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ELECTRICITY STORAGE THROUGH THERMAL STORAGE

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Non-Batery storage is an important alternative for electricity storage, despite the fact that the round trip efficiency is usually lower. They offer advantages like higher storage capacity, lower storage costs and longer life time than the available battery technologies. In the recent years there are several new ideas how to use thermal energy storage for electricity storage, or shorter for the power-to-heat-to-power. First of that was in combination with pressure accumulation systems, but now there are proposals for more or less pure thermal storage. The paper gives a short overview of those systems and explains the reasons for their relativly lower efficiency and the ways for increasing it. The importance of high temperature Pebble-Heaters in such systems is discussed in more details. It comments the effect of the entropy increase by transforming the electricity into heat and compare it to the case of fossil fuel power generation. At the end, the effect of ever cheaper renewable electricity, round trip efficiency and specific investment cost on the storage cost of such systems is discussed.

Keyword: *Energy storage, Power storage, Thermal storage, Non-Battery storage, Pebble-Heater*

1 Introduction

Electrical energy storage, or simpler energy storage, is a crucial way for wider penetration of renewable energy in the power generation and consumption. Those systems are required to smooth out the intermittent generation from wind and solar power. That is required in case of well-developed electricity systems, as well as in case of systems without a centralized grid.

The most extensive activities in field of energy storage are presently in the USA, especially in California, where it is recognised that the energy storage is a very important measure in overcoming the grid intermittency. Although the renewable generation was less than 20% of the total power generation in that time, as early as in 2012 it was estimated that grid intermittency will cause increased challenges in number of operational ramps across various time-frames, load-following up/down requirements and additional flexibility needs. The famous so-called “duck-chart” was plotted, with future scenarios of up to 33% renewable power generation in 2020 [1].

In Germany, the situation is quite opposite. Although it is considered very often as the leader in the renewable power generation with 33,1% in 2017 [2], the opinion in some expert circles close to politics was that energy storage is not required in the next 10 to 20 years, until a very high share of renewable power generation (even 90% !) is reached [3]. The anomalies that appeared on the power market in the last years have clearly shown that this was not the case. The share of renewables is increasing, while the electricity price on the stock market is falling, prices for industry and households increase with a rate of more than 5% per year, the steadily growing net export brings ever-smaller income and the most important fact: CO_2 and other GHG (greenhouse gases) emissions [2] are more or less stagnant! It is clear that the target for 2020 (reduction for 40%) will not be reached. The cost for stabilizing the grids, especially in case of high solar and wind generation, are increasing from year to year. Such measures range from curtailment and re-dispatching, till the export under very unfavorable conditions (even negative energy price!). Therefore, the previous opinion is changing fast and energy storage, together with new grids, are recognized to be the inevitable components of the German “Energiewende” – Energy Transition.

Different energy storage systems are already in use worldwide, many others are still in the development. They use different storage principles, from chemical batteries, mechanical fly-wheels, super capacitors, thermal energy storage, compressed air storage, to classic technology like the pump hydro energy storage. For distributed power generation from renewable energy sources (RES) there is more need for smaller, distributed storage system. However, in some power systems the renewable generation is not distributed any more, like in case of wind generation in North Germany. Therefore, the range of required storage capacities is also very wide, from kWh until hundreds of MWh per day. Some of the storage systems are already using thermal storage, at least partially. However, in the recent years there are developments for completely heat energy storage, which will be presented here. Those different storage systems are characterised by very different capital costs, round-trip efficiencies, maintenance costs and life-time expectations. The most important criterion, which will determine its applicability in a specific storage condition, is the levelized cost of electricity (LCOE), taking all those characteristics in consideration.

Generally, without the wide usage of energy storage, it will not be possible to reach higher penetration of renewable energy sources for power generation, as demanded by many energy policies, and therefore to reach the desired reduction of GHG.

2 Thermal storage

There are two principles for using thermal storage as the energy storage for electricity production. The first one is to store the heat coming from some RES (e.g. solar, biomass) or any other source and later to use it to produce electricity when there is a need for it. In the next chapter, few examples will be presented.

The second principle is to use the surplus of available electricity and to transform it into the heat that will be stored. When there is additional need for the power generation, the stored heat will be used for that. There is some new developments in that direction and therefore the reasonability of that principle will be discussed here in more details.

The first impression is that it is a nonsense: to transform the electricity into heat and then, later, again back to the electricity, but according to the laws of thermodynamics with a lower efficiency. It is a common truth that heat is the lowest form of energy. It means, the electricity may be transformed into heat with high efficiency, but transforming heat into electricity will be coupled with high losses. However, temperature defines the quality of heat, as shown in Figure 1 [4]. It is not the same if one transforms electricity into heat at 2,000°C or at 100°C. Moreover, heat available at 10,000°C has higher exergy then the natural gas, for example. Therefore, the common opinion mentioned here at the beginning is not generally right, but depends strongly on temperature. That is the reason why the electricity transformation into high temperature heat may be a reasonable solution for some storage technologies.

The second criterion that speaks in favour of this principle is the economy. The price for the renewable electricity generation is ever lower and lower. The lowest price achieved for photo-voltaic (PV) solar electricity is as low as 17.9 US$/MWh [5]. The lowest wind power price is even lower with 17.7 US$/MWh [6]! Moreover, those prices are expected to go down further. Important to mention: those prices are market prices, achieved in a public bidding, not the ones influenced by the politics.

It means, at least in those two cases the energy from renewable electricity is lower than energy from some fossil fuels (natural gas, fuel oil…). The consequence is: it is more viable to produce electricity from the surplus stored in form of heat, than from natural gas!

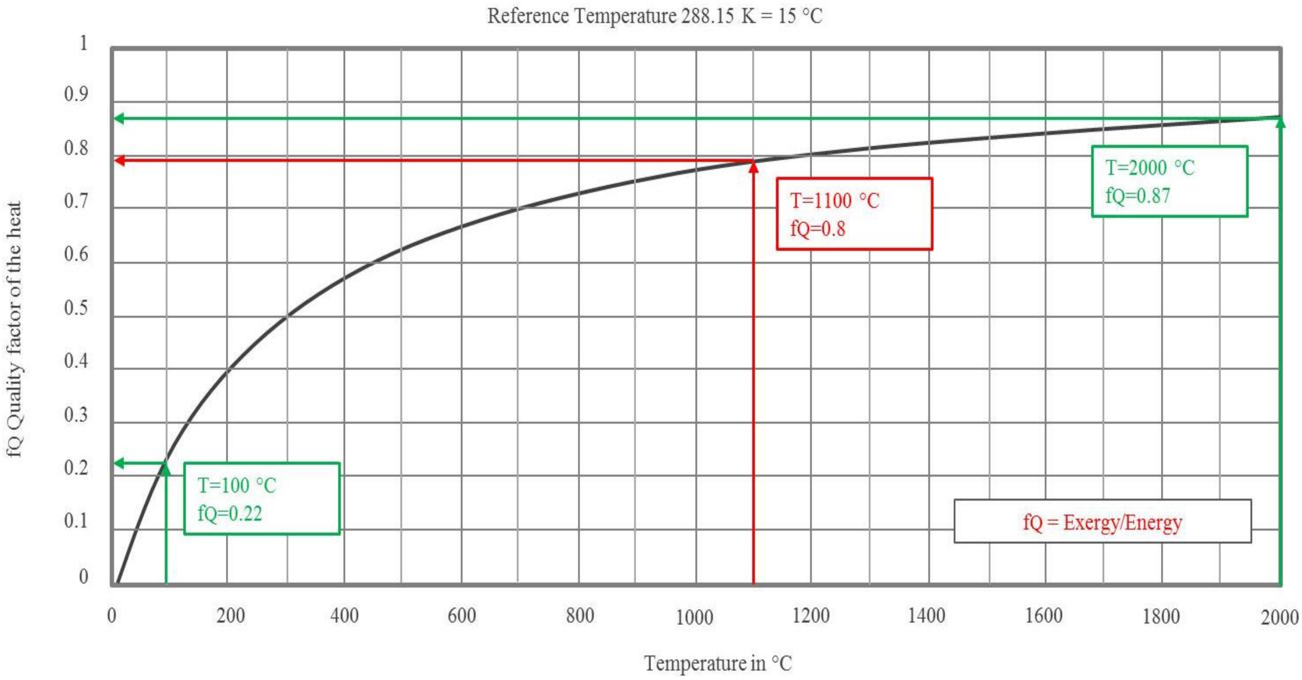

Fig. 1 The thermodynamic quality factor of heat, indicating the fraction of exergy in the amount of energy (adapted from [4])

However, let us stay with thermodynamics. We know very well that transforming electrical energy into heat will result in entropy increase. That increase will be lower with higher temperature of the heat, but it will always be some increase.

To achieve the right comparison, we should think about the entropy increase of the electricity generation. That is in most cases neglected and we make the entropy analysis starting from the given fuel. However, if the electricity is generated from the fossil fuel, the entropy increase will be tremendous higher than in case of renewable generation. The age of fossil fuels is millions of years and in less than a second it can be burnt. Moreover, resulting CO_2 is diluted into the atmosphere, leading to the additional entropy increase.

Therefore: The entropy increase of the whole process chain renewable-electricity-generation / transformation-to-heat / storage / electricity-generation is considerably lower than in the case of fossil electricity generation! Thus, this principle of the energy storage is reasonable, as it can compete the other storage technology and especially the lithium based battery storage. At the end of the day, different storage technologies will be the optimal solutions for different applications.

3 The first principle of thermal storage

As already mentioned, heat coming from some RES is stored when it is available and used later, when there is a need for additional electricity generation.

The well-known system based on that principle is the CSP (Concentrated Solar Power). Most present day solutions of CSP are coupled with heat storage, usually in form of latent heat of molten salts. In the so-called receiver, the concentrated solar power is used to heat and melt some salts. The liquid salt is used to produce steam that generate electricity through the steam turbine cycle. Some portion of that liquid salt may be stored in special insulated tanks and used for electricity generation during the night.

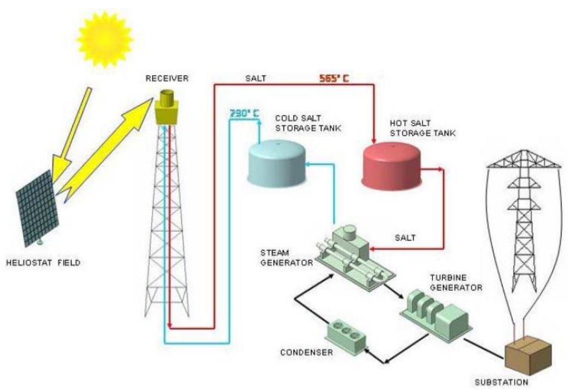

Fig. 2 CSP system with cold and hot salt tanks [7]

The first draw-back is the investment cost for that storage. Therefore, only 4 hours generation during the night (or generally periods without insolation) are realized in the present system. Recently, there are project with up to 12 hours storage capacity. The second draw-back is that the melting point of used salts is about 560°C [7], therefore the efficiency of steam cycle is not as high as in the most modern fossil fuelled plants. Usually it is only about 28% [8].

However, the biggest advantage of CSP systems is that it is a technology used in several operating big-scale facilities. In fact, that is the only available technology for such energy storage. There are some new projects with Li-Batteries, but they are still not at the same level of development.

In [9] it is described how the HiTES system (will be described in more details in the next chapter) may improve the efficiency and reduce the capital cost of a CSP system. Instead of molten salt, ordinary air is used to transport the high temperature heat from the receiver to a storage vessel (a kind of Pebble-Heater) filed with high alumina ceramic balls. That is the step, which reduces the capital cost. The next step is the usage of high temperature heat to drive a gas turbine, instead of the steam turbine. That increases the process efficiency to 45.8% [9]. However, that process still has to be fully developed, although all required components and technologies, including materials for a high temperature receiver, are available.

Fig. 3 Artistic view of high temperature receiver for Hyperion [11]

The company Hyperion Energy UG has also recognized the weaknesses of a classical CSP system. They proposed to use some solid blocks [10], instead of molten salt, in order to store the high temperature heat, even above 1000°C [11]. However, they stay with a steam cycle, probably with a higher efficiency compared to a classical CSP (due to higher temperatures), but there is no indication about its value.

4 The second principle of thermal storage

As mentioned earlier, the second principle is to use the surplus of available electricity and to transform it into the heat that will be stored. Some examples will be explained here.

The old idea of CAES (Compressed-Air Energy Storage) has been recently improved with heat storage, too. The improved system is called Adiabatic Compressed Air Energy Storage, named also ADELE [12]. It was under development of several big industrial companies. Adiabatic here means: additional use of compression heat to increase efficiency. As the compression heat origins from the electricity powering the compressor, it is also classified here.

The original CAES needed fossil fuel (natural gas) to heat up the compressed air before the expansion in the gas turbine. Otherwise, after the expansion, the air would have temperatures below the ambient and the efficiency of the round trip process would be very low.

In order to avoid that disadvantage, in ADELE (adiabatic) solution the compressed air is cooled down before the storage in a cavern. That heat is stored in a thermal storage, with solid storage elements. When the electricity is needed, compressed air is heated up with that stored energy, before its expansion in a gas turbine.

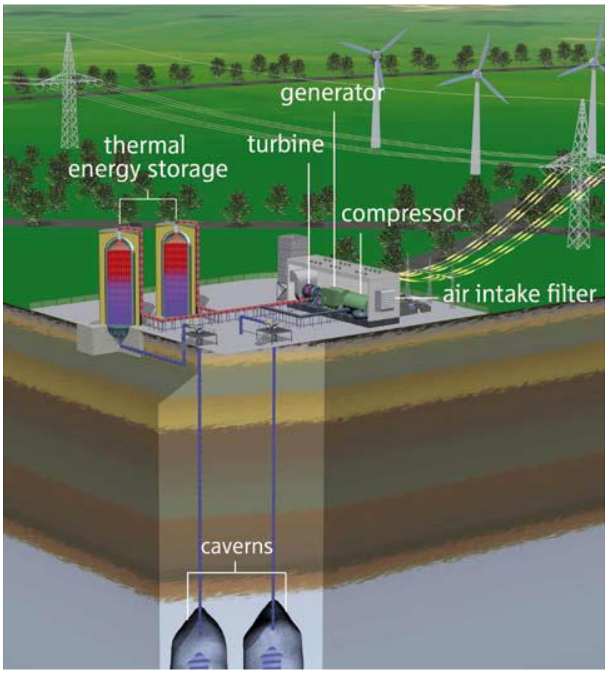

Fig. 4 ADELE system with heat storage [12]

Therefore, the ADELE solution does not need additional fossil fuels. The pressures may be higher, up to 100 bar and compression heat, stored in the thermal storage is even higher than 600°C. The expected round trip efficiency of 70% [12] is probably too optimistic, but that could be a very good storage possibility. The commissioning of the first plant was planned for 2019. Unfortunately, the project was cancelled in 2015, due to the lack of viable market conditions in Germany. Here it has to be mentioned that even the pumped hydro storage facilities in Germany have hard times, due to the same reasons. On the other hand, lot of renewable electricity has to be curtailed, or sold under very unfavourable conditions. Technically and economically, there is a tremendous need for storage technologies, but the energy policy has not succeeded to establish required market conditions. Therefore, once when those conditions are there, it may be expected that the ADELE system will be applied together with other solutions.

Just recently, Siemens announced their development of the thermal storage system [13], named SiFES (Siemens Future Energy Solution). The excess electricity, e.g. from wind mills in North Germany, will be converted to heat in rock fill and protected with an insulated cover. When additional electricity is needed, a steam turbine converts the heat energy back to electricity. The simple principle of this store promises an extremely low-cost set-up [14].

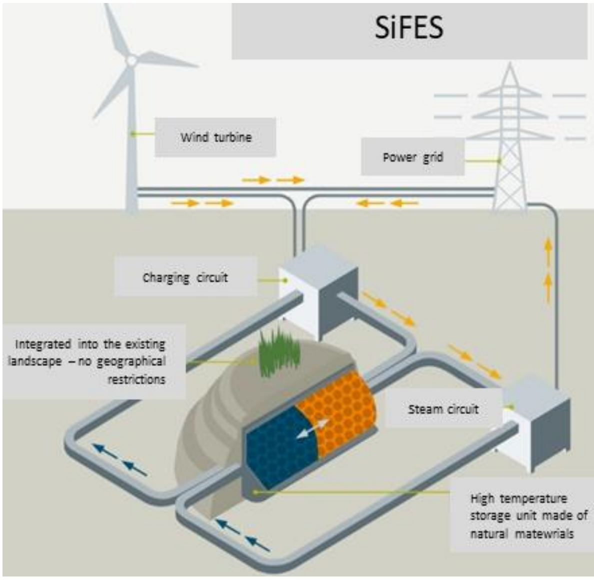

Fig. 5 SiFES system for thermal store of wind energy in natural rocks [14]

The store is being tested at temperatures above 600°C. A complete test facility is built close to Hamburg and will be able to store 36 MWh in a container with around 2,000 cubic meters of rocks. A compact steam turbine will be able to generate up to 1.5 MW of electricity for up to 24 hours a day. The round trip efficiency of that facility is expected to be 25%.

In the future, facilities of more than 100 MW output could have the efficiency as high as 50% [14], what is probably to high even for an ultra-modern (and expensive!) steam cycle.

Another thermal storage development for extremely high temperature storage is HiTES system (High Temperature Energy Storage). Compared to SiFES, the temperature is even higher (1100°C), so that even a gas turbine cycle may be used with high efficiency. From one side the efficiency is higher, but even more important, the starting time is extremely short, what is crucial for a storage facilities. Sometimes, they have to start with power generation several times per day, what is practically impossible with a steam turbine. Further-on, it is foreseen to build smaller, standardized facilities, in order to have low investment cost and a unit suitable for distributed renewable power generation.

This patented solution [15] is based on three proven technologies:

- Electric Resistive Heating
- Pebble-Heater technology
- Radial Gas Turbine.

The combination of those three technologies gives a rise to a new system that is suitable for medium-term storage, from several minutes up to several days. The details about principles of operation are given in [16] and other technology details in [17].

Figure 6 gives the flow diagram and nominal process parameters. The system of 4 small Pebble-Heaters may be seen there. They are used for cycle recuperation, so that the electricity may be used just for storing very high temperature heat in the main storage tank. The ceramic pebbles there are heated from 550°C to 1100°C.

With one heat storage tank it is possible to get 20 MWh of stored electricity (2 MW generator output for up to 10 hours). However, it is possible to increase the number of heat storage tanks to 2 or 3, thus increasing the power generation time to 20 h or even 30 h.

Due to a very effective gas cycle recuperation, the round trip efficiency of 40.3% is achievable, even with a standard and robust radial gas turbine of only 2 MW nominal output. The potentials for further improvements, with the same small radial gas turbine, involving fogging, water injection, increase of turbine inlet temperature (TIT), decreasing/optimising the pressure ratio, wet compression and intercooling, are thoroughly examined in [9]. Figure 7 presents those results. Up to 55% may be achieved with those relative small turbine optimisations.

Figure 8 present the artistic view of such facility.

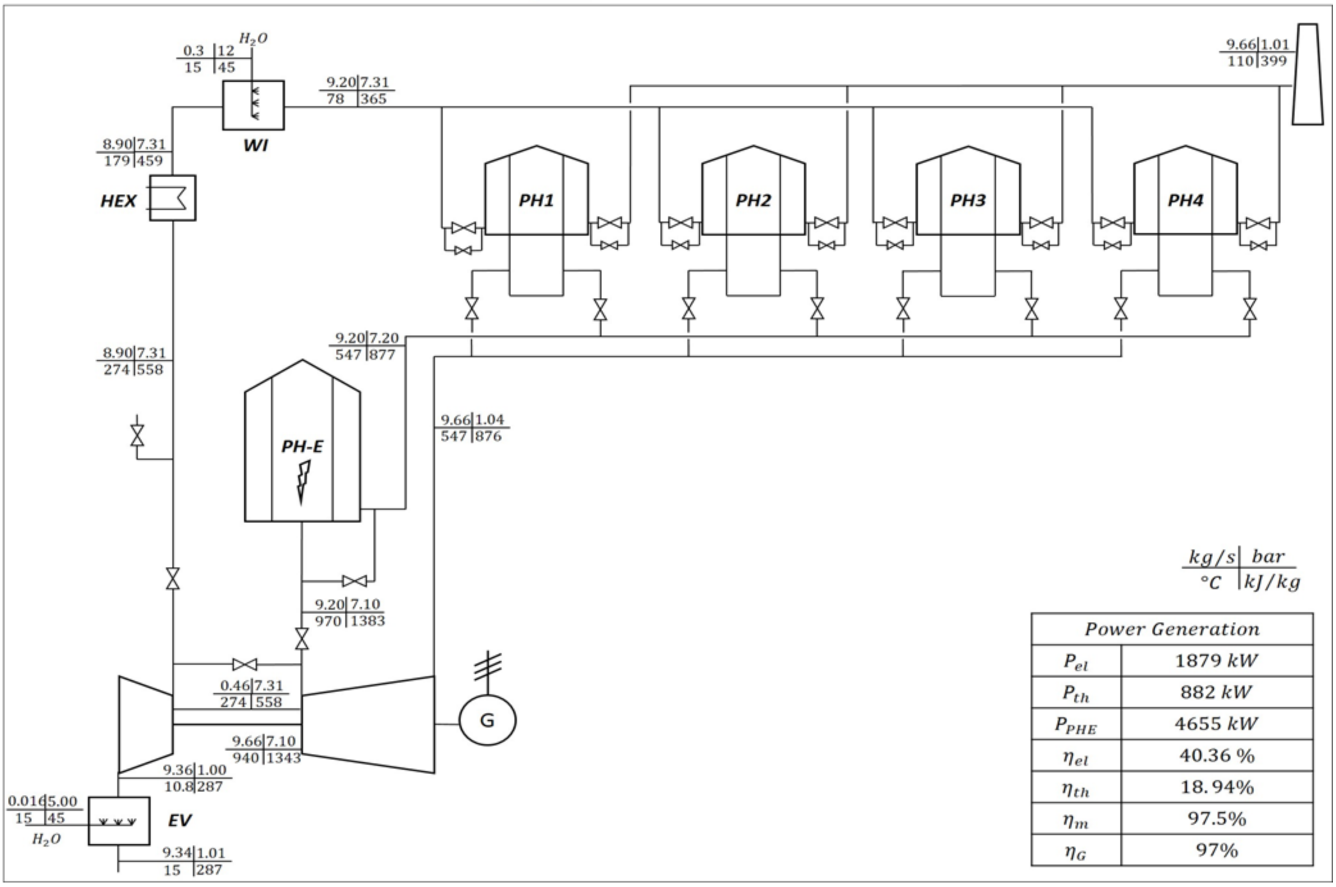

Fig. 6 Flow diagram and nominal process parameters of HiTES facility [16]

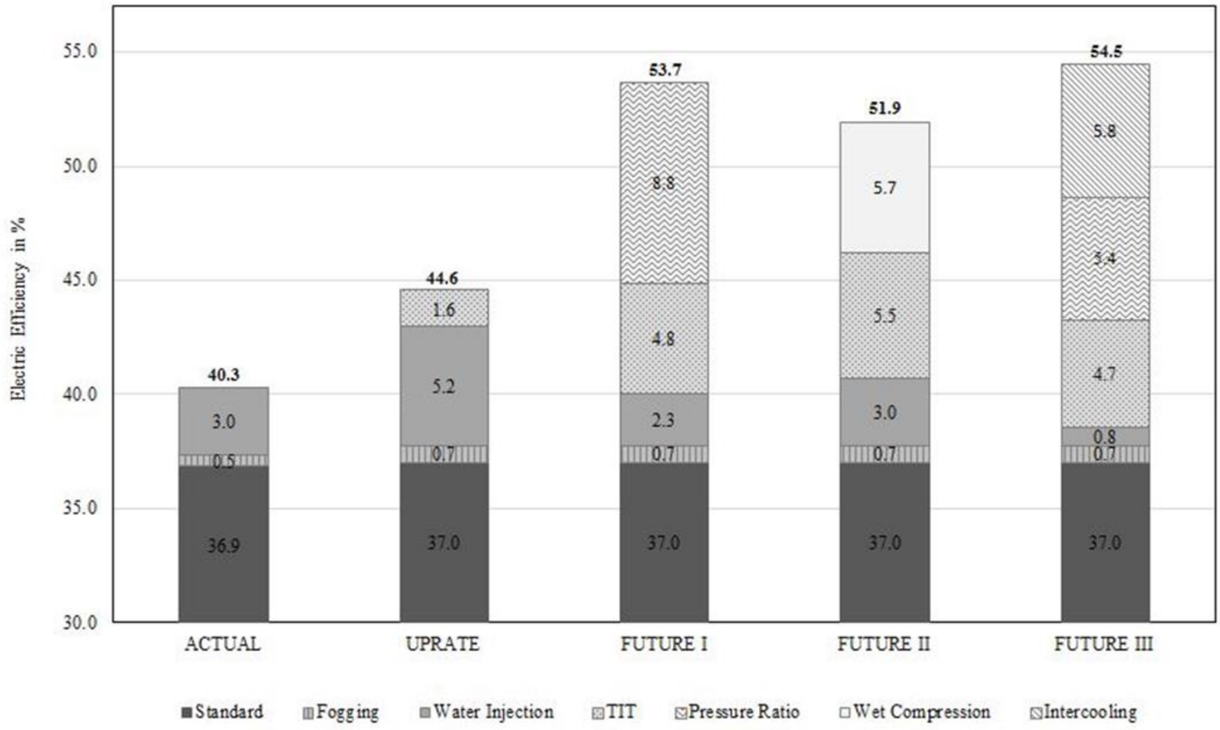

Fig. 7 Potential improvements of HiTES cycle efficiency [9]

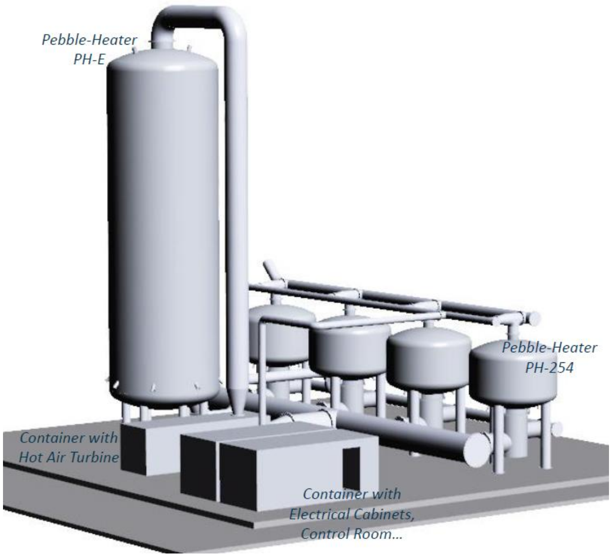

Fig. 8 Artistic view of the HiTES facility

There are some other developments that may be classified in this group of thermal storage principle. One of them is the development started by the British company Isentropic Ltd. It is based on a reciprocating heat pump and two thermal storage devices, one for heat, the other one for cold [18]. When the electricity is needed the reciprocating engine produces work and the electro-motor turns to be a generator, producing electricity. It works with argon at 25 bar and between 500°C and -160°C. A first small scale facility (150 kW, 600 kWh) has been built at the Newcastle University and the first operational experience is expected.

There are several development with cryogenic energy storage. Almost every company dealing with liquefied gases is involved in such developments. The most famous is the LAES (Liquid Air Energy Storage) under development from Highview Power Storage [19]. They already have some experience with a demonstration plant of 350 kW / 2.5 MWh. The main storage tank is for liquid nitrogen, but also some waste heat storage is needed. In case that some waste heat from an industrial process is available free of charge, the round trip efficiency is stated to be around 70%. The main advantage of that facility is a very low place requirement.

5 Levelized cost of electricity storage

There are many storage technologies, not just based on the thermal storage, which will compete on the market. Usually, the round-trip efficiency is the first criterion for comparing different energy storage technologies. However, knowing that a storage facility has to generate power for less than 4000 h/a, it is clear that the specific investment may play a more important role than the efficiency. Therefore some authors use the specific investment costs per kWh of stored electricity and the others prefer the specific investment costs per one kW of the output (or input) capacity. The problem is that comparisons based on such different criteria give quite different results [17].

Other criteria, like the maintenance cost, life expectation, capacity degradation during the lifetime, play also an important role. Therefore, the only right approach is to use the levelized cost of electricity storage (LCOES). It is similar to the model used for costs of electricity generation from power plants. It includes all relevant parameters: capital expenditure (*CAPEX*), annual operational expenditure (*OPEX*), energy output W_{el}, interest rate i and the lifespan n in years [16]. Due to some differences compared to the electricity generation costs, the LCOES has to be extended with the characteristics of energy storage systems: costs of the input electricity σ and the round trip efficiency η_{el}. The resulting formula for the levelized cost of electricity storage (LCOES) is given in equation:

$$LCOES = \frac{CAPEX}{W_{el}} \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} + \frac{OPEX}{W_{el}} + \frac{\sigma}{\eta_{el}}$$

In order to point out the most important parameters, in Fig. 9 only two technologies are compared, taking into account the costs of the input electricity (i.e. the influence of the round-trip efficiency) as well. Those two energy storage systems are compared [20]:

- One with high specific investment cost of 1600 €/kWh and with 85% round-trip; the cost may be reduced to 800 €/kWh due to the further development;

- The other system has a considerably lower round-trip efficiency of 40%, but also lower the specific investment cost of 250 €/kWh (e.g. HiTES with 20 hours discharge time); the round-trip efficiency may be improved to 50% and 60%, retaining the same specific cost.

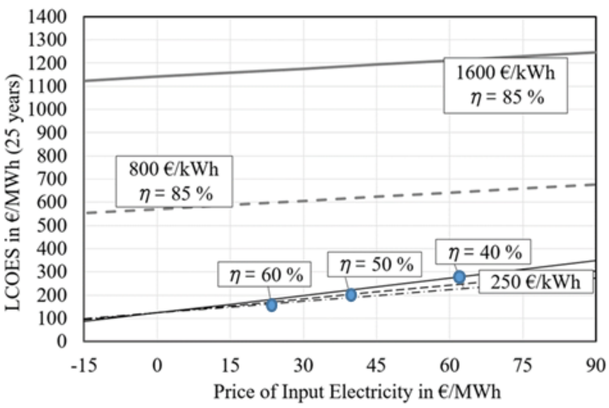

Fig. 9 Influence of specific investment, efficiency and price of input electricity on LCOES [20]

The storage costs LCOES (€/MWh) are given with presented curves, as a function of the input electricity cost (also €/MWh). As indicated in Section 2, the prices for solar and wind generation in the last years are falling tremendously. Moreover, due to high penetration of intermittent renewable power generation in some energy systems, it happens more and more often that the stock market prices are negative. Therefore, the negative input electricity prices are plotted in the graph, as well.

Two important conclusions may be drawn from the graph in Fig. 9 [16]:

- The specific investment costs are more important than the efficiency; the improvements in the investment cost are more important than the improvements in the efficiency;

- With the falling prices of renewable generation, the above effect becomes more and more important: In case of negative cost of the input electricity, lower efficiency gives lower LCOES(!).

6 Conclusion

There are many energy storage technologies. Non-battery storage systems already have a dominant role and it will probably stay like that, although batteries will also have their role, mostly for smaller capacities. Thermal storage is also a reasonable solution, even when electricity is transformed to heat. Especially high temperature heat is an attractive solution, as it means less exergy loss and higher efficiency for the re-transformation into electricity. At the end, it means smaller entropy increase, so that not only from the economical point of view is that solution viable. Anyhow, that entropy increase is tremendously smaller than in case of power generation from the fossil fuels and uncontrolled dilution of CO_2 into the atmosphere.

Which system will be the most attractive, regarding local conditions and required capacity, depends on the LCOES. It shows clearly than not only the round-trip efficiency is important, but even more the specific investment. The analysis of LCOES, which is the best comparison criteria, shows that some thermal storage systems are more favourable than the batteries. Even today, those systems could be used in a viable manner in countries with high insolation, or cheap wind electricity. In combination with photovoltaic plants, it gives lower cost of the electricity supply than concentrated solar plants (CSP).

The most important: Without energy storage, it is impossible to integrate in higher degree the generation of renewable electricity based on intermittent sources like wind and solar. The case that even old pumped hydro storage plants cannot operate in some power systems, clearly demonstrates the false preconditions of the present energy policies there.

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