Anhang zum Schriftenreihe-Bericht 4/2022: Sondierung des wesentlichen F&E-Bedarfs zur Optimierung von städtischen Energiespeichern in integrierten Energiesystemen (CityStore)

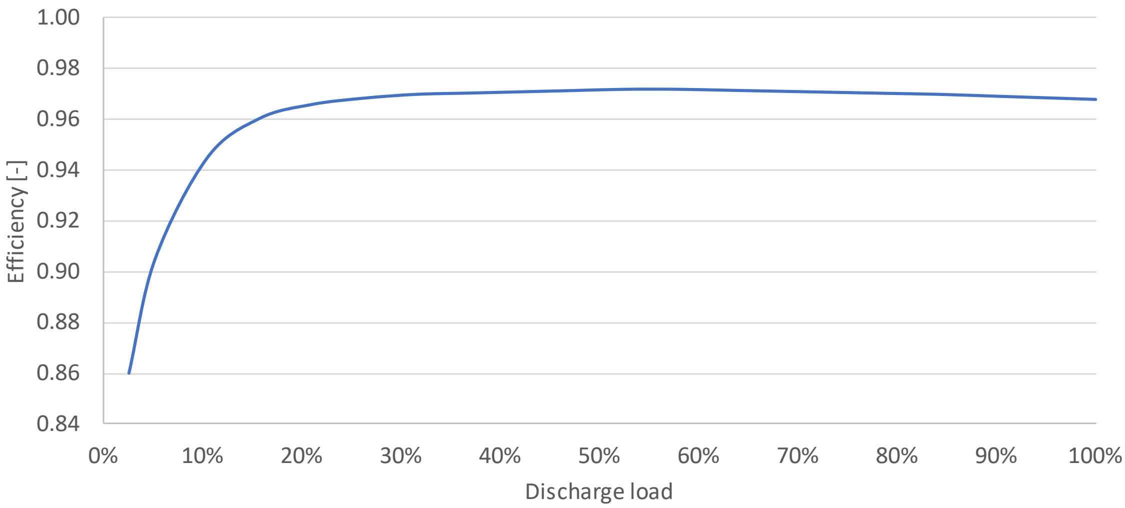
1.1. Technology description

1.1.1. Lithium-Ion (Li-Ion) Battery

A Li-Ion Battery System is an energy storage system based on electrochemical charge/discharge reactions that occur between a cathode, that contains some lithiated metal oxide, and an anode that is made of carbon material or intercalation compounds. The electrodes are separated by porous polymeric materials which allow for electron and ionic flow between each other and are immersed in an electrolyte that is made up of lithium salts, e.g. $LiPF_6$, dissolved in organic liquids. When the battery is being charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge (EASE, 2020).

The battery is fully discharged when nearly all the lithium ions have left the negative electrode and reacted with the positive electrode. If the battery is discharged beyond this point the electrodes chemistry becomes unstable and starts degrading. Overcharging, or prolonged storage at high state of charge (SOC) also accelerates degradation (DEA, 2020). In addition, self-discharge rates make storage periods of several months unfeasible, standby operation adds parasitic losses and unwanted chemical reactions degrades the Li-Ion Battery. These aspects call for shorter storage periods to obtain enough cycles (between a few thousands up to some ten-thousands) to reach positive revenue. In this sense, Li-Ion batteries have been deployed to provide frequency response with response time ranging from seconds to minutes (Research Interfaces, 2020) or time shifting with typical storage periods of a few hours (Shimpe Michael *et al.*, 2018).

Abbildung 1: Variation of the discharge effciency as a function of the part load to AC (own assessment based on (J. Weniger et al., 2020))



Future Li-Ion Battery improvements will be an increased energy density, cycle, and calendar life. Building up industrial capacity for mass production of industrial size cells and batteries (driven by automotive, energy storage and other mass markets) is poised to reduce system costs (EASE, 2020). Due to their high scalability and flexibility in power and energy, Li-Ion batteries are used in a large variety of applications (DEA, 2020):

- Peak load shaving to reduce peaks in a power system.
- Renewable integration, e.g. time or load shifting of photovoltaic power from day to night.
- They can be used to provide transmission congestion relief to reduce the load in the transmission and distribution system helping defer expensive upgrades of the transmission and distribution networks.
- They can provide primary control provisions such as frequency regulation.
- Improvement of network reliability by reacting immediately after a contingency for example by maintaining stability in the power system until the operator has re-dispatched generation or supporting black-starting distribution grids.
- Enhancing the power quality and reducing voltage deviations in distribution networks.
- Provide spinning reserves and regulate active and reactive power thereby improving the network voltage profile.

1.1.2. Flow Batteries

Flow batteries are rechargeable batteries which use two electrolytes – one with positive charge and one with negative charge. These electrolytes are stored in separate tanks and get pumped into the battery when required. An ion-selective membrane separates both electrolytes. This membrane selects during charging and discharging process the ions to pass and complete chemical reactions (EASE, 2020).

The existing design variants are based on two parameters. The first one is redox couples (e.g. vanadium, Zn-Br or polysulphide-bromide (PSB)). The second one is the battery system size where large system are designed in a modular structure. This allows group together several sub-stacks and gives redundancy and reliability (EASE, 2020).

In this technology power and energy ratings are fully decoupled. Meanwhile, power rate is defined by the active surface of the membrane and the hydraulic pumps management. Energy capability is linked to the volume of electrolytes and the capacity of the tanks. Therefore, the energy storage capacity can be increased by simply utilising larger storage tanks for the electrolytes (M.N. Nandanwar *et al.*, 2020).

Flow batteries have additional advantages, for example, operating at ambient temperature in contrast with other grid scale applications such as molten sodium batteries (Na-S and Na-NiCl2), reactions are in a solution which allows the user using the full energy storage capacity without battery degradation in contrast to batteries based on solid state. They have unlimited cycle lifetime within the technical lifetime (up to 20 years), the electrolytes can easily be recycled and reused (M. Guarnieri *et al.*, 2016; M. Manahan *et al.*, 2016). These batteries use the same active specie (e.g. vanadium) in both anolyte and catholyte. Leakage of reactants from one electrolyte into the storage container of the other electrolyte does not imply an electrolyte contamination generating, only a loss of energy storage capacity. This can be re-established by re-balancing the volume and active specie of the two electrolyte solutions (DEA, 2020).

However, flow batteries have relatively low grid-to-grid energy efficiencies in comparison to other batteries. This is because mechanical pumping losses, undesired shunt currents and leakage of reactant through the reaction cell membrane (DEA, 2020).

Finally, flow batteries are in the demonstration and early commercialisation phase. In Europe, flow battery research focuses on both, small and large devices, especially for developing cost-effective new membranes and increasing the power density of the cell. However, there is increasing competition from non-European companies and the world leaders in terms of installed capacity are in Asia (EP, 2015).

1.1.3. Sodium-Ion (Na-Ion) batteries

Na-Ion batteries are an energy storage system based on electrochemical charge/discharge reactions. The component parts and the working principle for Na-Ion batteries are similar to Li-Ion batteries. In this technology, Na^+ ions migrate between a positive electrode (cathode) composed of sodium-containing layered materials, and a negative electrode (anode) that is usually made of hard carbons or intercalation compounds (Y. You and A. Manthiram, 2017). The electrodes are separated by a porous material to allow ionic flow between them. They are immersed in an electrolyte that can be either an aqueous solution (e.g. Na2SO4 solution) or a non-aqueous solution (e.g. salts in propylene carbonate). When the battery is being charged, Na atoms in the cathode release electrons to the external circuit. They become Na^+ ions which migrate through the electrolyte toward the anode, where they are combined with electrons from the external circuit. During the discharge, this process is reversed (EASE, 2020).

Na-ion batteries are an attractive alternative to Li-Ion batteries as Na is an abundant resource, not only in the earth´s crust, also in seawater and has much lower costs. Na-Ion batteries can benefit from some developments made for the Li-Ion systems, can use a cheaper electrolyte (e.g. aqueous solution) and cheaper Al current collectors (W. Zhang *et al.*, 2019). In addition, Na-based components offer opportunities to obtain faster kinetics with the electrochemical reaction, for example, they may enable a high Na^+ conductivity in bulk solid within a wide temperature range and an easier charge transfer owing to less pronounced solvation (Y. You and A. Manthiram, 2017). However, Na cannot be simply swapped with Li used in the current battery materials, as it has a larger ion size and slightly different chemistry (W. Zhang *et al.*, 2019)..

The Na-Ion batteries are still in developmental phase. For Na-Ion batteries the key is to improve energy density to achieve a lower cost of stored energy over. These costs must be under 0,09 €/kWh which implies a Na-Ion battery with cycle life larger than 5.000 cycles and capital cost lower than 275€ of usable kWh installed. To achieve this objective the following development is expected (EASE, 2020):

- Improvement of negative and positive electrode materials
- Improved conductivity of electrolytes at room temperature
- Better Na-Ion electrochemical systems
- Large Na-Ion systems for bulk storage
- Validation of Na-Ion technology on large scale storage
- Applications in demonstration projects
- Improved manufacturing process

1.1.4. Pump Hydro Storage (PHS)

PHS stores electrical energy by utilizing the potential energy of water. It consists of two water reservoirs, tunnels that convey water from one reservoir to another, a reversible pump-turbine, a motor-generator, transformers and transmission connection (EASE, 2020). These systems need high investments and long construction times. However, it is possible to reduce them by extending an existing hydro plant which than can also be used as PHSs (DEA, 2020).

It is a flexible technology which takes advantage of low demand electricity periods and high available electricity, for example from vRES. During this period the water is pumped and stored in an upper reservoir. Then, during the periods with high demand and higher prices, the stored energy can be released generating electricity by a water turbine (typically Francis or Pelton (VOITH, 2020)) in a short reaction time. This allows this technology to reduce the gap between peak and off-peak periods and it can be used to stabilize the power grid. The primary intent of PHS is to provide peaking energy each day. However, it can be expanded to include ancillary services, such as frequency regulation (EASE, 2020).

PHS are highly dependent on local geography. Enough height between the two reservoirs and a high space to store the water are needed. In addition, when a new PHS is not built in connection with an existing hydropower plant there are also environmental concerns in flooding large areas (DEA, 2020).

Underground hydro pump storage (UPHS) is similar to (PHS) but predominately located under the ground. It can be either newly built, use caverns or re-used abandoned mines. There are currently no large size UPHS in operation, but it could be one of the most cost-effective large-scale storage technologies. As example, in 2006, in South-Korea, a two-stage UPHS project was presented with an exploitable head of 1500 m and 1000 MW of installed capacity. Recently, a replicable methodology was applied to calculate the UPHS potential as well as the financial feasibility for Italian territory. In this study reservoirs currently used for hydropower, irrigation, water supply and industrial use, are evaluated to be a possible part of the system. In this study, locations suitable for the construction of new underground spiral shape gallery reservoirs were selected according to their lithological characteristics (J. Alterach *et al.*, 2016). In parallel, the excavation technology has also made large progress with development of Tunnel Boring Machines (TBM). TBM are currently extensively experienced, mainly for rail roads and tunnels, but could easily be adopted to build a spiral underground reservoir. The already developed shields allowing simultaneously excavation and installation of the final coating with precast concrete segments can push forward the development of UPHS (A.A. Podvysotski and A.A. Borodulin, 2015).

UPHS has similar potential than PHS to contribute to the integration of vRES, high cycle efficiency, capacity to deliver large power over long periods, long life-time and it does not require high surface topographic gradients and offers the possibility of exploiting existing cavities. However, there are still several remaining challenges such as a lack of regulatory framework, dynamical stress behavior of rock masses, fluid-mechanical and chemical properties of mine water (N. Uddin and M. Asce, 2003; J. Alterach *et al.*, 2016).

1.1.5. Small-scale water tanks

Hot water energy storage is a mature, cheap and well proven technology used at large scale in Europe and all over the world (DEA, 2020). A heating device produces hot water outside or inside an insulated tank where it is stored for a short period of time (a couple of days maximum). The stored energy depends on water temperature and on the tank volume (EASE, 2020).

The use of solar energy and heat pumps (HP) is more and more employed to produce hot water with a high efficiency. Other energy sources like electricity, gas, heating oil or wood are applicable. In general terms, this technology has no local environmental impact.

The performance of the storage tank and the thermal losses in time depend highly on the insulation of the tank and on the flowrate of hot water. When the heated water is used for room heating (hot water between 55 °C and 65 °C), the flowrate depends on the outdoor temperature. When the heated water is used for sanitary water heating (between 60 °C and 70°C), the flow rate depends on the amount of water being tapped per time unit.

Small-scale thermal storages can enable shifting the thermal load storage taking advantages of the cheaper electricity prices during off-peak hours. Reshaping the load curve improves the utility's capacity factor of the equipment and its financial health. Although, the capacity of this thermal storage is small, the overall installed capacity can be very large due to the high number of installations. This could be used as flexibility option to absorb electricity peak production from vRES such as wind power or photovoltaic (EASE, 2020).

Nevertheless, this technology has some disadvantages such as a comparably large environmental footprint, partly due to insulation or risk of legionella bacteria inside the tank. It is also possible that the high return temperatures produced in district heating systems increases energy losses.

Research focuses on the development of small-scale thermal storage with high storage density and reduced losses to increase solar heat share in households. In this sense, Austrian research institute AEE INTEC has recently inaugurated a pilot research facility where two low-pressure vessels filled with 750 kg of zeolite beads or spheres each are tested (Helen Oy, 2018).

1.1.6. Ice Storage

There are three components of a glycol-based ice storage system that differ from a conventional chilled-water system: the ice storage tank, the ice-making chiller, and a heat-transfer fluid.

A static tank is the most common type of ice-storage. It is a closed vessel where the ice serves only as a medium to store thermal energy. This tank has a heat exchanger to freeze water during one part of the day, and then melt the ice during another part of the day. This heat exchanger is typically constructed of steel, polyethylene or polypropylene tubes that are connected to a common header. In this system, the water from the melting ice does not leave the tank. In a static tank, the effectiveness of heat transfer varies throughout the freezing process. In a first step, water freezes on the outer surface of the heat-exchanger tubes, then continues to freeze outward. At the beginning of the freezing process, ice is very thin on the outer surface having a low impact on the heat transfer. Nevertheless, the heat transfer is reduced when the ice becomes thicker. To maintain the same freezing rate with a degrading heat transfer, the temperature of the fluid entering the ice storage tank must decrease near the end of the freezing process.

The same chiller that is used to cool the building can also be used to make ice. The dual roles of an ice-making chiller can substantially reduce the installation cost of the system. However, an ice-making chiller operates at maximum capacity when in ice-making mode, until all the water inside the ice storage tanks has been frozen.

Ice storage systems require a heat-transfer fluid that remains liquid at temperatures below the freezing point of water. Typically, the heat-transfer fluid is a mixture of water and antifreeze and the most common antifreezes option in a glycol-based ice storage system are ethylene glycol and propylene glycol.

Adding ice storage to an HVAC (Heating, ventilation and Air Conditioning) system can shift the operation of the chiller from high-cost electricity periods to low-cost electricity periods. This implies, that the ice storage systems can reduce utility costs by melting ice to satisfy building cooling loads during the on-peak period. This avoids, or significantly reduces, the electricity cost required to operate the chiller during that time frame. The operation of the chiller is shifted to the off-peak period when electricity costs are lower and the buildings cooling demand is lower or non-existent. The chiller is used during that period to freeze the water storing the thermal energy until the on-peak period.

A “full-storage system”, takes places when building cooling loads that occur during the on-peak period are satisfied by melting the stored ice, and the chiller is turned off. However, the installed cost of a full-storage system may not be feasible. Normally, ice storage systems have only enough capacity to satisfy a portion of the on-peak cooling loads. This type of system is named “partial-storage system”. In this case, the cooling loads during the on-peak period are satisfied by melting ice and operating the chiller. The chiller operates at a reduced capacity consuming less energy. Cooling loads greater than the capacity provided by the chiller are satisfied by melting the stored ice (TRANE, 2012).

1.1.7. Active building envelope (ABE)

ABEs consist of two panes, separated by an air gap, which may contain a shading device. Air or Water passes through the cavity, driven by either natural or mechanical means. ABEs contribute to energy efficiency as well as providing a 'high-tech' image for a building. Moreover, they have good acoustical performance, can be used in conjunction with naturally driven ventilation systems and should enhance the thermal comfort of occupants (International Energy Agency, 2003).

Air and water are commonly used fluids for thermal storage and transfer, from this perspective, ABEs could be categorized into the following classes (Y. Luo *et al.*, 2019):

Air-based active building envelopes: An air layer-based envelope has higher thermal resistance and the movement of the air facilitates to remove the thermal energy excess. The hot air passes through the air layer in building envelopes increases effectively indoor thermal comfort in winter and prevent heat loss (G.A. Florides *et al.*, 2002). It is possible to take advantage of solar energy which can be incorporated into the design of air-based heating wall systems. As for the air-based active cooling envelope systems, the natural cold sources from relatively low air temperature at night and underground are effective channels (P. Barton, C.B. Beggs, and P.A. Sleigh, 2002). The thermoelectric cooling device is suitable to be integrated into cooling facades due to silence operation, easier control and fast cooling speed (D. Zhao and G. Tan, 2014). Other conventional HVAC techniques like absorption or evaporative chillers can also be integrated into glazing facades (Y. Luo *et al.*, 2019).

Water-based active building envelopes: In some cases, water can improve system efficiency due to the higher heat transfer capability and larger thermal capacity. The basic component of active pipe-embedded wall are water pipes, which must be durable and have a good thermal conductivity. In addition, the pipe installation must be reliable and leak resistant, and require minimal maintenance (X. Xu *et al.*, 2010). In this pipe-embedded envelope system, high temperature cool water and low temperature hot water is used respectively in summer and winter to reduce or eliminate the cooling/heating load of the building envelope. This system can use several devices for cooling or heating such as cooling towers, air source heat pumps, solar thermal energy, ground water and ground heat sources (Y. Luo *et al.*, 2019). In active pipe-embedded wall systems, only energy input for water pumps or fan power is needed for the delivery of cool or heated water. In cooling tower involved systems (C. Shen and X. Li, 2016), water is either cooled through total heat exchange in open system or through sensible heat exchange in a closed system. The efficiency of the former type depends on the wet-bulb temperature of the ambient air and the latter one on dry-bulb temperature of air. This distinctive difference determines that open cooling tower involved active walls can be more efficient. However, cooling tower, heat pump or solar collector integrated active wall systems are confronted with the limitation of application and operation in the cooling season to provide usable cool water. This problem can be solved by using geothermal energy (Romaní, Pérez and de Gracia, 2017). Because the temperature of ground soil and water usually can be maintained around a stable level which is a natural cooling source in summer and heating source in winter. This can safely ensure the operation of pipe-embedded wall throughout the year (Y. Luo *et al.*, 2019).

1.1.8. Large-scale water tanks

Steel tanks are used as short-term storages in connection with thermal and CHP plants in district heating systems to support operation and reduce emissions (J. de Wit, 2007). The installed capacity for small district heating applications ranges from 500 to 5.000 m^3 but this capacity can be scaled up to 50.000 m^3 in case of large district heating applications (EVN, 2008). These tanks can store hot water with a maximum temperature of 95°C. In case the tank is pressurized the temperatures can achieve levels around 100-120°C (DEA, 2020). These tanks are covered with a layer of 300-450 mm of insulation material and heat losses are influenced by the size and height/diameter factor. For example, it is estimated that a large-scale water tank of 500 m^3 with a factor of 1.8 has heat losses of 2.1% per week. Meanwhile the losses for a volume of 5.000 m^3 are reduced to 1% per week at 90°C water temperature and 0°C outside temperature (DEA, 2020).

The typical storage period depends on the heat demand and varies from a few hours to around two weeks. This allows for large-scale water tanks being used to cover peak demands by, for example, charging the tank at night and along the day to cover morning and evening peaks. In small district energy systems, these water tanks can be used for seasonal storage. Moreover, steel tanks with a capacity up to 10.000 m^3 are the most cost-effective option compared to small-scale pit heat storages (DEA, 2020).

Large-scale water tanks can increase short-term flexibility of operation in district heating plants and can in some cases keep the pressure in district heating systems. It is a cost-effective heat storage solution because of water being the most cost-effective storage medium for thermal energy storage at low (0 - 20°C) to medium (20 - 100°C) temperature. Another advantage is their low investment cost. Nevertheless, they have some negative aspects such as large space requirements, energy losses, the use of N2 or steam against corrosion, influence on the surrounding landscape and risk of leakage.

Large scale water tanks can be divided into pressurized and atmospheric water tanks based on working pressure.

Pressurized large-water tanks (maximum working temperature 160°C (C. Hofer, 2018)) are mainly used in combination with high temperature district heating. When water temperature is larger than 100 °C, the pipeline pressure must be higher than the saturation pressure to avoid evaporation. This is also applicable to thermal energy storages to avoid evaporation at the top of the system. District heating systems which work with superheated water are quite widespread specially in large district heating systems. Usually, pressurized thermal energy storages are directly connected to the district heating network where storage and pipeline operates at the same pressure level. In this case, pressurized thermal energy storages can also operate as a pressurization vessel. This is an essential component in district heating networks, particularly when the regulation is performed by varying the supply temperature which produces changes in specific volume. In case of direct connection, the installation of a dedicated pressurized vessel can be avoided by exploiting the thermal energy storage. In terms of control mechanisms, the pressured thermal energy storage configuration is simpler with respect to the atmospheric thermal energy storage. However, the maximum temperature span that can be accepted between cold and hot resources is 50–55°C because of thermal tensioning in the tank (E. Guelpa and V. Verda, 2019). However, pressure thermal energy storages are more expensive than atmospheric ones. Decisive for this are the higher pressures. An overpressure of 6 bar is given as the threshold for economy. At higher required pressures, the investment costs for pressurized accumulators rise sharply because of the wall thicknesses and steel requirements. A part of the technical criteria for determining the storage size, space requirements and existing infrastructure also play an important role (R. Geyer *et al.*, 2017).

Atmospheric thermal energy storages are mainly used in combination with low temperature district heating. This means when maximum temperature in the storage does not exceed 100 °C and the temperature gap does not exceed 30-40 °C. Atmospheric thermal energy storages are connected indirectly to the district heating network because of the pressure differences respect to the pipeline. In this case, pumps and valves assure the correct pressure difference between the pipeline and the atmospheric thermal energy storages. In addition, this type of thermal energy storage should be preferred when the number of hours of operation is limited because of the lower investment cost (E. Guelpa and V. Verda, 2019). In addition, the grade of stratification inside the heat storage tank limits the amount of heat which can be discharged at the required supply temperature level. This makes a good understanding of the main factors for a proper stratification necessary (A. Herwig, L. Umbreit, and K. Rühling, 2018). Atmospheric thermal storage tanks can be divided into two sub-categories: *one-zone heat storage tanks* and *two-zone heat storage tanks*.

Stander one-zone atmospheric heat storage tanks (maximum working temperature 98°C (C. Hofer, 2018)) are built as pressure-less standing steel cylinders with one radial diffuser at the bottom and another one at the top. These heat storage tanks are optimized for capacities of up to several 10,000 m^3. During the charging process, warm water is entering the tank through the top radial diffuser and cold water is leaving through the bottom radial diffuser. The discharging process is done in the opposite way. When charging and discharging temperatures are well-defined through thermal stratification. A layer of high temperature above a layer of lower temperature is formed, with a thermocline in between. The grade of stratification inside the heat storage tank limits the amount of heat which can be discharged at the required supply temperature level (A. Herwig, L. Umbreit, and K. Rühling, 2018).

The atmospheric two-zone heat storage tank (maximum working temperature 130°C (C. Hofer, 2018)) has the same design features as the one-zone atmospheric heat storage tank, but it is divided into two zones by an insulated intermediated floor. Each storage zone has two radial diffusers for charging and discharging. A vertical compensation pipe is used as hydraulic connection between the upper and lower storage zone. This allows for compensating the density changes of the lower storage zone during charging and discharging and safeguard against negative pressure or overpressure in the lower zone. The hydraulic coupling of both storage zones allows that the pressure level in the lower storage zone is sufficiently high to store water at temperatures above 100°C. This implies that the volume-specific heat capacity of the two-zone heat storage tank is higher compared to a one-zone heat storage tank of the same size. This means that the higher total investment costs can be compensated with respect to the amount of stored energy. However, the exchange of fluid between the two storage zones can negatively influence the thermal stratification in a storage zone (A. Herwig, L. Umbreit, and K. Rühling, 2018).

Additional R&D of large steel tanks is necessary to improve energy performance and flexibility. These developments include improvements at the operation at lower temperatures and temperature differences in district heating grids, the use of large-scale steel storage for cooling purpose and should take advantage of the water stratification (DEA, 2020).

1.1.9. Seasonal heat storages: ATES - Aquifer Thermal Energy Storages

ATES is an open-loop energy storage system which consists of tube wells in one or more pairs that pump groundwater to extract or store thermal energy. This systems are scalable from single houses to district or regional scale (DEA, 2020).

Buildings are cooled during summer seasons using the groundwater from the cold well. Heat is transferred from the building to the cold groundwater rising groundwater temperature from around 5-8°C to 14–20°C. Then, this hot water is stored in the warm well and is used for heating during winter seasons. In case that free cooling is not possible, a heat pump can be used as a back-up to cool down the groundwater of the cold well. When heat is requested in autumn or winter the pumping direction and heat transfer process can be reversed extracting groundwater from the warm well. In this case, a heat pump needs to boost the groundwater to around 40°C which is the necessary temperature to heat the buildings. The heat is transfer from the groundwater to the building and the cold water is stored in the cold well (M. Bloemendal, M. Jaxa-Rozen, and T. Olsthoorn, 2018).

ATES system is the shallow geothermal technology with the highest energy efficiency. However, this technology strongly relies on the aquifer properties and working conditions of the system. In case that ATES is working as cold storage system the efficiency can range from 70 to 100%. Nevertheless, in the case that the systems are working as heat storage (which includes injection, storage, and recovery of heated water) the efficiency is lower, ranging from 50 to 80%. Integrated or combined heat and cold ATES may offer an improved efficiency over cold-only or heat-only storage systems, particularly in large-scale applications (C.R. Matos, J.F. Carneiro, and P.P. Silva, 2019).

ATES systems has a high influence on the temperature in the aquifer because of the extraction of large volumes of groundwater. In these systems, thermal energy is lost at the boundary of the stored temperature volume. This is only noticed at the end of the wells' extraction period of the following season. In addition, the interaction between wells at the boundary of their temperature fields could affect the ATES efficiency due to the risk of thermal coupling (S. Haehnlein, P. Bayer, and P. Blum, 2010).

ATES has several advantages such as low investments and operational costs, small physical footprint, scalability, flexible application, and high storage capacity in each borehole-pair. On the other hand, this technology has certain difficulties such as risk of thermal short circuit of ground water, low storage temperatures to around 20°C, direct use of ground water in aquifer which could contaminate or have geological implications. Furthermore heating the aquifers to more than 20°C could produce bacterial growth (DEA, 2020).

1.1.10. Seasonal heat storages: BTES – Borehole Thermal Energy Storages

BTES is a closed-loop system that stores thermal energy in the bedrock using borehole heat exchangers (sometimes more than 100 wells) in combination with heat pumps. This technology allows to extract heat from a building during the summer, or via solar panels, and then reuse it during the winter season. BTESs are characterized by requiring a relatively small area of land as the surface can be used for other purposes and they operate in a temperature range from 0°C to 30°C but they can also be used for storing higher temperatures (up to 90°C). The efficiency of a BTES can reach up to 40%. Nevertheless, the efficiency can rise to 90% or 100% when operated around the average natural temperature of the ground. A condition would be that there is no strong natural groundwater flow (C.R. Matos, J.F. Carneiro, and P.P. Silva, 2019).

Therefore, BTES have several advantages such as relatively small space, very limited visual impact, expandability, limited risk of leakages and long lifetime. On the other hand, there are some difficulties such as ground conditions to allow for possible seasonal storage, risk of higher investment costs and heat loss due to ground water flow and the need of heat pumps to boost water to required suitable temperature levels (DEA, 2020).

BTES systems can be integrated with district heating networks. In these cases, it is frequently to increase the temperature of the subsurface area to a significantly higher level (> 40 °C). Although, these type of systems have similar schemes in spite that they can differ regarding to size (approximately 10000–60000 m3), borehole spacing (2–4 m), drilling depth (30–65 m), and operational temperature range (45–60 °C). This configuration can be linked to solar thermal systems. In this case, solar energy is used to increase BTES temperature to higher levels than the undisturbed soil temperature. Then, during winter season, the thermal energy stored in the BTES is extracted by circulating cold water through the borehole field. Normally, one or several short-term thermal storage tanks are used to interconnect solar collectors, BTES systems and heating networks to improve the stability and thermal efficiency of the system. The solar fractions of these systems range from 30% to 70% (F. Guo *et al.*, 2020).

BTES systems coupled with CHP systems can rise gradually the annual storage efficiency up to 90% after some years of operation. Therefore, a possible direction for the further development of high-temperature BTES is to increase the storage volume to satisfy the needs of large-scale urban central district heating for enhancing the thermal storage efficiency and the penetration of sustainable energy in the overall urban energy system. With an increase in the storage volume, some aspects of the design pattern of BTES may be significantly changed, including the heat loss protection measures, the layout of the BTES and borehole connection. Moreover, large-scale BTES can be utilized as centralized thermal storage to accommodate a variety of small distributed heat sources (F. Guo *et al.*, 2020).

1.1.11. Seasonal heat storages: PTES - Pit Thermal Energy Storages

PTES are large water reservoirs for storing thermal energy, being the most common seasonal storage technology and most cost-effective solution for large volumes (S.K. Henninger, K. Ellehauge, and J.C. Hadorn, 2008). The simplest and most common pit heat storage is an excavation shaped as a truncated pyramid placed upside down in the ground, lined by a water-proof membrane, filled with water, and covered by a floating and insulating lid. It is possible to reduce the handling and transport cost of soil creating embankments around the upper part of the storage with the soil excavated from the bottom part of the storage. These systems allow, for example, to store during several months the heat generated from large solar thermal systems during the summer period. The additional use of a heat pump can expand this period by cooling down the storage further. In addition, PTES can be developed for operation at relatively high temperature levels (90°C all year round) using the excess heat from industries and waste incineration as heat source (DEA, 2020).

Typical capacities for seasonal heat storages are 50.000-500.000 m^3 or 5.000-40.000 MWh at one full charging cycle (S.K. Henninger, K. Ellehauge, and J.C. Hadorn, 2008). Nevertheless, the optimal storage period and total installed capacity of the PTES is bounded by the local demand needs and the existing and available heat sources. Installed capacity can be also limited by specific location restrictions regarding the maximum size and shape of a heat storage (DEA, 2020).

Heat losses in PTES depend on several parameters of technical, operational and weather parameters such as geometry, storage temperatures, operation patterns, cycle duration and weather conditions (PlanEnergi *et al.*, 2009). The heat losses of PTES are larger during the first two years than afterwards, as the surrounding soil will be heated reducing heat transmission. In general, heat losses are reduced by increase the storage capacity. In this sense, a small storage with a volume of 20 m^3 heat losses referred to the stored energy eight times higher than 10,000 m^3. This is because the better surface/volume ratio of the larger PTES. Also, it is possible to reduce annual heat losses by using a heat pump to cool the stored water (PlanEnergi *et al.*, 2013).

PTES has several advantages such a quick charging and discharging with high capacity, high specific heat capacity and cheap storage medium with good heat transfer characteristics that enables stratification. Nevertheless, there are negative aspects such as the storage requires a relatively large area of land, vulnerable liner and insulation materials and the risk of leakages (DEA, 2020).

1.1.12. Seasonal heat storages: CTES - Caverns Thermal Energy Storages

In CTES, energy is stored as hot water in an underground cavern. These systems have very high injection and extraction powers (just matter of pump capacity).

Potential structures for CTES include abandoned mines, tunnels or rock caverns, natural karst structures and artificially constructed caverns (K.S. Lee, 2013). These storage options are technically feasible, but applications are limited because of high investment costs. In this context, artificial caverns have been demonstrated in full scale, constructing large underground water reservoirs, but they are still too expensive to become an alternative to other hot water storage systems. The reconstruction of existing caverns or abandoned mines could however make CTES economically feasible (B. Nordell, 2012).

In these systems, heat losses will be substantial to the surrounding rock mass. This is especially relevant during the first two years after charging. After this period, the cavern develops a relatively stable thermal halo whereby the temperature, starting from the warm center, decreases. There are still heat losses, but they should be less than 10% during one operational cycle under favorable conditions as dry rock is generally a poor heat conductor. It is also very relevant to maintain a stratified temperature profile in the cavern. To facilitate this, hot water must be injected at the top of the store and colder water must be extracted from the bottom (K.S. Lee, 2013).

During the design of large-scale CTES it is necessary to consider several factors such as the estimation and control of the thermal, hydrological and mechanical behaviors of rock mass and storage caverns, ensuring the structure safety, storage efficiency, the selection of suitable storage site or the thermally induced environmental impact. This last point is related to the temperature changes in the water surface and groundwater and the corresponding effect on vegetation (Park *et al.*, 2014b).

There are few examples of CTES. Being the first two worldwide the Swedish Avesta and Lyckebo storages. The Avesta storage was built for research purpose in 1981. It is a short-term energy storage with a capacity of 15.000 m^3 and it is fed with heat produced from an incineration. The Lyckebo thermal storage was constructed in 1984 and it is connected to the Uppsala district heating net plant (B. Nordell, 2012). It has the shape of a ring with a height of 30m, a width of 18m and a diameter of 75m. The cavern roof is insulated 30m below the rock surface. The storage volume is 100.000 m^3 and the cavern walls are not insulated (C. Brunström, B. Eftring, and J. Claeson, 1987b). It has a maximum water temperature of 90°C and it can store 5.500 MWh of heat between seasons. Lyckebo storage is working well except for deposits in the heat exchanger and the excessive heat losses estimated in 20% (Bergensund, Eriksson and Häger, 2015)

Recently, the energy company Helen Oy is planning to build a CTES in Helsinki. It will be interconnected to the district heating network and it will avoid, during the coldest winter days, the start-up of separate natural gas and oil-fired heating plants. It consists of three large caverns used previously to store heavy fuel oil. Its expected storage capacity is 260.000 m^3 and heat power is expected to be 120 MW with an operating time of four full days (Helen Oy, 2018).

1.1.13. Hot water pumped storage hydropower plant

This technology combines the advantages of pumped storage technology and heat storage. This new system stores and supplies electricity, heat and cooling energy as required. In principle, this technology can be used to meet up to 90% of our energy requirements (C. Pelzl, 2018).

The first element is an underground pumped hydro storage, where subterranean tunnels are used to create the elevation difference between two underground reservoirs to produce electricity. The second component is a heat accumulator, typically at 90°C, where water serves as an additional thermal energy storage medium. In case that heat demand is high, heat can be supplied directly to consumers via district heating networks. The high temperature level is achieved from different heat sources such as thermal solar panels or via district heating transmission lines. A heat exchanger or a secondary system is used to store and extract the heat from the water of the system. The surrounding mountain is not only a natural thermal isolation, but it is also an additional heat-storing mass. In addition, the installation of an air pressure compensation shaft into the system can prevent heat and evaporation losses (F.G. Pikl, W. Richter, and G. Zenz, 2020).

Finally, it is possible to integrate district cooling technology in the shape of absorption chillers into this concept. The hot water drives the chillers, which produce cooling energy that is distributed via district cooling networks. To ensure a constant supply of cooling energy to various temperature zones, this system can be modified by cooling the water of the underground pumped storage hydropower scheme becoming a “cold-water pumped storage hydropower plant” (C. Pelzl, 2018).

The combination electricity and heat storage, with efficiency factors around 80% for electricity and heat storage, provides an annual energy turnover and a volumetric energy density much higher in contrast to separate usage. This solution also stands out for its profitability with short payback period. This system has additional advantages such as the possibility to have zero-emission during the operation, no open spaces are required, and it does not affect the natural water balance reducing the environmental impact (C. Pelzl, 2018). In addition, the expandability of the storage volume at any time or the possible asymmetrical size design of the storage caverns or a performance upgrade offers additional flexibility options to adapt the combined storage system to changing supply requirements or (energy) economic conditions (F.G. Pikl, W. Richter, and G. Zenz, 2020).

1.1.14. Blending hydrogen into natural gas grid

Blending hydrogen into the existing natural gas pipeline network is proposed as a solution to reduce greenhouse gas emissions when the hydrogen is produced from RES or from low-carbon energy sources such as nuclear or fossil with carbon capture and storage (CCS). The generated benefit would be like the introduction of biogas into the natural gas pipeline. This strategy of storing and delivering carbon free energy to markets can be viable without significantly increasing risks when relatively low concentrations, from 5 vol. % to 15 vol. % hydrogen, are implemented. However, the appropriate blend concentration may differ significantly between pipeline network systems and natural gas compositions. Therefore, any introduction of a hydrogen blend concentration requires an extensive study, testing, and modifications to existing natural pipeline network. This could produce additional costs that must be weighed against the benefit to provide a more sustainable and low-carbon gas product to the consumers (M.W. Melaina, O. Antonia, and M. Penev, 2013). Blending hydrogen into natural gas pipeline networks can be means of delivering pure hydrogen to markets, using separation and purification technologies as downstream (pressure swing adsorption (PSA), membrane separation, and electrochemical hydrogen separation (EHS, or hydrogen pumping) (M.W. Melaina, O. Antonia, and M. Penev, 2013)) to extract hydrogen from natural gas. This can be a cost competitive solution in comparison to build dedicated hydrogen pipelines or other costly delivery infrastructure during the early market development phase (M.T. Trouvé *et al.*, 2019).

The volumes of blended injectable hydrogen into natural gas infrastructures depend on the following critical parameters: nature of pipelines and network equipment, the existence of energy storage tanks, the ability to dilute injected quantities and the CO2 sources availability in case that the mechanisation route is considered. Another key factor is the type of customers connected downstream of the injection point, for example, the presence of industrial customers who are highly sensitive to gas quality (M.T. Trouvé *et al.*, 2019). The injection of hydrogen into the networks can influence the accuracy of existing gas meters and the proper metering by volume and conversion into energy. Recalibration of the existing gas meters will be necessary and installation of certificated new ones. In this sense, measurement uncertainties must be checked on the turbine meters due to the lower density of the CH4/H_2 mixture. However, other technologies, e.g. ultrasound, accept a hydrogen content of up to 15% with little or no dispersion. In addition, new billing tariff solutions will be necessary (M.T. Trouvé *et al.*, 2019).

There are several problems due to injection hydrogen into the natural gas network. The first one is the potential impact of contaminants in case that the hydrogen production system does not produce pure hydrogen (M.W. Melaina, O. Antonia, and M. Penev, 2013). The second problem is hydrogen embrittlement which is the diffusion of hydrogen into the crystalline mesh of steels which can lead to a weakening of the steel (reducing ductility) and an increase in the speed of the propagation of defects (M.T. Trouvé *et al.*, 2019). The third one, is the risk of fire and explosions in high populated areas, which can affect specially the distribution pipeline system. This is because of hydrogen leakage that makes additional leak detection systems necessary(M.W. Melaina, O. Antonia, and M. Penev, 2013).

In particular, the Austrian natural gas network for domestic gas use can be fed up to 10 vol.% hydrogen with all components working in a functional and safety way with only a slightly increase of explosion risk compared with pure natural gas. However, measurement deviations can already occur with this level of hydrogen (ÖVGW, 2019).

1.1.15. Compressed H2 in pressurized storage tanks

Hydrogen storage in pressurized tanks is a system for small and medium scale storage. There are three main problems when trying to compress and store hydrogen in a tank. The first difficulty is the integrity of the materials; hydrogen storages pressure tanks work over a high number of cycles with pressures that range from 50 bar to 1000 bar and temperatures which rises while compressing the hydrogen inside the tank. This causes a warming of the materials of the tank from inside generating critically damage in case that the temperature exceeds certain levels. Actually, this limitation, together with operational cost, result in large-scale storage pressurized tanks which cannot exceed 200 bar at ambient temperature (J. Andersson and S. Gronkvist, 2019). The second problem is hydrogen embrittlement which is a process in which metals, like steel, react with hydrogen. This makes them brittle and susceptible to cracking (DEA, 2020). The third one is hydrogen permeation which takes place when hydrogen molecules, due to their small size, tend to go through the walls. This can produce a pressure drop inside the tank as well as result in a decrease of the stored hydrogen (E.D. Rothuizen, 2013).

Hydrogen pressure tanks are divided into 4 types according to the materials they utilize (H. Dagdougui *et al.*, 2018):

- ***Type I:*** These tanks are seamless steel or aluminium tanks. They are resistant to hydrogen permeation but not hydrogen embrittlement. These tanks are bulky and heavy with thick walls and designed for pressures up to 250 bar being a cheap solution for stationary applications.
- **Type II:** These tanks are seamless metallic, usually aluminium, tanks with filament windings like glass fibre/aramid or carbon fibre around the metallic cylinder. They are heavy and designed for pressure ranges from 450 to 800 bar. They are cost competitive due to the relatively low amount of fibres used for the wrapping.
- **Type III:** These are made from seamless or welded aluminium liners fully wrapped with fibre resin composite. They are lighter and have thinner walls compared to Type I and II but more expensive. They are designed for pressure ranges from 300 to 700 bar and are less susceptible to hydrogen embrittlement
- **Type IV:** They are completely made of carbon fibre with a polymer (thermoplastic) liner. The carbon fibre wrapping provides enough strength to withstand pressures up to 1000 bar while the thermoplastic liner acts as a permeation barrier. They are the lightest but also the most expensive tanks and are used (along with Type III tanks) mainly in the automotive industry for short term storage.

Hydrogen pressure tanks have several advantages such as hydrogen can be stored for relatively long periods without losing significant energy content, it is a widespread and proven technology and they are cost-efficient solutions in comparison with other industrialized storage methods especially for type I and II. However, they have some disadvantages such as the high cost to transport large quantities of hydrogen over long distance because of the need to use trucks to carry the pressure tanks, high costs for materials for pressure tanks and safety issues (hydrogen is an explosive gas with a flammability range from 4% to 75% hydrogen in air) (DEA, 2020).

1.1.16. Hydrogen storage in caverns

Salt caverns are man-made cavities in thick underground salt deposits. Those are constructed from the surface by injection of water down a well drilled into the salt rock. Depending on the specifications and the technical feasibility, they can be constructed at depths of 2000m, have geometric volumes until 1.000.000 m^3, typical heights of 300-50 m, and diameters of 50-100m. Depending on the depth, they can be operated at pressures of up to or even above 20 MPa. This enables the storage of very large quantities of gas. For instance, a typical large gas cavern can hold more than 60 times the volume of a spherical gas tank. Nevertheless salt caverns have a very irregularly geographical distribution (J. Michalski *et al.*, 2017).

The overall technical potential in Europe, including both onshore and offshore locations, is estimated to be 84.8 $PWhH_2$, with 23.2 $PWhH_2$ of this potential belonging to onshore formations. In that case, a maximum distance of 50 km to the coast is applied to the onshore salt caverns in order to take into account the economic and ecological aspects of brine disposal pipelines and onshore potential decreases down to 7.3 $PWhH_2$ (D. Gulcin Caglayan *et al.*, 2020).

The storage of hydrogen in depleted oil and gas reservoirs has the advantage of reducing the geological exploration efforts. To achieve this transformation, the caverns are flooded to displace methane while a high pressure is maintained. Then, hydrogen is produced via electrolysis or steam methane reforming, and compressed to be stored. For extracting the hydrogen gas, gas withdrawal units are employed, and this gas can be used to generate electricity in a gas turbine or a fuel cell. The operation of this type of system is highly dependent on compression and expansion of the hydrogen into the caverns between the minimum and maximum pressure limits. 80% of this initial pressure is the recommended maximum pressure and 30% of the maximum pressure is the recommended minimum pressure (DEA, 2020). However, as a result of the contamination caused by the previous hydrocarbon extraction, contamination control and gas upgrade units for purification may be required (D. Gulcin Caglayan *et al.*, 2020).

There are several advantages of these type of systems such as the large storage volume to support grid balancing, long-term storage solution with unlimited lifetime and low footprint, suitable for short-term peak shaving operations and much lower investment costs per storage unit compared to hydrogen tanks. However, they have lower energy density compared to oil stored in caverns and there are limited useful salt structures available (DEA, 2020).

There are several researching activities to improve hydrogen storage in cavers to reduce undesirable reactions due to hydrogen embrittlement and loss of wall integrity and to improve compression technologies. The research in the field of market mobility and hydrogen cost production will also determine the potential of this large storages (A. Le Duigou et al., 2017).

1.1.17. H2 - Cryo-compressed storage

Cryogenic hydrogen has a density nearly twice that of compressed hydrogen at 70 MPa. Liquid hydrogen is stored in specially insulated cryogenic tanks under pressure, which have provisions for cooling, heating, and venting. However, liquefaction is an energy-intensive process. Estimates are about 12.5-15.0 kWh/kg for liquefaction compared to about 6.0 kWh/kg for compression to 70 MPa (J.W. Sheffield, K.B. Martin, and R. Folkson, 2014). Cryo-compressed hydrogen storage can include liquid hydrogen, cold compressed hydrogen, or hydrogen in a two-phase region (saturated liquid and vapor) (R.K. Ahluwalia *et al.*, 2010).

In this storage concept, hydrogen is cooled down to the temperature of liquid hydrogen (20K) and additionally hydrogen is compressed to a pressure of up to 350 bar or even 700 bar. This leads to a storage energy density of maximum 7 wt% and 0.07 kgH_2/l, which is only possible by expending an enormous amount of energy and technological effort to cool and compress hydrogen (L. Baetcke and M. Kaltschmitt, 2018).

The design requirements of a storage vessel to contain hydrogen under the temperature and pressure condition are extremely high. Cryogenic tanks must withstand extremely cold temperatures, only aloe for trivial heat transfer, and tolerate occasional large pressure and temperature swings from relatively warm to extremely cold. The tanks must maintain these properties for the whole lifetime, which can be a challenge for tanks insulated with vacuum jackets where the vacuum and thus insulation properties can degrade over time. In addition, these systems typically require instrumentation and other potential sources of heat conduction that penetrate the layers of the tank. To achieve low heat transfer, the system design must have few penetrations and still perform all required functions (US Drive, 2017).

The initial capital investment is high because the need for liquefaction equipment as part of the hydrogen storage and because the liquefaction process is very energy-intensive the operation cost is also high. However, new installations can take advantage of scale-economy, because despite larger plants with higher liquefaction, capacities have higher initial costs. The hydrogen cost and energy to liquefy hydrogen decreases per kilogram of hydrogen liquefied (J.W. Sheffield, K.B. Martin, and R. Folkson, 2014).

While compressed hydrogen storage is typically at ambient temperatures, cold and cryogenic compressed hydrogen storage is also being investigated for light-duty vehicles due to the higher hydrogen gas densities. These systems also offer potential advantages for heavy-duty vehicles and fleet applications that utilize consistent drive cycles and require long driving ranges (US Drive, 2017). Recently, supercritical cryo-compressed hydrogen storage has been proposed by BMW company and developed by many others. Their concept consists of storing hydrogen in a pressure vessel that can operate at cryogenic temperatures (as low as 20 K) and high pressures (e.g. ~35 MPa) (Z. Yanxing *et al.*, 2019).

1.1.18. H2 - Liquid Organic Hydrogen Carrier (LOHC)

LOHC storage systems are similar to conventional fuels. H_2 can be stored in a liquid form under atmospheric pressure and environmental temperature. The storages have a high volumetric energy density which allows for a viable alternative for energy transport, automotive purposes as well as stationary applications. Nevertheless, LOHCs are still new in the market and only a few systems have been built (M. Niermann, S. Drünert, *et al.*, 2019).

LOHCs essentially are liquids or solids which are accompanied by the reversible hydrogenation and dehydrogenation at elevated temperatures (P.T. Aakko-Saksa *et al.*, 2018). The concept behind LOHC hydrogen storage and the chemical principles can be divided in the following steps (DEA, 2020):

- **Hydrogen production.** Hydrogen can be generated from an electrolyser. This system should work to high pressure to support the hydrogenation process
- **Hydrogenation process**. This is a process of chemically binding hydrogen to the LOHC. This takes place in temperature range of 50-250°C and high-pressure range of 10-70 bar.
- **LOHC storage**. Loaded LOHC is cooled and decompressed to be stored in ambient conditions. Minor hydrogen is lost during decompression (under 0.1% hydrogen weight).
- **Dehydrogenation & usage.** The hydrogen in the loaded LOHC is separated in a reactor by providing heat and in the presence of a catalyst. The unloaded LOHC is then stored for further cycling. For some LOHCs, the hydrogen obtained from the dehydrogenation process is not fully pure and needs further purification.

During the hydrogenation and dehydrogenation energy losses take place. In this sense, thermal efficiencies in the order of 60% and electrical efficiencies in the order of 40% has been reported (P.T. Aakko-Saksa *et al.*, 2018).

LOHCs have the possibility to be stored in large scale and use the current existing transport infrastructure such as pipelines, ships or trucks (P. Preuster, C. Papp, and P. Wasserscheid, 2017). Transporting hydrogen in the form of LOHC involves loading and extracting hydrogen at the destination. However, it is necessary to transport LOHC molecules back to the origin which makes the whole process expensive.

LOHCs can store hydrogen indefinitely and the loss of hydrogen during storage is negligible. Economically, 60 days is an optimum time span for storage when compared to compressed hydrogen storage. Long-term storage under ambient pressure is one of the advantages of using LOHCs (M. Niermann, A. Beckendorff, *et al.*, 2019).

Therefore, LOHCs has several advantages such as it is ideal to store hydrogen on a large-scale, long-life operations with low maintenance, easy installation and low footprint and it is very safe for high storage capacity. On the other hand, a strict assessment on toxicity of LOHCs need to be performed and heat integration for hydrogenation and dehydrogenation needs to be improved (DEA, 2020).

1.1.19. Underground natural gas storage

Underground storage is primarily used for natural gas (almost pure methane, CH_4), but other gasses may also be stored underground. This can include hydrogen; however, this implies that surface facilities need be designed considering that hydrogen is much more explosive and also aggressive towards steel structures. In addition, costs would be larger, since the heating value per volume is about three times less (DEA, 2020).

In case that biogas (65% CH_4 and 35% CO_2) is going to be stored, it is necessary to remove CO_2 before increasing the energy density. It is also convenient to remove the CO_2 because stores always contain some water which in contact with CO_2 becomes acidic creating potential problems for the surface facilities (DEA, 2020)

The short-term regulation for these systems is not relevant for the overall gas system, as the gas transmission and distribution pipelines have substantial storage capacity (so-called line pack). In case that a power plant wishes to start up from zero to full load in a moment, the required gas volume is ready by the gate. The gas pressure in the pipeline will drop a little, but within the operational limits, the pressure will soon rebuild by drawing gas from other parts of the system.

There are three main type of underground natural storages: depleted gas reservoirs, aquifer reservoirs and salt caverns (DEA, 2020).

Depleted gas reservoirs are most prominent and common. These are reservoir formations from natural gas fields which have produced all their economical gas. These facilities are economically attractive because, with suitable modifications, it is possible to re-use the extraction and distribution infrastructure remaining from the productive life of the gas field. They are well known because their geological and physical characteristics were already studied. Therefore, depleted reservoirs are generally the cheapest and easiest to develop, operate, and maintain of the three types of underground storage.

Salt caverns are strong and impervious to gas over the lifespan of the storage facility. Once a salt cavern is suitable for the development of a gas storage facility a cavern is created within the salt feature. This is done by the process of cavern leaching. Fresh water is pumped down a borehole into the salt. Some of the salt is dissolved leaving a void and the water, now saline, is pumped back to the surface. The process continues until the cavern is the desired size. Once created, a salt cavern offers an underground natural gas storage vessel with very high deliverability. Cushion gas requirements are low, typically about 33 percent of total gas capacity.

Finally, aquifer reservoirs are underground, porous, and permeable rock formations that act as natural water reservoirs. Usually, these facilities are operated on a single annual cycle as with depleted reservoirs. The geological and physical characteristics of aquifer formation are not known ahead of time and a significant investment must be made to evaluate the aquifer’s suitability for natural gas storage.

1.1.20. Power to Heat (P2H)

P2H technologies offer major potential to drive forward the energy transition. They convert electricity into heat and can be additionally combined with heat storage units (*What exactly is meant by 'power-to-heat'?*, 2020). These technologies can be divided into centralized and decentralized systems. Centralized systems generate the heat at certain distance from the location of the demand and heat is distributed by district heating networks (D. Olsthoorn, F. Haghighat, and P.A. Mirzaei, 2016). In contrast, decentralized systems generate the heat to the location of heat demand. In reality, the line between centralized and decentralized options is fuzzy as heat may be jointly provided for only a few flats or houses in local or neighborhood heating networks (H. Lund *et al.*, 2014).

P2H can contribute to integrate the expansion of additional vRES making better use of temporary renewable surplus electricity generation. This implies an overall CO2 reduction due to a higher utilization of RES (D. Patteeuw *et al.*, 2015). Furthermore, P2H solutions can be done in a cost-effective way where cost reductions are driven by the substitution of fossil fuels (K. Hedegaard *et al.*, 2012), better use of capital invested, less need for costly auxiliary technologies or power storage, more efficient operation of thermal power plants and the use of existing district heating infrastructure. Nevertheless, there is the possibility that the electricity prices rise due to the increase of the electricity demand because of the expansion of P2H into the energy system. However, the high efficiency of heat pumps and the flexibility of new loads may counteract this effect to some extent (D. Böttger *et al.*, 2015).

Centralized P2H approaches either draw on largescale heat pumps that make use of geothermal (i.e. ground-sourced) energy, waste heat or brine, or on large electric boilers, often in the form of electrode boilers. These options are also available as decentralized heating options. In this last case, smaller-scale heat pumps are usually air or ground-sourced. Resistive heating comes in the form of electric boilers or electric heating elements in boilers that are primarily fueled by some other energy carrier (hybrid heating) e.g. a water-based residential heating system with a boiler that is primarily fueled with natural gas and has an additional electric heating element (S. Heinen, D. Burke, and M. O'Malley, 2016).

Heat pumps are reversible mechanical-compression cycle refrigeration systems. A heat pump uses external power (electricity) to accomplish the work of transferring energy from the heat source to the heat sink (J. Bundschuh and G. Chen, 2014).

Small-scale heat pumps for building application (around 6 kW) have highly efficient conversion rates of energy to heat, a competitive price and lower running and maintenance cost compared to other combustion heating systems and very long lifespan of up to 50 years. However, these systems have a high start-up cost, are difficult to install and some of the fluids used for heat transfer are of questionable sustainability (UK Renewable Energy Hub, 2020).

The use of large central heat pumps (100kW to > 1MW) linked to high-temperature (> 70°C) district heating networks, where other heat plants are connected, have several advantages: large heat pumps can be operated to optimize the overall district heating network relatively easy to extend the scheme to more buildings and in case that the return temperature is low enough, large heat pumps can be used for initial heating of the return flow leading to high heat pump COPs. However, some disadvantages could be produced such as distribution of unnecessarily high temperature leads distribution losses and a lower COP. In case that large heat pumps are connected to a medium temperature (40-70°C) network to provide space heating higher COPs can be achieved due to lower network temperatures; but the network temperature may be too low to be used directly to cover the domestic hot water (DHW) demand making an additional system for provision for DHW necessary or a means to raise the network temperature locally at the demand point (British Departm of Energy & Climate Change, 2016).

Electrode boilers use electricity flowing through streams of water to create steam. The properties of water are employed to carry electric current. They are used for industrial applications and excellent for intermittent or cyclical operations (Alabama Power, 2020b). Electrode boilers are connected to a medium voltage (1-35 kV) alternative current (AC) source and can work on single phase and three phase supplies. In case, that the electrodes are connected to a direct current source the electrolysis of the water generating H_2 takes places at the cathode and O2 at the anode. The conductivity of water together with the applied voltage determine the quantity of generated steam in each steam water. During the operation, boilers are fed with water which contains conductive substances like salt. The departing steam is free of these substances, this produces an increase of the conductivity of water increases making it necessary to remove part of the water and replace it with fresh water to certain limits. These systems have several advantages; they have an efficiency of 99.9%, very quick response time, does not directly generate pollution, no boiler component is at high temperature except the water itself, easy to control and maintain and dropping water levels inhibits current flow allowing the boiler to self-regulate. On the other hand as some disadvantages, water level should be maintained up to a certain level to maintain the circuit and scale formation (Wikipedia, 2020).

Electric resistance boilers consist of an electrically resistive element. As a consequence heat is transferred to the water, heating it to the desired temperature (Alabama Power, 2020a). Generally, the boiler will have a large water tank attached to it. In the bottom, the resistance is located, and a water pump sends the hot water to radiators and taps when it reaches the right temperature. These systems don’t produce waste gas which allows to achieve efficiencies of 99%. In addition, this technology has low environment impact at local level, is a compact technology as no fuel tanks neither fuels are needed, has low investment and operational costs and no risk of gas/fuel leaks. Nevertheless, there are a few downsides such as the higher price of the electricity increasing running costs and lower heat generation capacity than gas which makes this technologies useful for small homes but can struggle to effectively heat a larger property (Warm.co.uk, 2020).

1.1.21. Power to Hydrogen (P2H2)

Large hydrogen production from renewable power in combination with hydrogen storage can provide long-term seasonal flexibility to the system. Electricity is used in an electrolyzer to produce hydrogen and oxygen from water. Then, hydrogen is stored for electrical applications and it is re-electrified (e.g. via fuel cells) recombining hydrogen with oxygen to produce electricity. Alternatively, gas turbines or engines can be used to reconvert hydrogen into electricity as well (EASE, 2020). Hydrogen has a high flexibility being able to be used not only in the power sector providing balancing between demand and supply. It can be a cost-effective solution instead to develop a grid extension, blended directly with the natural gas into the gas grid, used for Fuel Cell Electric Vehicles, converted into methanol or used as a commodity by the chemical industry (IRENA, 2019). There are four electrolysis methods: Alkaline water electrolysis (AWE), PEM water electrolysis, Solid oxide electrolysis (SOE) and Microbial electrolysis cells (MEC) (M.N. Nandanwar *et al.*, 2020).

AWE is a well-established technology up to the megawatt range for commercial level. In this technology at the cathode side two molecules of alkaline solution (KOH/NaOH) are reduced to produce one molecule of hydrogen (H_2) and two hydroxyl ions (OH-). H_2 is eliminated from the cathode surface in a gaseous form and the OH- are transferred through the porous diaphragm to the anode, here discharged to ½ molecule of oxygen (O2) and one molecule of water (H_2O). Alkaline electrolysis operates between 30 to 80 °C with aqueous solution (KOH/NaOH) as the electrolyte is within a concentration range between 20% to 30% (K. Zeng and D. Zhang, 2010).

PEM water electrolysis is accrued by pumping water to the anode where it is spilt into oxygen (O2), protons (H+) and electrons (e-). These protons travel via proton conducting membranes to the cathode side. The electrons exit from the anode through the external power circuit providing the driving force (cell voltage) for the reaction. At the cathode side the protons and electrons re-combine to produce hydrogen (M.N. Nandanwar *et al.*, 2020). PEM water electrolysis has great advantages such as compact design, high current density, high efficiency, fast response, small footprint, operation temperatures between 20 to 80°C and produces ultrapure hydrogen and oxygen (N. Nikolaidis and A. Poullikkas, 2017). Additionally, balancing PEM electrolysis plants is very simple, which is more attractive for industrial applications. However, PEM electrolysis uses noble metals such as Pt/Pd which makes it more expensive than AWE (S.S. Kumar and V. Himabindu, 2019).

SOE produces ultra-pure hydrogen with greater efficiency (A. Brisse, J. Schefold, and M. Zahid, 2008). This technology operates at high pressure and high temperatures 500–850°C, utilizes steam water and conventionally uses the O2- conductors which are mostly from nickel/yttria stabilized zirconia (M. Liang *et al.*, 2009). Nowadays, some of the ceramic proton conducting materials have been developed and studied in solid oxide fuel cells. These materials demonstrate higher efficiency and superior ionic conductivity than O2- conductors at an operating temperature of 500–700°C (F.M. Sapountzi *et al.*, 2017). SOE has some issues related to lack of stability and degradation, which must be solved before going to commercialization the technology on a large scale (M.A. Laguna-Bercero, 2012).

In a MEC process, in the anode the substrate is oxidized by microbes and then produces CO2, protons and electrons. The electrons travel to the cathode side through the external circuit and the protons travel to the cathode via proton conducting membranes (electrolyte). Protons and electrons are combined to produce H_2. Compared to water electrolysis MEC processes require a small amount of external voltage. However, MEC technology is still under development having to address several challenges, such as high internal resistance, electrode materials and complicated design before being available for the market (S.S. Kumar and V. Himabindu, 2019).

Currently, there are many power-to-gas projects emerging in Germany and other European countries covering installed capacities from a few kW to several hundreds of MW. They have the advantage to be able to operate with short ramp-up time associated with intermittent renewable generation following, for example, the load changes produced by the output of a wind farm. Nevertheless, future developments are necessary to position this technology into the market such as up-scaling the electrolyser and cost reduction, large demonstration projects employing salt caverns as hydrogen storage, increase the hydrogen content into the natural gas infrastructure including conventional gas turbines and up-scaling of the methanation step (EASE, 2020).

In water electrolysis the specific consumption rates decrease in partial load mode, resulting in an efficiency rise for lower loads (S. Schulte Beerbühl, M. Fröhling, and F. Schultmann, 2015; J. Ikaheimo *et al.*, 2018). However, inefficiencies from balance of plant (BOP)[1] are significant at minimum loads resulting in low efficiencies. Consequently, the most efficient operation range is around 20-40% load (M. Lappalainen, 2019).

[1] Auxiliary equipment typically including: water treatment plant, gas/water separators, pumps, heat-exchangers, dryers/purifiers, gas storage, monitoring and ventilation systems

1.1.22. Power to Methane (P2M)

P2M concept is a promising option to absorb surplus renewable energy, balance power, utilizate factors, CO2 sources and infrastructure, provide flexibility services to the grid through a smart management of process energy consumption and achieve the targets under Renewable Energy Directive (RED) and Fuel Quality Directive (FQD)(EASE, 2020).

Hydrogen is produced by water electrolysis while carbon dioxide is captured from a flue gas via post-combustion capture units (S.K. Hoekman *et al.*, 2010). Both gases are converted to a gas mixture which contains methane and water by using a methanation unit (M. Gotz *et al.*, 2016). Then, this gas is enriched to get a methane-rich gas, named synthetic natural gas (SNG) (T. Zoss, E. Dace, and D. Blumberga, 2016). The efficiency of the conversion from hydrogen to methone is 83%, whereby the remaining 17% is released as heat (K. Ghaib and F.Z. Ben-Fares, 2018). The overall efficiency can be increased by the utilization of waste heat from the electrolyzer unit in combination with a high temperature heat pump. Moreover, the utilization of reaction heat could also increase the overall efficiency (EASE, 2020).

There are low experiences with the entire P2M system with few plants worldwide (K. Ghaib and F.Z. Ben-Fares, 2018). An example of P2M plants is the ZSW 250-kWel demonstration plant located in Germany. It consists of a 250-kWel alkaline high-pressure electrolyzer, a methanation unit and a process control system that ensures an optimal operation. Also in Germany, the Audi e-gas plant is operating as an industrial P2M facility (M. Bailera *et al.*, 2017). In this plant, carbon dioxide is captured from biogas by amine absorption system. Meanwhile hydrogen is generated by three alkaline electrolyzers with a total capacity of 6 MW. These are powered by an offshore wind park in the North Sea (J. Köbler, 2011). Hydrogen is stored in a tank before fed into the methanation reactor at approximately 10 bar (M. Schmidt *et al.*, 2018).

Further developments are necessary to make this technology competitive under market conditions. This efforts should be oriented to up-scaling methone reactor units, increase the carbon conversion to nearly 100% by adding hydrogen to raw syngas, develop new reactors to improve reaction kinetics and energy efficiency together with a reduction in capital costs and develop new catalysts for more durable and cost-effective processes (EASE, 2020).

1.1.23. Power to Ammonia (P2A)

NH3 is a high caloric energy carrier with 45% higher volume energy density than H_2 and can provide a pathway to fully CO2 neutral electricity storage and generation of CO2 neutral electricity on a scale that is not limited by scarcity of materials or storage space. NH3 has a potential to be used as a chemical storage medium due to high efficiency, energy density and low cost of nitrogen sourcing. There are concerns about the safe handling of NH3, however with the large amount of experience in the chemical industry this appears very well manageable (IST, 2017).

The process to generate NH3 starts with feeding Water (H_2O) to the electrolyser, where it is split into O2 and H_2. H_2 stream is saturated with H_2O and contains a limited amount of O2. The O2 is removed by reacting with the H_2 over a metal catalyst to form H_2O. This gas mixture is passed over a zeolite bed which selectively adsorbs H_2O generating pure H_2. On the other hand, N2 is produced using a cryogenic air separation unit (ASU). Then, N2 and H_2 are mixed to the required composition for the synthesis of NH3. The pressure of the synthesis gas is increased using a centrifugal compressor. As NH3 synthesis is limited by chemical equilibria a recycle stream is used to increases the conversion. In addition, a purge stream is used to prevent the build-up of any inserts (IST, 2017).

NH3 can be used as a fuel in a power station by cracking the NH3 into H_2 and N2 before combusting in gas turbines. Cracking NH3 is nowadays only done on a small scale. The technology for large scale cracking must be developed in the coming years. Time to market for large scale applications is estimated to be between 5 and 10 years. The production of NH3 with vRES (mainly wind and solar power) will produce a positive impact on the electric grid. This is because the use of P2A will be able to balance the grid when the share of wind and solar power increases. Therefore, the combination of demand side management and local energy storage can contribute to the reduction of the necessary investments in the grid. Moreover, P2A enables energy to be transported and stored for periods of days, weeks or even months (IST, 2017).

In this context, benefits of using ammonia as a green solution for long term energy storage includes the utilisation of vRES, peak energy saving by flexibly producing NH3 when renewable excess is available, CO2 emission reduction when utilising ammonia or producing it from electrolysis and NH3 is stored in inexpensive pressure vessels at ambient temperature (e.g. NH3 is liquid @ 7,6 barg) and NH3 solves the long term storage issue as opposed to batteries that self-discharge after a short period of time (Proton Venture, 2018).

1.1.24. Power to Methanol (P2MeOL)

Energy transition towards a high penetration level of renewables requires the storage of large amounts of electrical energy for balancing the grid. For that balancing, P2MeOL technologies are under development and are based on electrochemical splitting of water into H_2 and O2 with subsequent catalytic hydrogenation of CO2 to liquid methanol (G. Harp *et al.*, 2015).

Methanol or methyl alcohol has the simplest composition of alcohols (CH3OH) (Nordic Energy Research, 2011) and its production is linked mainly to two industries: the synthesis and blending of fuels and the synthesis of commodity chemicals (Q.I. Roode-Gutzmer, D. Kaiser, and M. Bertau, 2019). In this sense, methanol can be blended with petrol or used alone in modern petrol engines with slightly modifications. It can be the bases to synthesize dimethyl ether (DME) or biodiesel for modern diesel engines, used in fuel cells or burned in existing power generation plants (Nordic Energy Research, 2011). Methanol can also be readily converted into products such as gasoline in the methanol-to-gasoline process (MTG) or olefins in the methanol-to-olefins process (MTO) (H. Nieminen, A. Laari, and T. Koiranen, 2019).

At present, most methanol comes from the catalytic conversion of synthesis gas (syngas) that is usually generated by steam reforming of natural gas. The syngas, a mixture of hydrogen, CO, and CO2, is converted into methanol on copper and zinc oxide (Cu/ZnO)-based catalysts at temperatures of 200–300 ◦C and pressures of 50–100 bar. The low pressure allows for operating conditions which favour the conversion of methanol and nearly completely inhibit the production of by-products. This leads to a high selectivity of > 99% (L.E. Lücking, 2017).

Alternative to syngas, methanol can be produced by directly hydrogenating pure CO2 with H_2 with high selectivity on conventional Cu/ZnO-based catalysts. However, the reaction rates are lower than those with syngas feeds. The equilibrium conversions are also lower compared to CO hydrogenation. In addition to the thermodynamic limitation, methanol synthesis from pure CO2 is complicated because of the increased water formation. In the absence of CO, water is produced both as the by-product of CO2 hydrogenation and by the reverse-water gas shift reaction. The increased formation of water leads to kinetic inhibition and accelerated deactivation of the Cu/ZnO catalysts (H. Nieminen, A. Laari, and T. Koiranen, 2019).

Reactor design in methanol synthesis is important for preserving catalyst life, for achieving acceptable production rate and quality, and for controlling process conditions (D.S. Marlin, E. Sarron, and O. Sigurbjörnsson, 2018). To avoid catalyst poisoning, sulfur and chlorine content in the feed gas must be below 0.1 ppm. All methanol reactors are operated with a recycling loop of unconverted syngas after methanol separation to enhance the overall conversion (G. Harp *et al.*, 2015). Existing methanol synthesis facilities typically comprise BWRs which are expensive and complex but are required to handle large temperature peaks due to the exothermic nature of methanol synthesis. Alternative reactors typically comprise adiabatic or cold-shot reactors, which are less expensive but require the use of multiple reactors to achieve acceptable conversion rates (D.S. Marlin, E. Sarron, and O. Sigurbjörnsson, 2018).

1.1.25. Power-to-Vehicle (PtV) and Vehicles-to-Grid (V2G)

The main characteristic of electric vehicles (EV) is that drivers can plug them in to charge from an off-board electric power source. Powering the vehicle with electricity from the grid reduces fuel costs, petroleum consumption and tailpipe emissions compared with conventional vehicles (EERE, 2020).

There are two types of EVs: All-electric vehicles (AEVs) and Plug-in hybrid electric vehicles (PHEVs). AEVs are powered by one or more electric motors and they receive electricity by plugging into the grid and store it in batteries. AEVs include Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs). Meanwhile, PHEVs use batteries to power an electric motor, plug into the electric grid to charge, and use a petroleum-based or alternative fuel to power the internal combustion engine (EERE, 2020). EVs are considered essential in reducing greenhouse gas emissions and in facilitating e-mobility through the high penetration of renewable energy sources. EVs can act as an energy storage system to shift load from peak to off-peak hours, and hence help in reducing electricity bills (W. Kempton and L. Steven, 1997). In this context, V2G technique is suitable for large-capacity requirements in the distribution grid, facilitates a smart grid approach during fluctuating electric loads, and supplies ancillary services to the grid. V2G also has faster response times than traditional power plants making V2G attractive for voltage and frequency control. Furthermore, batteries are also more efficient than most other energy storage technologies (Solanke *et al.*, 2020).

In the V2G system, the main objective is to realize charging–discharging coordination and maintain a charging equilibrium plan to eliminate the problems of stress on the power grid, charging urgency, power balance, stability, and unstructured energy deviations in V2G applications (Solanke *et al.*, 2020). Under this situation the Power Electronic Unit (PEU) of the EV connected to battery which converts from AC line voltage to the DC battery voltage must act also in the other direction converting DC battery voltage to AC line voltage.

EV charging–discharging methods define the type of interaction of the EVs with the electric grid. Technically, the charging–discharging method is dependent on the location of the majority of parked EVs, and the load demand. EV charging–discharging schemes can be either controlled and uncontrolled charging. Controlled charging can be further classified into four sub-groups: indirect controlled, bi-directional controlled, intelligent controlled, and multistage controlled (Solanke *et al.*, 2020).

Uncontrolled charge–discharge method: In uncontrolled charging, EVs start to receive charge immediately when are connected to the power grid during off-peak and peak hours. In this method, the grid operator does not receive any user information about the system, which may result in problems with grid stability, power quality, operational efficiency, and battery state-of-charge (SOC) (S. Micari *et al.*, 2017).

Controlled charge–discharge method: This coordinated method can be quickly adopted and monitored by the operator, who prepares the charging–discharging schedule to avoid issues with power quality and disruptive destabilization while meeting the driver's charging requirements and satisfying financial or operational review objectives. The controlled charging-discharge method can be:

- *Indirect controlled charge–discharge method*: This method considers consumers' behaviour and decisions. In recent years, indirect charge-discharge is increasing in popularity because of the electricity market time framework with adjustable price incentives. Increasing energy prices are expected to push some charging loads to off-peak hours when spare grid capacity is available, thereby preventing grid overloading (M.A. Tamor and M. Milacic, 2015).

- *Intelligent charging–discharging method*: It refers to a system whereby a data connection is shared between an EV and a charging station, and the charging station is connected to a transmission/distribution system operator. Intelligent charging allows the operator of the charging station to track, control, and limit the remote use of their devices to optimize energy demand. Optimization techniques usually aim to keep power quality and stability within marginal levels to avoid disruptive grid instability and to satisfy all charging criteria (Solanke *et al.*, 2020).
- *Bi-directional charge–discharge method*: It authorizes EVs to inject energy into the grid. This is convenient since the vehicles are usually parked for 90–95% of their total lifetime. Furthermore, less availability or the EV owner's willingness do not allow maximum EVs to inject power into the grid during peak hours. Various smart bi-directional charging functions can be used to extend the long-term benefits of V2G, such as connect/disconnect, soft start/stop, auto charging–discharging, and ramp rate functions. These functions provide EV owners with reduced charging costs, smoother EV voltage output, and voltage stabilization. Additionally, EVs can collectively serve as a reservoir in bi-directional V2G filling the gap between unpredictable supply and random demand and allows electricity to be restored to the electrical grid (Solanke *et al.*, 2020).
- *Multistage hierarchical controlled charge–discharge method:* This method consists of a multilevel decision-making tool that operates on a priority basis. Using the existing infrastructure control technique, multistage hierarchical charging–discharging provides a unique solution using decision-based control through a genetic algorithm (GA) with fuzzy- or artificial intelligence-based control tools. The working mechanism of the hierarchy is maintained by organizing four distinct distribution divisions according to the load capacity of the current infrastructure, priorities such as battery SOC, charging costs, and time-of-use. During peak times, these distribution divisions are connected to the grid while recognizing supply and demand rates according to the highest number of connected EVs parked in the area. When there is a mismatch between demand and supply rates, all aggregators start communicating to determine the maximum number of EVs that can inject power into the grid. This control mechanism also helps with frequency regulation, voltage fluctuations, and power quality, and improves other critical optimal solutions (Solanke *et al.*, 2020).