around the clock and across the year to be economically worthwhile. Additionally, those sinks should be in the vicinity of the RES generation units to be able to reduce the strain on the electricity network. Prevailing restrictions for the integration of flexible loads are the additional costs and complexity that are imposed on the system. However, the resulting coupling of the heat, gas, mobility, and electricity sectors contributes to a decarbonization of those sectors that are currently predominantly based on fossil fuels. In systems with high shares of RES, the PtG technology has significant advantages as it has the ability to electro-chemically store vast amounts of energy over long periods if integrated into the natural gas network. On the other hand, PtH is a less sophisticated and comparably cheap technology that can be integrated into the system in the short and medium term. Compared to PtG, PtH can only integrate the heat sector and is dependent on the divergent heat demands of the winter and summer season. Regarding the provisioning of ancillary services in the electricity network, PtG and PtH are able to provide control power and to support the network operation. In order to provide positive control power, the flexible loads must be operated at part load during the times of provisioning. Nevertheless, flexible loads cannot provide essential ancillary services, such as reactive power and black start capability. For the economic integration of flexible loads into the electricity network, the future development of the frequencies and costs of feed-in management measures, such as curtailment and redispatch, as well as the decreased costs for a reduced network extension could serve as an economical benchmark. Since some of the flexible load technologies, such as the PEMEL, are rather new developments, economies of scale and improvements in the material science can reduce future costs of those technologies. The enhanced utilization of flexible loads in the sense of sector coupling is supposed to increase the total electricity demand significantly due to the substitution of other energy carriers.

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