Chapter 2

High Temperature Energy Storage (HiTES) with Pebble Heater Technology and Gas Turbine

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Additional information is available at the end of the chapter

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Abstract

In modern power systems with high penetration of renewable energy generation, the energy storage is very important, not just for the load control for quite different time periods, but even in the frequency control. If it is missing, the anomalies occur, like the stagnant CO_2 emission, export of the overproduction under unfavourable conditions, curtailments of wind-mills and/or negative market prices for electricity. The new technology is a high temperature thermal electric energy storage. It is based on the combination of three state-of-the-art technologies: pebble-heater, radial gas-turbine and electric resistive heating. Due to very high temperature (1100°C), low exergy losses during the heat transfer and water injection in the gas-turbine process, the round-trip efficiency is high even with nowadays available components. With some moderate improvements of the gas-turbine it could be increased towards 60%, even at 2MW low generator capacity. The discharge time is 10 h; due to the modular design, it may increase to 20 or even 30 h. The analysis of LCOES (levelized cost of electricity storage) shows that even today that system could be used in a viable way in countries with high insolation or on sites where an autarchic power supply may replace expensive market electricity.

Keywords: energy storage, high temperature, pebble-heater, radial gas turbine, hot air turbine, resistive heating, power-to-heat-to-power, LCOES

1. Introduction

Energy storage is used to store an overproduction of electricity and to use it again in periods of higher power demand. The pumped hydro storage is one of the oldest systems, especially for mass storage, which has been in use for many years. Previously it was used only for load control, that is, for smoothening the electricity consumption, mostly between day and night, in systems with higher capacities of base-load plants, like coal and nuclear power plants. Instead of reducing their output and entering into the zone of lower process efficiency, their overproduction was stored, always enabling the optimal operation parameters. Those were well-defined periods of time, well planned and without rush load changes.

1.1. Influence of renewable power generation

In the modern systems with high penetration of renewable energy generation, like from wind and solar, the situation has been drastically changed. Not the consumption, but the generation is now what has to be smoothened. Those changes may be very fast and may last very long, even several days or weeks. It means the modern power storage devices have to participate in the load control for quite different time periods but additionally even in the frequency control.

The problems with the intermittent generation do not start immediately after the installation of the first unit. Big power generation systems may absorb easily small disturbances in the system. It depends on many factors, but the experience shows that with about 20% penetration of the intermittent power generation, big problems occur. Then there is a strong need for higher usage of energy storage systems, together with other measures, like new grids, demand response, etc. Otherwise, curtailment or export under unfavourable conditions has to take place. However, it is important to understand the difference between the effects of new additional grids and the energy storage systems: With a grid, it is possible to transport a local power overproduction to some other areas with higher demand at that moment; however, a time shift, like with storage systems, is not possible. Moreover, new big grids implicitly lead to a more centralised generation, which was not the idea with the introduction of renewable power generation. Therefore, the best long-term solutions are energy storage systems that support distributed power generation.

1.2. Examples for the need of energy storage

In Germany, which is one of the leaders in the renewable power generation with some 33% in 2015, the opinion [1] was that in the next 10–20 years, there is no need for energy storage. That will change first when a very high share of renewable power generation (even 90%!) is reached. Meanwhile, in the last years, many anomalies that appeared on the market demonstrated that this is not the case. The electricity price on the stock market is falling, as the share of renewables is increasing. On the other hand, prices for industry and households increase with a rate of more than 5% per year. The net export is steadily growing but brings ever smaller income. The most important and the most absurd fact is that, in spite of all efforts with increasing the usage of renewable generation, the emission of CO_2 is more or less stagnant! That infliences fast changing in the previous opinion: it is now recognised that energy storage, together with new grids expansion, is the inevitable component of the German "Energiewende". That case of Germany was described in detail in [2], showing that 40% of intermittent renewable electricity cannot be used domestically and has to be exported. In 2016 that trend has continued, as presented in [3]. Although the yearly increase of intermittent electricity was small (only 4.0 TWh), all of that increase had to be exported! On the other hand, the curtailment of many wind mills occurs very often, as the last option to get rid of the electricity overproduction. The need for energy storage in Germany is obvious.

California is the US state with the highest penetration of wind and solar power generation. Contrary to Germany, they have started thinking about and analysing the potential problems of intermittent generation much earlier. The “Duck Chart” was created by the California Independent System Operator to show that increasing solar generation paired with conventional base-load plants that cannot be turned off (e.g. nuclear and less flexible natural gas) can cause over-generation in the afternoons during certain months [4]. The chart shows that the shape of the net load curve begins to shift dramatically in 2015 due to increasing solar generation and there is potential for over-generation during the afternoons beginning in 2018. An especially big problem is a very fast ramping between 17 and 19 h (13.5 GW in 2 h!). To solve those potential problems, several measures were planned, like demand response, import/export, curtailment and energy storage. Being unfavourable measures, import/export and especially curtailment were minimised. Nowadays California is the area with the most installed energy storage systems, and several new projects are planned.

In some areas of Chile, there is a locally very high penetration of the solar power generation, based on photovoltaic systems. As the insolation is very high, the price of that electricity is low (<3 ₵ /kWh). However, every day at around noon, the market price goes into the negative area, as there are not enough consumers when the generation reaches its daily maximum. Therefore, there are some projects for energy storage facilities and some new generation facilities but based on concentrated solar power (CSP) with integrated molten salt storage.

Many countries with high insolation will be very soon in the same situation. In fact, many of them are waiting on a suitable solution for the energy storage in order to start a wide range of usage of solar power, which is a very competitive solution there.

1.3. Thermal energy storage

There are many technologies for energy storage. Some are suitable for long-term storage, the other for short-term and some of them even for the frequency control, with very fast response time. They are all using different principles, and therefore they have different advantages and disadvantages. Roughly, there are mechanical, chemical, electrical and thermal storage technologies.

Thermal energy storage is mostly famous for the molten salt facilities. They are used almost exclusively with the concentrated solar power (CSP) systems, where solar heat is stored and later used for power generation through the steam turbine cycle. The efficiency is about 32–36%, and the investment cost is still high. Due to the storage capacity of up to 10 h (some special cases), they are attractive, as that is the only available technology nowadays to store solar power for a longer period. There is also development to transform the electricity into heat and store it underground in some rocks or gravels (see the web presentation of Siemens [5]). Afterwards, that heat is used to generate electricity, again over a steam turbine cycle. In that case, the temperature is limited to 600°C. The HiTES system [6] has a considerably higher temperature: up to 1100°C. The leading idea is that the exergy of stored heat is much higher at elevated temperatures. The quality of heat at 600°C is about 65%, while at 1100°C it is already 80% [7]. That makes it possible to reach a higher round-trip efficiency, even with heat storage systems. That system is presented in more details in the next chapters.

2. Components of the HiTES system

High **T**emperature **E**nergy **S**torage (or shortly HiTES) is a new technology for energy storage based on three technologies that are state of the art:

- Pebble heater technology
- Radial gas turbine
- Electric resistive heating

Those three technologies are combined in a new system, which suits well for medium-term storage, from several minutes up to several days. Electricity is used to heat up the heat storage material (pebbles) in a high temperature pebble heater by electric resistance heaters, during periods with electricity overproduction. If there is a need for additional electricity, a gas turbine coupled with a generator will produce it from the stored high temperature heat.

2.1. Why high temperature?

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** [8]. It is not the same if one transforms electricity to heat at 2000°C or at 100°C. Moreover, heat available at 10,000°C has higher exergy than 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 has been selected in this storage process.

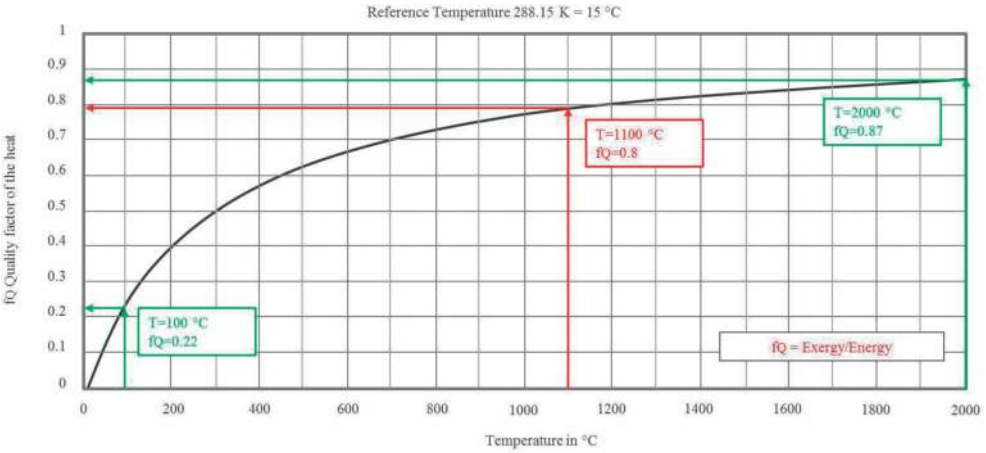

Figure 1. The thermodynamic quality factor of heat, indicating the fraction of exergy in the amount of energy (adapted from Klimstra [8]).

Material is the limiting factor—is not easy to realise, for example, 2000°C. In the case of HiTES, it is 1100°C: all available components are made of material that can withstand it, and the quality factor is still very high (0.8).

2.2. Why pebble heater technology?

The pebble heater technology has been selected as it is very suitable for high temperatures, and due to high heat exchange surface, it produces very low exergy losses. Such an example is presented in **Figure 2**. A heating gas enters the bed with 1350°C and has 160°C at the outlet. During the next phase, a gas which has to be heated (air in this case) has 90°C at the inlet and leaves the bed with 1280°C. The temperature difference between those two gases is only 70 K on both sides of the pebble bed. That gives an exergy efficiency of 95.2%. It is even less than 50 K in many applications. The recorded minimum was 15 K, leading to the exergy efficiency of above 98%.

Those characteristics make the pebble heater technology very efficient for the applications like thermal oxidizers (recuperation efficiency above 98% [9]), hot gas supply at temperatures above 1400°C (even H_2 has been preheated), steam superheating (1200°C) for some special chemical reactions, steel converters [10, 11], blast furnaces [12], regenerative burners [13], etc. For HiTES technology, the pebble heater is a component which is crucial for reaching high process efficiency. For more details about that technology, see Chapter 3.

2.3. Why radial gas turbine?

That type of gas turbine sets has been selected due to its extraordinary reliability recorded even in extreme conditions on oil rigs and gas fields, from sea platforms till Siberia. Despite small capacity (approx. 2 MW electric) and its simplicity, a modern design leads to

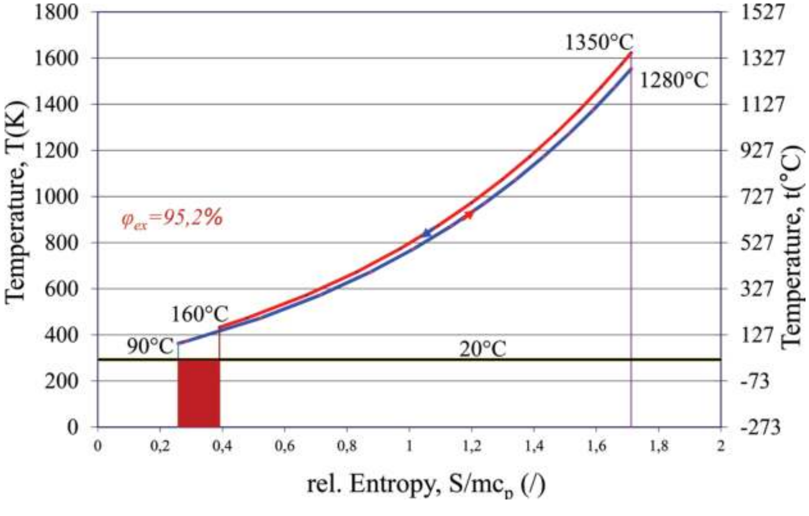

Figure 2. Entropy increase during the heat transfer in a pebble heater.

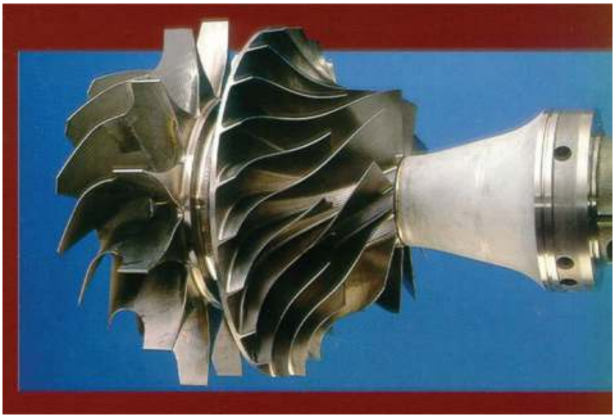

Figure 3. Rotor of a radial gas turbine with expander (left) and compressor (right) [14].

the efficiency of even 25% in a simple open cycle. They are very robust, have single shaft with cold end drive, have easy maintenance, have low lube oil consumption and have long inspection intervals. The models present on the market (produced by OPRA from the Netherlands and Dresser-Rand with its production facilities in Norway) have proven its abilities in much more than 1000 units built. The design for external firing, which is required for the HiTES system, is now also available. **Figure 3** [14] presents a modern all-radial design (expander, compressor and shaft).

3. Pebble heater

The name "pebble heater" is already known in the field of regenerative heat exchangers. It may operate at high temperatures for heating and cooling gaseous media by means of bulk material consisted of spherical balls, called pebbles. That is common for the previous and the new design of the pebble heater.

The most important difference is the flow direction: the bulk material is fixed between two vertical, concentric and permeable cylinders (hot and cold grid), so that the fluid flows radially. At the first sight, small difference results in further extraordinary advantages. As there is no danger of fluidization, the flow velocity may be increased, and smaller pebbles may be used. That improves dramatically the heat transfer, especially through very high ratio of surface to volume, that is, specific surface. With those characteristic it is easy to reach a thermal recuperation efficiency of 95%; even 98% has been achieved with a unit in operation. As a result, the exergy losses are small, and the temperature difference between two gases (heating and cooling) is as little as 20 K—all that at temperatures up to 1500°C!

That intensive heat transfer results in a temperature gradient as high as 2000 K/m. Therefore the bed of pebbles is thin, and the pressure drop stays low or acceptable. The units are compact, which lead to low investment cost—the most important fact for investors.

3.1. Physical description

Outside, the pebble heater is a cylindrical vessel. Inside, there are two permeable grids with a pebble bed fixed in between. The inner grid (hot grid) is always at high temperature. It is composed of high-quality ceramic bricks. Each brick has a hole that ends with a honeycomb segment, in order to prevent the pebble fluidization. Those bricks are tested up to 1500°C, first in an industrial scale pilot facility and later in tenths of industrial facilities. The improved quality of the honeycomb segments will enable higher temperatures, up to 1700°C, as required for some special applications.

The outer grid is on the cold side and therefore referred as the cold grid. It is constructed of a perforated steel plate. There is no possibility for pebbles to fluidize or circulate, as they are fixed between those two grids. The cold grid temperature is usually held under 250°C. In such cases, the material for the outer vessel may be a conventional steel. Moreover, the outer insulation is not required, only some touch protection in some cases. Indeed, as presented in blue in **Figure 4**, some fire-clay insulation is only required at the hot gas inlet/outlet (bottom) and for the so-called dome, which closes the hot grid on the top.

In the case of applications with very high temperatures, the bed of alumina pebbles (>99% Al_2O_3) is the best choice. They are very resistant to the thermal shocks, so that the temperature

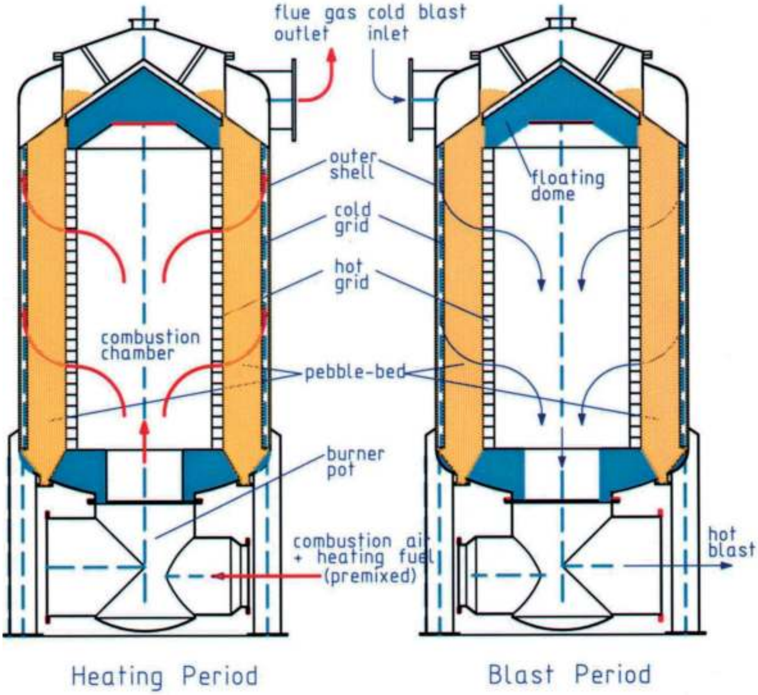

Figure 4. Pebble heater with radial design [12].

cycling of even over 400 K cannot cause any damage. In the case of less demanding applications, bulk materials like fire-clay balls or even river gravels are much cheaper solution.

The thermal expansion of the hot grid does not cause any sealing or stress problem, as it may expand together with the "floating" dome upwards freely; see **Figure 4**.

3.2. Operation of pebble heater

Being a regenerative heat exchanger, at least two units of pebble heater are required for a continuous operation. One unit is producing hot gas (blast), while one or more units are reheated. After a certain time, the reheated unit will switch to the blast phase, and the other unit will switch to the reheating phase. On that way a continuous supply of hot gas is secured.

The operation of pebble heater during those two phases is seen in **Figure 4**. In the case that the heating gas is a combustion product, the combustion takes place mainly in the chamber inside the hot grid. Flue gases enter the bed through the hot grid. Flowing radially through the bed, flue gases leave their heat to it and have a low temperature at the end of the bed. Cooled gases pass upwards, through the gap between the cold grid and the outer wall of the vessel, towards the exit.

When the bed is fully reheated, the burner stops, and the vessel is pressurised at the cold blast pressure. Then it enters and flows in opposite direction: first it distributes in the gap around the pebble bed and then passes through it. Heat is now transferred in reverse direction, from the pebbles to the gas. In the chamber inside the hot grid, the hot blast is collected and flows out through the hot blast main.

In some cases an existing waste hot gas may be used for reheating phase. Then there is no need for a burner, as the pebble heater recuperates the waste heat from that gas and uses it for preheating air or some other gas.

3.3. Mathematical modelling of pebble heater

To simulate the operation of such pebble heater with radial flow, the mathematical model has been developed, based on Crank-Nicholson numerical method [18].

The heater is axial-symmetric, and the upper and bottom walls are adiabatic, so the heat is transferred just in radial direction. Due to a very high specific surface available for the heat transfer (usually between 500 and 1000 m^2/m^3), the difference between gas and pebble temperature is almost negligible when compared to the temperature change during each phase. Vortmeyer and Schäfer have presented a so-called "homogeneous" model [15], which uses only one energy balance equation and gives good results in such cases. Originally, the equation of Vortmeyer and Schäfer describes a cylindrical pebble bed with axial flow. For the radial geometry, it was rewritten as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\Lambda_r\frac{\partial T}{\partial r}\right) = \frac{\partial}{\partial r}\left(m_o\,c_{Pf}\,T\right) + \left[(1-\psi)\,\rho_s\,c_s + \psi\rho_f\,c_{Pf}\right]\frac{\partial T}{\partial t} \qquad (1)$$

with the following notation: r is the radial coordinate; t – time; Λ_r – "effective" heat conductivity; T – temperature; m_o - mass flux of gas; $\Psi\psi$ - void fraction (i.e. bed porosity); c_s, c_{Pf} – specific heat (solid and gas phase, respectively); ρ_s,ρ_f – density (solid and gas phase, respectively).

All physical properties, including the "effective" heat conductivity, are functions of the temperature and indirectly of the radial coordinate, as temperature changes significantly with the radial position. Due to the change of the flow cross section with the radial coordinate, the mass flux of gas is also a function of the radial position. The "effective" heat conductivity in radial direction (Λ_r), which is introduced in this model, differs from the "classical" heat conductivity in the usual *Fourier* equation as it includes the effects of convection and radiation, besides the heat conductivity of fluid and solid. One can find several correlations for those terms in the literature. The correlations given by Bauer [16] and Till [17], which are valid up to a *Péclet* number of $Pe = 30$, are used here.

Eq. (1) is a partial differential equation of the second order. To solve it, one initial and two boundary conditions are required. The initial condition is some given temperature distribution over the bed radius. The boundary conditions are heat fluxes on the hot and cold end (i.e. hot and cold grid), which have to be defined.

As the "effective" heat conductivity and gas flux are not constant, there is not an analytical solution for Eq. (1). That type of *Fourier* equation may be effectively solved by using the Crank–Nicolson numerical method, as shown in [18]. That method is implicit, which is its main advantage, because it enables long time steps with good stability of the calculation process. Based on that method, a numerical code for simulation of the pebble heater operation has been developed, with typical results of the characteristic temperature profile through the bed given in **Figure 5**.

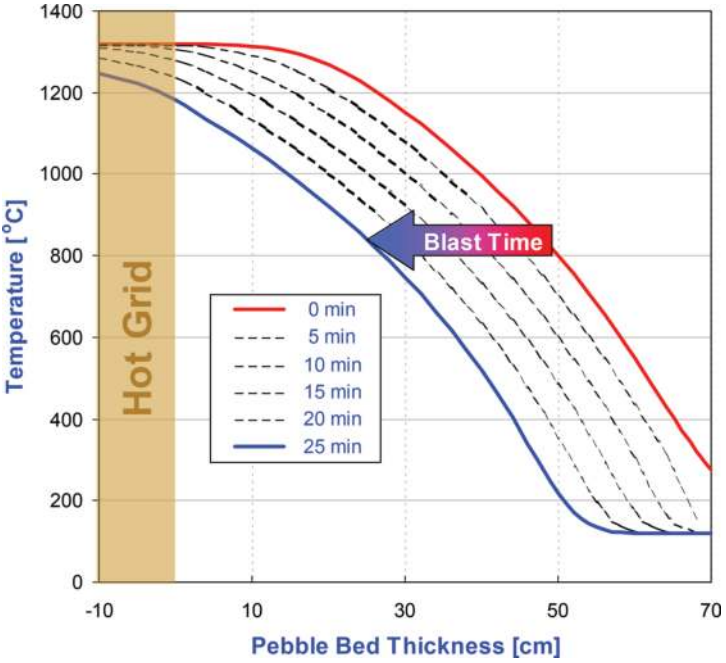

Figure 5. Typical temperature distribution inside the pebble heater.

Solving the energy Eq. (1) runs side by side with calculating the pressure drop through the pebble bed, through integration of the following equation:

$$\frac{dp}{dr} = \frac{1}{\psi^2}\mu\xi\frac{\rho\, w_o^{\,2}}{2\,D_e} \tag{2}$$

with following parameters: p – pressure; $\mu\xi$ – friction and path factor; w_o – gas velocity; D_e – equivalent pebble diameter.

The usual way for calculating the friction and path factor $\mu\xi$is the famous Ergun equation [19]. The comparison with measured values has shown that the correlation of Kast [20] is more accurate. Based on own measurements, the new correlations have been defined, which give even better results. Especially in the case of irregular shape of pebbles, those advantages were distinct.

3.4. Performance of pebble heater

Figure 5 presents the typical, S-shaped temperature profile inside the bed, which is an extraordinary characteristic of the pebble heater technology. It arises from the intensive heat transfer and resulting low temperature difference between gas and solid phases. That S-shape enables a temperature change of more than 400 K in the middle of the bed, and correspondingly high storage capacity, while the hot grid (and hot blast at the exit) exhibits a very moderate temperature drop.

Therefore the hot blast temperature stays almost constant at the first two thirds of the blast phase. Only in the course of the last third of the blast phase, there is a more intensive drop of the blast temperature (ΔT = 30–100 K, in different designs and operation mode. The same is with the temperature changes on the cold), usually in the range ΔT = 100–150 K. That is the reason for low mean value of the flue gas temperature and resulting low exit loss.

An extensive test series on the pilot unit PH 104 (10,000 $m_{i.N.}^3$/h) has proven the extraordinary characteristics of this new concept of heat regenerators:

- Between 92 and 95% of thermal recuperation efficiency
- Ability to sustain high temperature operation
- Stability of the hot blast temperature

In that test series, all main operational parameters (like blast rate, cycling time, flame temperature, etc.) were modified from test to test, in order to cover any possible operating condition. Those tests have proved that the recuperation efficiency of the pebble heater overpasses by far the efficiency of the modern stoves, even with recuperative heat exchangers for preheating combustion air and/or fuel gas.

In the meantime, since 1996 more than 20 facilities have been built. Most of them were used as thermal oxidizers; however, the biggest units are for hot blast supply for iron and steel industry. In the next years, even bigger units are expected to replace the old Cowper technology for blast furnaces.

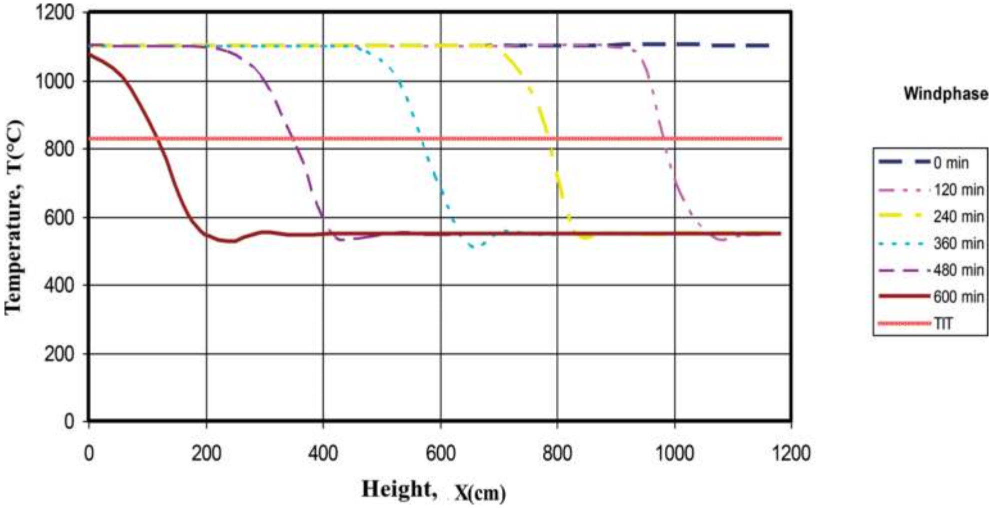

Figure 6. Typical temperature distribution inside the storage tower during 10 h discharging.

3.5. Application for energy storage

The extraordinary characteristics of the pebble heater technology are of decisive importance for the energy storage concept presented in this article. Each storage module consists of four smaller pebble heaters for the gas turbine recuperation (temperature range up to 550°C) and one more than 12 m tall electrically heated pebble heater. Small pebble heaters are in operation during gas turbine operation, and they are intermittent in charging-discharging operation, with time sequences of about 30 min.

The big pebble heater (or storage tower) is electrically charged when the gas turbine is out of operation. During that time (up to 10 h per tower), the temperature of pebbles rises from 550°C towards 1100°C. When the gas turbine is in operation, it delivers the high temperature compressed air for the turbine drive.

Figure 6 gives the typical temperature distribution inside such storage tower with a column of 12 m filled with 12 mm pebbles, during a discharging phase of 10 h. At the beginning, all pebbles are at the highest temperature of 1100°C. Then the compressed air with 550°C enters from the bottom (the right side of **Figure 6**) and flows upwards (to the left side). It is heated to 1100°C and the pebbles are cooled down. The S-type temperature profile is established, resulting with stable outlet temperature for a long time.

4. Operation of HiTES

The principles of HiTES operation are based on the patent document [6] and given in [7]. When the system is charging, only one pebble heater (PH-E in **Figure 7**) is in use. Electrical heaters

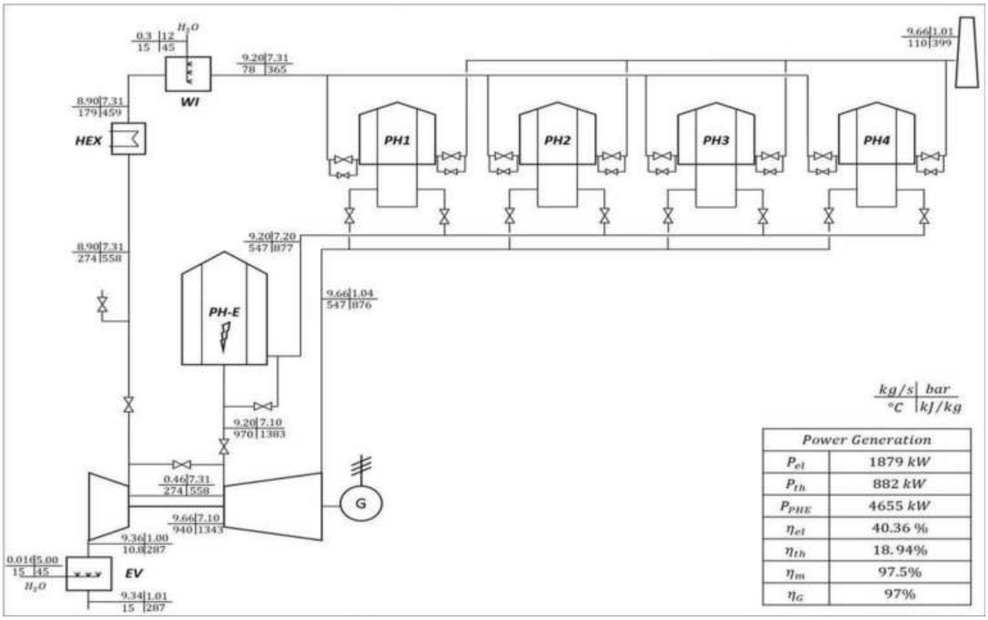

Figure 7. Flow diagram and nominal process parameters of HiTES [7].

heat up the storage material from 550 to 1100°C. That is very important for achieving good round-trip efficiency, as the charging electricity is stored only in form of high temperature heat.

When the system is discharging, all system components presented in **Figure 7** are in use. First, the low temperature pebble heaters (PH1…PH4) preheat compressed air to 550°C, and then it enters the high temperature PH-E where it is preheated to the end temperature of 1100°C. Hot compressed air enters the gas turbine and expands there, releasing mechanical work for compressor and generator drive. Expanded exhaust air heats up again the low temperature storage PH1…PH4. That heat is used later for preheating the compressed air, by activating the set of presented valves. In that way, always one pebble heater is in compressed air loop, and the remaining three are in the exhaust air phase. When a certain time (e.g. 20 min) has elapsed, another PH changes over to the compressed air loop, and the previous PH goes to the exhaust air loop and so on.

In the first step, it is preferred to use a radial gas turbine existing on the market, instead of developing a new one. Even the existing gas turbine (2 MW output power) in the HiTES system will reach approx. 40% of the round-trip efficiency that enables the profitability of the first units. After the maturity of this technology is proved in the industrial application, a new or modified gas turbine will be used, leading to higher efficiency and increased profitability of the system.

Some additional components have to be introduced with the existing gas turbine model in order to reach that high round-trip efficiency. Those are the fogging of the inlet air and compressed air cooling with water injection. The following description gives more precise process parameters (based on the ISO conditions 15°C, 1.013 bar abs).

When the system is discharging, the ambient air at 15°C, 1.013 bar absolute and a relative humidity of 60% enters into the compressor. In front of compressor, that air is cooled down by fogging. On one hand that decreases the compression work, and on the other hand, the fogging increases the mass flow by increasing the density. At the compressor outlet, the air has 7.3 bar and 275°C. The subsequent heat exchanger takes out some amount of heat from the compressed air, and by water injection, the further cooling is achieved. It is possible to inject 0.3 kg/s of water, before reaching the dew point temperature. Again, that leads to the higher mass flow rate and lower temperature of the compressed air. That injected water can be considered as a replacement for the fuel mass flow missing in such application of the gas turbine. In that way, the compressor and the expander work very close to the design point. The cooling of air entering the pebble heaters PH1…PH4 is important for the efficient heat transfer, as it leads to lower outlet temperatures during the exhaust air phase, meaning lower heat losses. Such preconditioned compressed air passes through one of the pebble heaters (PH1…PH4). Due to previously described advantages of the pebble heater technology, the air is preheated almost to the turbine exhaust temperature, leading to the high recuperation of the gas turbine cycle. After the low temperature PH, the compressed air flows through the high temperature pebble heater (PH-E), where it is heated further to 1100°C. In front of the expander, the air temperature is adjusted to the required inlet parameters (970°C), by controlling the bypass valve. That air is mixed with the turbine cooling air, preventing the overheating of the turbine guide blades. In that way, the turbine inlet temperature (TIT) of 940°C is reached. At the turbine outlet, the expanded air is at about ambient pressure and 540°C. It flows through the remaining three pebble heaters and heats up the pebbles. Thus it is cooled down to about 110°C and with that temperature leaves the system through the chimney.

Starting from the nominal turbine output of 2 MW and the round-trip efficiency of 40%, the suitable high temperature storage capacity of pebble heater PH-E is 50 MWh (i.e. 10 h heating with 5 MW of input power). In that case the discharging phase may deliver maximum 20 MWh of electricity (again 10 h with 2 MW electrical power). In a modular concept of the facility, two or three identical PH-E may be coupled with one gas turbine set. Respectively, the output of 2 MW power may be delivered for 20 or even 30 h.

With the refractory inside the PH-E made of high-quality fibre modules, the storage time of the high temperature heat may be from several minutes up to several days. **Figure 8** presents the temperature drop through such refractory over 5 days. Storing times longer than 7 days are not feasible, due to considerable efficiency reduction, as approx. 1% of stored heat would be lost per storage day. It means that after 5 days, some 5% of heat would be lost, as presented in **Figure 9**, leading to the reduction of the round-trip efficiency from 40 to 38%. The results presented in both **Figures 8** and **9** are based on the heat transfer calculations for a cylindrical structure with inside refractory made of silica-based fibre modules. According to the product sheet of a famous refractory supplier, those modules have an excellent heat conductivity coefficient. Although it increases with the temperature, at 1100°C it is only 0.25 W/mK (at 200°C 0.05 W/mK). That temperature dependence is taken into account in the calculations.

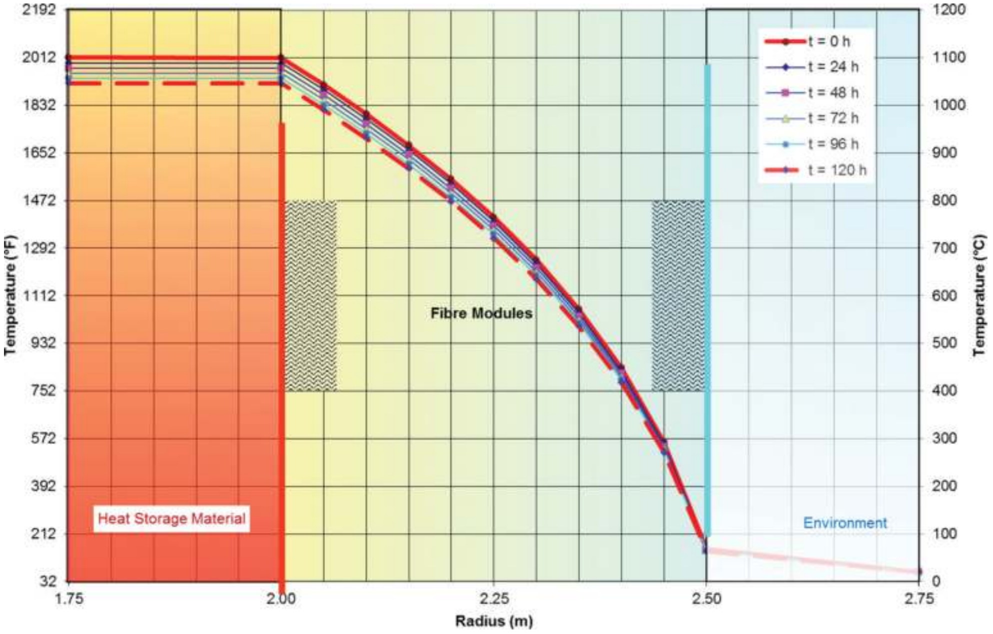

Figure 8. Temperature drop through the refractory of high-quality fibre modules, over 5 days.

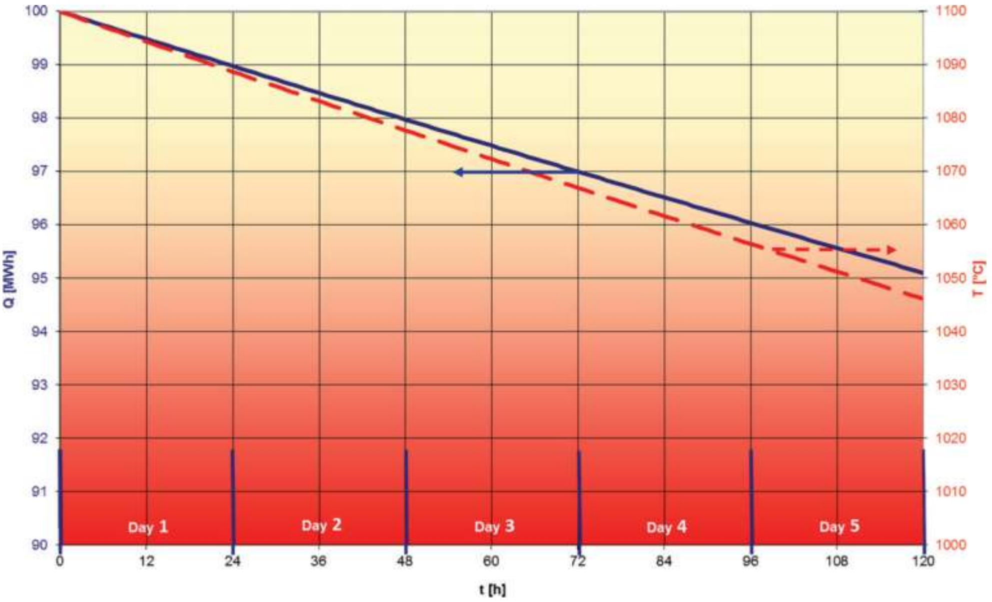

Figure 9. Decrease of stored heat due to heat losses and the drop of temperature inside the storage tower, during 5 days.

5. System improvements

As mentioned previously, some well-known measures may improve the actual round-trip efficiency of the existing process. Those measures and their effects, including the turbine optimization, have been analysed in [21]. In some cases those improvements may be done with the existing gas turbine; in other words it would be required to make more or less complex optimizations or design changes. In the case of the existing design, the pressure ratio was 7.27 and the isentropic compressor efficiency 80.89%. The turbine mass flow was 9.663 kg/s and the isentropic turbine efficiency 83.96%. For the improved optimised designs, the same characteristics were assumed, except that in the case of "pressure ratio", it was reduced to 3.5. Here follows a short overview of those measures, and the summary at the end gives the effect of all measures that could be applied simultaneously on the existing or on the related improved designs.

5.1. Fogging or evaporative cooling

Fogging is a measure well analysed in theory [22–24] and successfully used nowadays. It brings the biggest effects in climates with hot and dry ambient air. The compressor inlet air is saturated with water, which causes its temperature to drop, as the water evaporation takes the energy from it. The wet bulb temperature is the resulting temperature, causing the mass flow to rise due to the density increase. For example, for ambient air at 15°C and the relative humidity of 60%, the wet bulb temperature comes to 10.8°C. Respectively, the compression energy drops and the turbine efficiency increases.

5.2. Water injection

Water injection into the compressed air makes the same effect as the evaporative cooling. Due to water evaporation, the temperature drops. Although that evaporation energy is lost for the external heat usage, the mass flow rate and the heat capacity increase and so the turbine power releases, too.

The compressor work stays constant, and the generator gets the whole increase of the turbine output, leading to the higher power generation efficiency.

5.3. Turbine inlet temperature, TIT

An increased TIT leads to a higher inlet enthalpy and increases the specific turbine work. The robustness of materials is improving continuously with the progress in material science. Presently, some expander rotors operate with the turbine inlet temperature of 1050°C, without blade cooling. Therefore it seems just a matter of time until 1100°C will be reached, maybe with some additional measures, like blade coating. That would be another significant step forward compared to 970°C in the nowadays available gas turbine.

5.4. Pressure ratio

It is well known that in a simple cycle, there is always an optimum pair of the pressure ratio and the inlet gas turbine temperature. However, that optimum is not the same for a recuperated gas cycle. There, the optimum pressure ratio depends on the recuperation efficiency and is much lower for the same inlet temperature. The gas turbine in consideration here is optimised for a simple cycle operation, and the selected pressure ratio of 7.27 is too high for the recuperated cycle. If it would be reduced to, e.g. 3.5, the efficiency would rise by 8.8% points.

5.5. Wet compression

A further improvement at the compressor inlet may be reached by wet compression. In that case water is sprayed above the saturation point into the inlet air. It is oversaturated with small droplets, which evaporate during the compression and therefore cool the air inside the compressor. The effects are similar to those of fogging, i.e. water injection, as the higher density and increased flow rate improve the efficiency.

As presented in several literature references [22–26], the droplet size is the most important factor for the impact of the water injection, as it defines the evaporation rate. A maximum of 3% water can be sprayed, when a pressure ratio is about 7 [23]. In case of the HiTES cycle, that is about 0.3 kg/s. The increase of electric power is about 320 kW, while the power generation efficiency climbs by 6.2% points.

5.6. Intercooling

The intercooling is an old and well-known method for improving the gas turbine cycle. The compressor is divided in two units, and between them there is a heat exchanger where the air is cooled. Due to the intercooling, the compression work is reduced in the second compressor by the higher density, as the air temperature is lower. The available shaft power for the generator increases due to the higher difference between the expander and the compressor power. In the case of a recuperative cycle, there is not a negative impact of the lower compressor outlet temperature. The electric efficiency and the generator power increase drastically.

5.7. Summary of all improvem.5ents

The summary of all those improvements is presented in **Figure 10** [21]. In the “uprate” scenario, all measures that may be done with the existing gas turbine are collected. As the round-trip efficiency would rise to 44.6%, it is obvious that the effect is not negligible.

Contrary to those measures, considerable design improvements and/or optimizations are required for the scenarios “Future I”, “Future II” and “Future III”. In all three scenarios, TIT is raised to 1100°C, and therefore at least some improved materials are required, together with an optimised expander design. The pressure ratio is reduced to 3.5 in the “Future I” scenario, increasing the efficiency to 53.7%.

Only in the scenario “Future II” the wet compression is used. The pressure ratio is preserved at the old value of 7.3, and therefore the efficiency with 51.9% is lower than in the previous case. The advantage is that the power output jumps to above 2.8 MW (+50% compared to the actual case). At least a new design of the gear box and power generator would be needed.

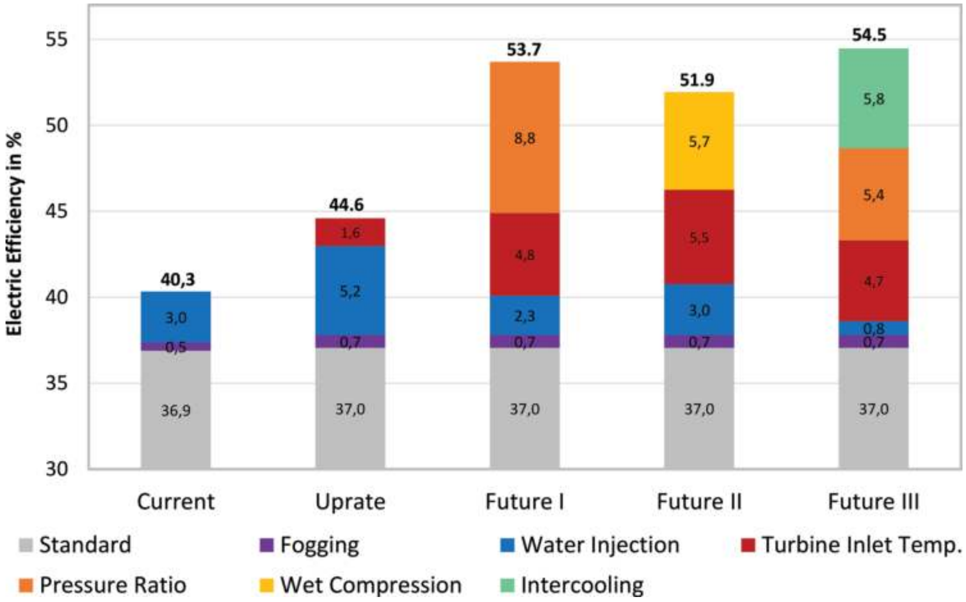

Figure 10. Potential improvements of HiTES cycle efficiency [21].

The scenario “Future III” includes the effects of intercooling together with reduced pressure ratio. The total pressure ratio is achieved in two stages with equal pressure ratios of 1.87 but reduced again to 3.5. The compressed air cools down to 37°C by water injection between two compressor units. The power output is above 2.5 MW (+35% compared to the actual case), and the round-trip efficiency rises to 54.5%.

The advantage is that all those improvements are not a special technological challenge and the robustness and simple design of the original gas turbine can be preserved. Eventual higher costs (e.g. expander blades for higher inlet temperature) will be overwhelmed by the increase in the power output, so that the specific costs will not rise.

6. Levelized cost of electricity storage

The round-trip efficiency is usually the first criterion for comparing different energy storage technologies. The concern is to keep the electricity losses induced by the storage at a minimum. However, in order to achieve the economic viability of the storage system, the investment cost has to be acceptable, too. Therefore some authors use the specific investment costs per kWh of stored electricity, and the others prefer the specific investment costs per 1 kW of the output (or input) capacity. The problem is that comparisons based on such different criteria give quite different results.

Using the levelized cost of electricity (LCOE) is the most correct approach for that comparison. It is similar to the model used for costs of electricity 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 [7]. Due to some differences compared to the electricity production costs, the LCOE 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 Eq. (3):

$$\mathrm{LCOES} = \frac{\mathrm{CAPEX}}{W_{el}} \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} + \frac{\mathrm{OPEX}}{W_{el}} + \frac{\sigma}{\eta_{el}} \tag{3}$$

The above formula is the most objective way for comparing the energy storage technologies. However, all technology details have to be known and well analysed for a correct comparison. There is a difference between the capacity which is achievable in praxis and the nominal discharge capacity of some technologies. In such cases there is a drastic reduction in the lifespan if the full discharge cycles would performed regularly. For example, it is well known that in the case of chemical batteries, there is a significant difference in the capacity at the beginning and at the end of their lifespan. Therefore, a realistic pair of capacity and lifespan must be selected in such cases.

With LCOES it is possible to analyse the whole complexity of the energy storage. In the available literature, there are data about many available storage technologies that vary for more than a factor 2 in some cases. On the other hand, some important parameters, like the specific

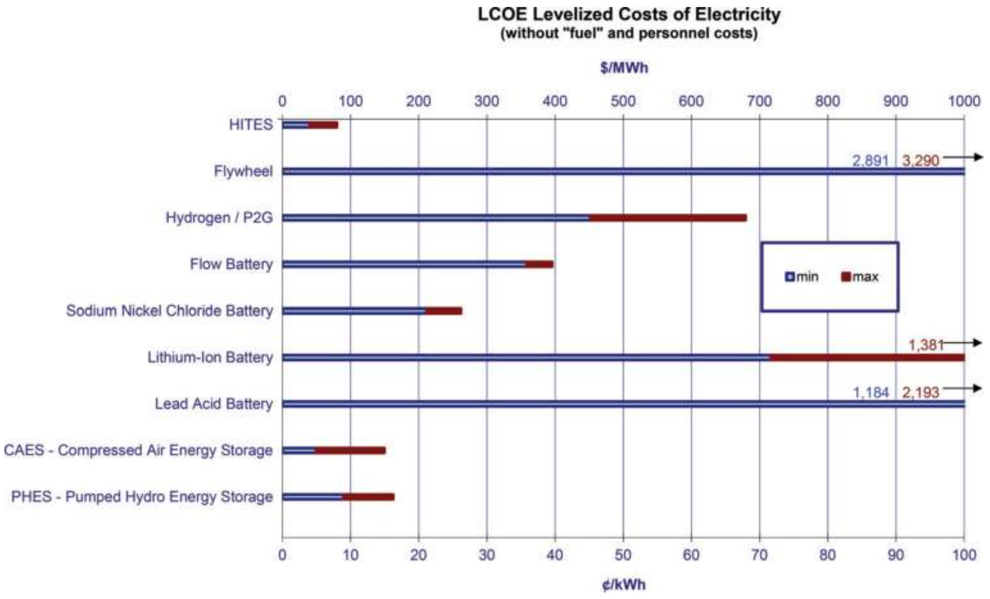

Figure 11. Comparison of LCOES for different storage technologies, based on data from [27].

investment cost and the efficiency, are subjected to steady improvements. Therefore, it is difficult to calculate reliable value of LCOES for the related technology and to compare them. As an example, **Figure 11** gives such a comparison, based on data from [27]. The following parameters are taken the same for all technologies:

- Power output 2 MW
- Time on power generation 4150 h/a
- Power generation 8300 MWh/a
- Life time 25 years (if lower, related investment cost increased)
- Loan cost 6.5% interest rate, 10 years long

For the simplicity of presentation, those figures do not include the price of the input electricity, nor the eventual cost for personnel operating the storage plant. The minimal (blue) and maximal (red) costs are presented, illustrating the wide range of different input data. Therefore, in order to point out the most important parameters, in **Figure 12** 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:

- One 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 h discharge time); the round-trip efficiency may be improved to 50 and 60%, retaining the same specific cost.

The change of storage cost LCOES (€/MWh) is given with presented curves, as a function of the input electricity cost (also €/MWh). The development of the solar and wind generation technologies in the last years has resulted in a tendency of steady price reduction of generated electricity. The lowest recorded prices from a photovoltaic system are 25 €/MWh in Chile and 20.7 €/MWh in Abu Dhabi, and just recently 15.3 €/MWh have been bided in Saudi Arabia [29]. 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, as well.

Two important conclusions may be drawn from the graph in **Figure 12** [28]:

- 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; of course that is limited to the values which are common for the contemporary systems.
- With the falling prices of renewable generation, the above effect becomes more and more important: the efficiency is not as important as the investment cost. (In the case of negative cost of the input electricity, lower efficiency gives lower LCOES.)

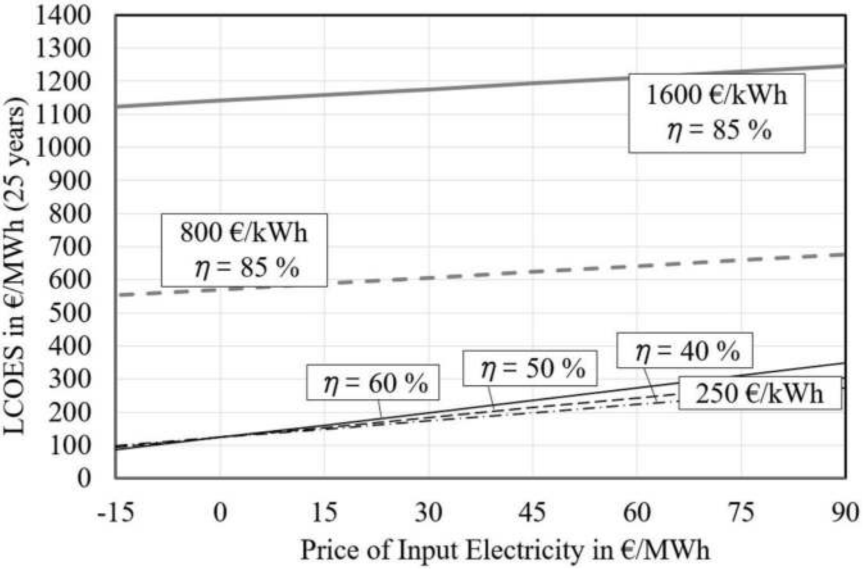

Figure 12. Influence of specific investment, efficiency and price of input electricity on LCOES [28].

The further improvements of HiTES should go in direction indicated in the presented analysis: reduction of investment costs before the efficiency improvements. It is not allowed to pay the efficiency improvements with increased investment cost. The main potential for the reduction of the specific investment costs is an increased number of installed units.

7. Concluding remarks

Without energy storage, it is impossible to implement the generation of renewable electricity based on intermittent sources like wind and solar. Although there are many different technologies available nowadays, they are still not widely used, as they are still very expensive and not suitable for distributed power generation. One possibility with a huge potential is the HiTES technology, which is attractive because of its relative low specific investment cost, its long discharge time (10, 20 or even 30 h) and its potential to improve its efficiency easily towards 60%. Thus, its round-trip efficiency is considerably higher than the efficiency of some other long discharge systems, like power-to-gas, or molten salt. With its relatively low capacity compared to CAES and PHES, it is especially suitable for distributed generation. That shows how the previously developed technology for biomass CHP [30, 31] may be adjusted for new tasks, preserving its simplicity and improving the efficiency.

The analysis of LCOES, which is the best comparison criteria, shows that those systems are more favourable than the battery storage. Even today, that system could be used in a viable manner in countries with high insolation. In combination with photovoltaic plants, it gives lower cost of the electricity supply than concentrated solar plants (CSP).

The specific investment cost is considerably more important than the round-trip efficiency. With the steadily falling prices of the renewable generation, that effect will become more and more pronounced.

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