High Temperature Energy Storage based on Hot Air Turbine and Pebble-Heater Technology

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***Abstract*—The HiTES energy storage is a high temperature thermal electric energy storage. It consists of a heating coil, a heat storage and a recuperated hot air turbine. HiTES can be applied to smooth out intermittency due to renewable energy sources, for load control, or other flexibility options. The low investment cost and the high efficiency make the HiTES energy storage economically feasible even today. The economic feasibility can be increased by improvements of the round trip efficiency and by decreasing investment costs. For that reason several improvements scenarios were analyzed. The most correct comparison between different energy storage systems is based on the levelized cost of the electricity storage – LCOES. It shows that HiTES is more economic than lithium ion batteries. The paper gives a short parametric analysis of the main parameters that influence the levelized cost of energy storage, like the specific investment cost, the round-trip efficiency and the price of the input electricity.**

Keywords—energy storage; high temperature; pebble-heater; radial gas turbine; hot air turbine; resistive heating; LCOE

I. Introduction

With the increased rate of electricity from renewable energy sources, energy storage systems are required to smooth out the intermittent generation from wind and solar power. That is the case for the well-developed electricity systems, as well as for the systems without a centralized grid. The well-established technology based on the pumped hydro storage is the first choice, however it is not always deployable due to geographical restrictions and the higher capacities (usually above 100 MW) required to achieve profitability. Different new technologies, mostly more distributed solutions, are in very intensive development. The most extensive activities in that field are to be found in the USA, as energy storage there is recognized as a very important measure in overcoming the grid intermittency, as for example in California. As early as in 2012, although the renewable generation was less than 20% of the total power generation, it was recognized 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 future scenarios with up to 33% renewable power generation in 2020 are presented in the so-called “duck-chart” [1].

In Germany, that is the leader in the renewable power generation with some 33% in 2015, the situation is quite opposite. As presented in [2], the opinion 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. However, the anomalies that appeared on the market in the last two years, have shown that this is 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 emissions are more or less stagnant! Therefore, the previous opinion is changing fast and energy storage, together with new grids expansion, are recognized as the inevitable components of the German “Energiewende”.

There are many more or less known systems for energy storage, from chemical batteries, mechanical fly-wheels, super capacitors, thermal energy storage, compressed air storage, to classic technology like the pump hydro energy storage. They are characterized by very different capital costs, as well as by different round-trip efficiencies. However, the most important factor which will determine its applicability in a specific storage condition is the levelized cost of electricity (LCOE), which takes both characteristics in consideration.

II. What is HiTES?

High Temperature Energy Storage (or shortly HiTES) is a new technology for energy storage based on three technologies which are state-of-the-art:

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

The combination of those three technologies gives a new system that is suitable for medium-term storage, from several minutes up to several days. During time periods with electricity overproduction in the system it is used to heat up the pebbles (heat storage material) in a high temperature pebble-heater by electric resistive heaters. When there is a need for additional electricity, the stored high temperature heat is used to run a gas turbine coupled with a generator.

A. Why HIGH Temperature?

It is well known and commonly accepted that heat is the lowest form of energy. E.g. one can transform electricity in heat with high efficiency, but vice versa will work only with high efficiency losses. The quality of heat depends on its

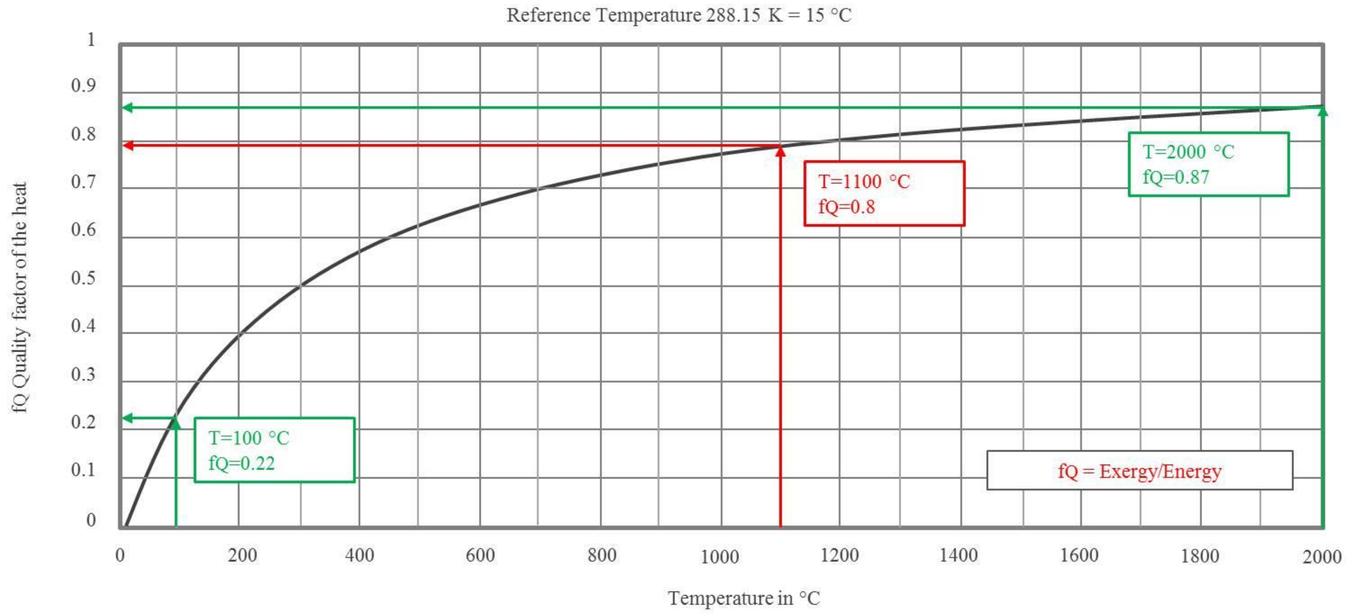

Fig. 1. The thermodynamic quality factor of heat, indicating the fraction of exergy in the amount of energy [1]

temperature, as shown in Fig. 1 [3]. Therefore, it is not the same if one transforms electricity to heat at 2000°C or at 100°C.

The limitation factor is the material – therefore, 2000°C is not easy to realize. But with 1100°C, that is the case for HiTES, the quality factor is still very high (0.8) and the available materials and components can withstand that temperature.

B. Why Pebble-Heater Technology?

A Pebble-Heater is a regenerative heat exchanger very suitable for high temperatures that enables very low exergy losses and therefore an almost reversible heat transfer. Fig. 2 shows such an example, where the heating gas enters the pebble-bed with 1350°C and leaves it with 160°C. In the next phase a "cold" gas (air in this case) enters with 90°C and heats up to 1280°C. On both bed sides the temperature difference is only 70K, thus enabling an exergy efficiency of 95.2%. In some applications that temperature difference is less than 50K (the minimum was about 15K!).

Due to those characteristics the Pebble-Heater technology has been used for thermal oxidizers (recuperation efficiency above 98%), hot gas supply (temperatures above 1400°C), steam superheating at 1200°C for some chemical reactions, steel converters, blast furnaces, regenerative burners etc. In HiTES technology that is a crucial component enabling high process efficiency.

C. Why Radial Gas Turbine?

Gas turbine sets with all-radial design have some characteristics which enable an extraordinary record of reliability undere extreme operational conditions, like on oil rigs, gas fields etc. On the other hand the efficiency in a simple open cycle may reach 25% with modern designs, despite relatively small capacity and simplicity. They are very robust, single shaft with cold end drive, easy maintenance, low lube oil consumption and long inspection intervals. Those turbines are now available in a design with so-called external firing, that is a precondition for the usage in a HiTES system. An example of the state-of-the-art design of radial compressor and expander is presented in Fig. 3 [4].

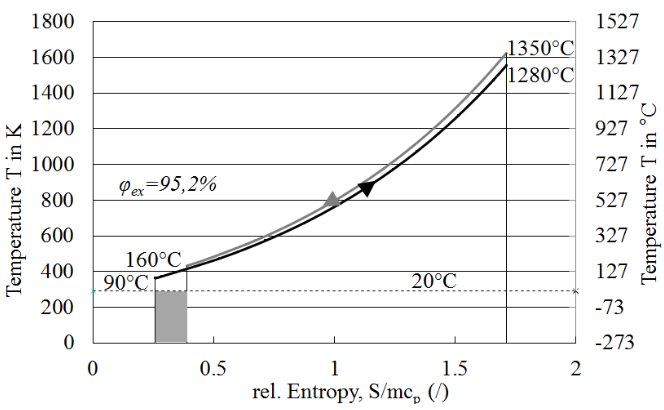

Fig. 2. Entropy increase during the heat transfer in a Pebble-Heater

Fig. 3. Rotor of a radial gas turbine with expander (left) and compressor (right) [4]

III. OPERATION OF HITES

The principles of HiTES operation are based on the patent document [5]. During the charging phase, only the Pebble-Heater PH-E (see Fig. 4) is in operation. The heat storage material there is electrically heated from 550°C to 1100°C. In that way, the electricity is used just for storing the high temperature heat, which is very important for the round-trip efficiency.

During the discharging phase, the whole equipment presented in Fig. 4 is in operation. Compressed air is preheated in the low temperature Pebble-Heaters (PH1…PH4) to 550°C and then further to 1100°C in the high temperature storage PH-E. Hot compressed air expands in the gas turbine and released mechanical work is used for compressor drive and electricity generation. After the expansion, the exhaust air heat is stored in the low temperature storage PH1…PH4 and used again for preheating the compressed air. By activating the set of presented valves, always only one Pebble-Heater is in compressed air loop and the remaining three are in the exhaust air phase. After a certain period (e.g. 20 minutes), another PH is switched to the compressed air loop and the previous PH is switched to the exhaust air loop, and so on.

The intention is to use a radial gas turbine which already exists on the market, rather than to develop a new one which could be optimized for the HiTES operation conditions and therefore could achieve a higher round-trip efficiency. With the existing gas turbine of nominal 2 MW output power the round-trip efficiency is approx. 40%, what is sufficient to reach the profitable operation of the first units. Afterwards, when this new technology is confirmed in the industrial application, more efforts and time may be invested in a modified gas turbine, which will further increase the profitability of this type of energy storage.

In order to reach that high round-trip efficiency with the existing gas turbine model, the fogging of the inlet air, as well as compressed air cooling with water injection, are foreseen. More precise process parameters are given in the following description, based on the ISO conditions (15°C, 1.013 bar abs).

During the discharging phase, the compressor drafts in ambient air at 15°C, 1.013 bar absolute and a relative humidity of 60 %. Upstream the compressor the ambient air is cooled by a fogging unit in order to decrease the air inlet temperature and to ensure a higher mass flow by raising the density. In the compressor the air is compressed to 7.3 bar and temperature rises to 275°C. The following heat exchanger extracts heat from the compressed air and the further cooling is done by water injection. The water injector normally sprays in 0.3 kg/s of water, till the dew point temperature is reached. This increases the mass flow rate and again decreases the temperature of the compressed air. That water can be seen as a substitute for the missing fuel mass flow. It ensures that the compressor and the expander work as closely as possible to the design point. The air cooling is important for the efficient heat transfer in the Pebble-Heaters. Lower compressed air inlet temperatures in the Pebble-Heater mean lower outlet temperatures during the exhaust air phase and thus lower heat losses. The compressed air flows through one of the Pebble-Heaters (PH1…PH4), which acts as a recuperator in the gas turbine cycle. Because of the high recuperation efficiency and the lower compressed air mass flow, it is heated almost to the turbine exhaust air temperature. The heated compressed air leaves the low temperature PH towards the high temperature Pebble-Heater (PH-E). In PH-E the air temperature increases up to 1100°C. Upstream of the expander the hot air is cooled to the turbine inlet temperature (about 970°C). This is done by opening a control valve that controls the temperature of the air with a bypass to the PH-E inlet. That air mixes with the turbine cooling air that is necessary to prevent the overheating of the turbine guide blades. This reduces the turbine inlet temperature (TIT) to 940°C. Then the hot, compressed air flows through the expander. After the expansion, the exhaust air leaves the expander with ambient pressure and about 540°C through the remaining three Pebble-Heaters. Every 20 minutes another Pebble-Heater can be discharged, while three others are charging. The air runs through the Pebble-Heaters and heats the pebbles. After that the exhaust air with a temperature of about 110°C flows through the chimney into the ambient.

Based on the nominal turbine output of 2 MW and 40% round-trip efficiency, the energy storage Pebble-Heater PH-E may be heated 10 hours long with 5 MW of input power. The amount of stored high temperature heat is 50 MWh. The discharging phase can last again up to a maximum 10 hours, i.e. total of 20 MWh of electricity may be supplied. The whole facility will be modular, meaning that two or three identical PH-E may be used with one gas turbine set. In that case 2 MW power may be supplied for 20 or even 30 hours.

Due to the high quality refractory inside the PH-E, the high temperature heat may be stored there from several minutes up to several days. Storage for longer than 7 days is not very feasible, as the round-trip efficiency would be reduced. Approx. 1% of stored heat is lost per one day of storage. E.g. after 5 days some 5% of heat would be lost and the round-trip efficiency would drop from 40% to 38%.

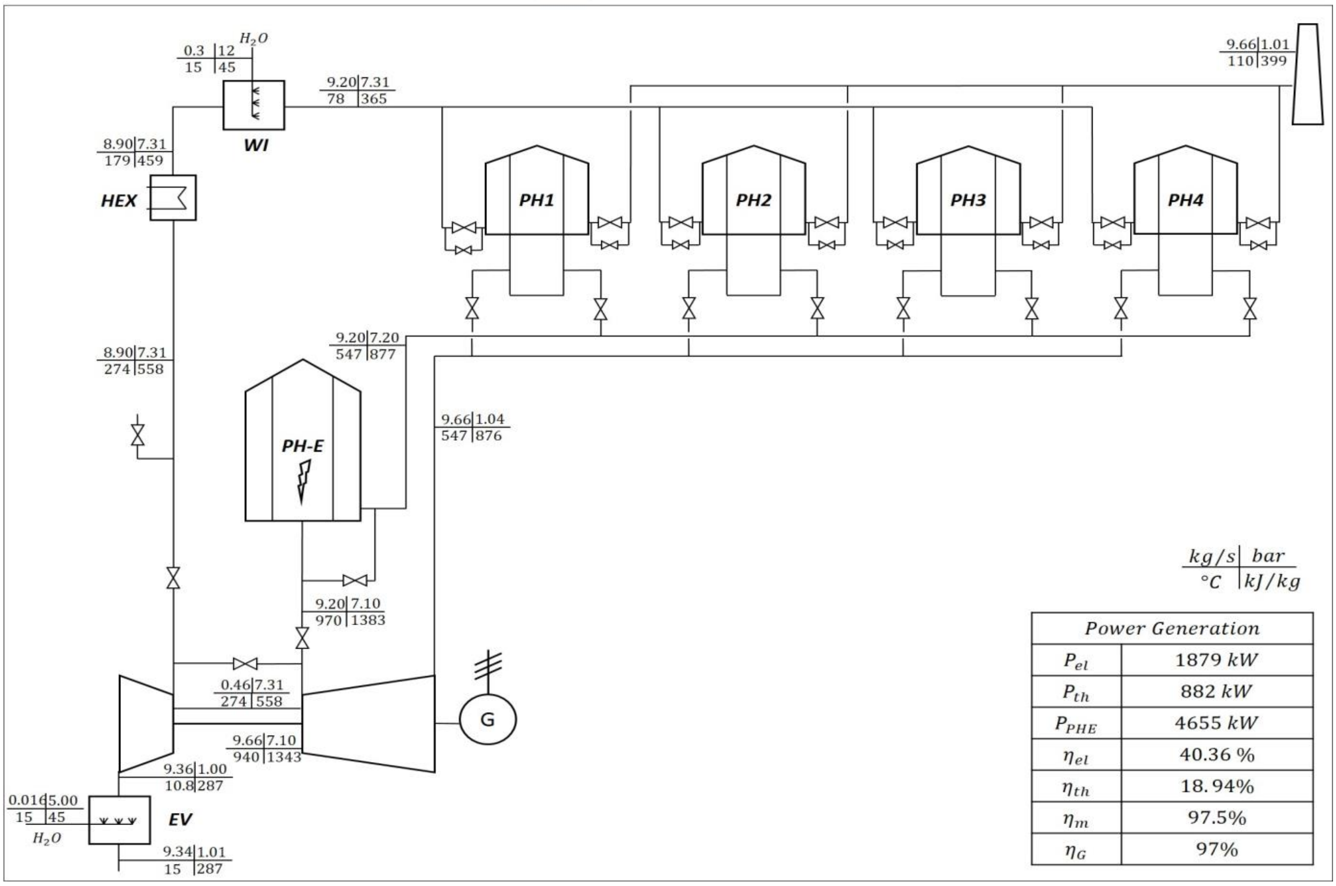

Fig. 4. Flow diagram and nominal process parameters of HiTES

IV. Improvements Potential

As mentioned in the previous Chapter, the actual round-trip efficiency of the existing process may be improved with some well-known measures, i.e. turbine optimization. The effects of all those possibilities have been analyzed in [6]. Some measures may be done with the existing gas turbine, for others more or less complex optimizations or design changes may be required. Here follows a short overview of those measures.

A. Fogging or Evaporative Cooling

Fogging is a measure used nowadays mostly in climates with hot and dry air. By saturating the compressor inlet air with water the temperature drops as the energy is consumed for water evaporation. The resulting temperature is the wet bulb temperature. The inlet air mass flow rises because of the increased density due to the lower air temperature. For example, for 15 °C and 60 % relative humidity the wet bulb temperature is 10.8 °C. The energy required for air compression is lower and the efficiency rises. At higher outside temperatures this effect becomes more and more important.

B. Water Injection

By injecting water into the compressed air the same effect as by evaporative cooling occurs. The temperature drops because of the water evaporation. That amount of energy is lost for the external heat usage, but it increases the mass flow and the heat capacity through the turbine and so its power release. As that water injection happens after the compressor, the compressor work stays constant and the whole increase of the turbine output goes further to the generator. The generator output rises, as well as the efficiency of the power generation.

C. Turbine Inlet Temperature - TIT

A higher TIT results in a higher enthalpy at the turbine inlet and, therefore, in a higher specific turbine work. With the prospective progress in material science the robustness of materials are improving continuously. Presently turbine inlet temperatures of 1050°C are possible for some expander rotors without cooling. With some additional measures, like blade coating, it seems just a matter of time until 1100°C will be reached. That will be another significant improvement towards 970°C in the present gas turbine.

D. Pressure Ratio

In a simple gas turbine cycle there is always an optimum pair of inlet temperature and the pressure ratio. In the case of a recuperated gas cycle that optimum is not the same. For the same inlet temperature the optimum pressure ratio is considerably lower. The existing gas turbine is optimized for a simple cycle operation. In the case of reduced pressure ratio, e.g. from 7.3 to 3.5, the efficiency will rise by 8.8 percent points.

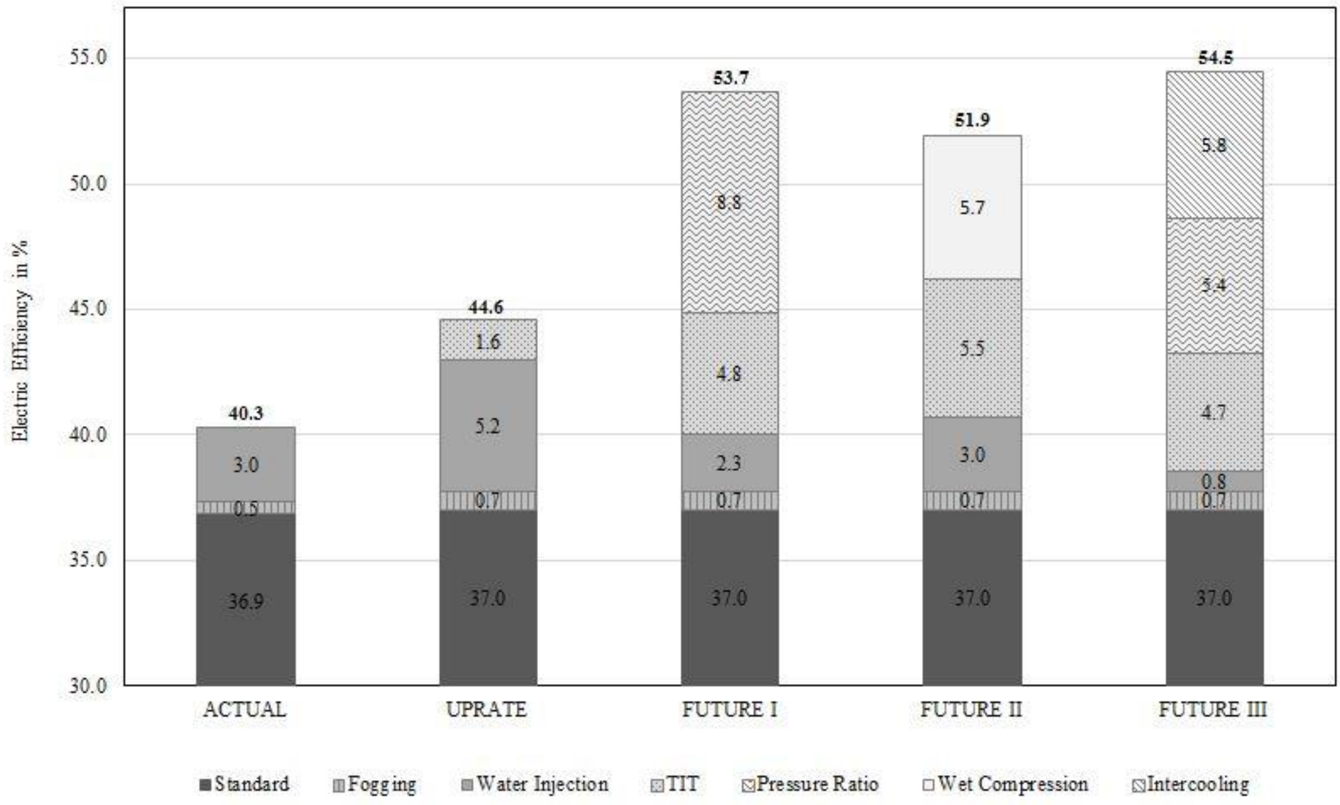

Fig. 5. Potential improvements of HiTES cycle efficiency [6]

E. Wet Compression

Wet compression is an improvement of the gas turbine at the compressor inlet. In case that water is sprayed into the inlet air above the saturation point, the air is oversaturated with small droplets. Those droplets evaporate during the compression and therefore cool the air inside the compressor. Due to higher density and increased flow rate, the effects are similar to those of water injection.

The impact of the water injection is mostly dependent on the evaporation rate and therefore on the droplet size. With a pressure ratio of about 7 a maximum of 3% water can be sprayed in. That is about 0.3 kg/s for the HiTES cycle. The electric power increases about 320 kW and the electric efficiency climbs by 6.2 percent points.

F. Intercooling

The intercooled cycle is one of the oldest possibilities to improve the gas turbine cycle. The air is compressed by a first compressor and then cooled down by a heat exchanger. A second compressor is used to get the air to the final pressure. Intercooling means less compressor power has to be used as the compression work is reduced by the higher density due to the lower air temperature. The shaft power increases because of the higher difference between the expander power and the compressor power. The lower compressor outlet temperature does not have a negative impact in the case of a recuperative gas turbine cycle. So the electric power and the electric efficiency increase drastically.

G. Summary of all Improvements

Fig. 5 presents the summary of those improvements [6]. In the scenario “Uprate” are all measures which could be integrated in the existing gas turbine with some slight design modifications. The effect is not negligible, as the round-trip efficiency would rise to 44.6%.

For the scenarios “Future I”, “Future II” and “Future III” considerable design improvements and/or optimizations are required. First of all, in all three scenarios TIT is raised to 1100°C. This requires some improvements in selected materials, as well as an optimized design of the expander. Further on, in the “Future I” scenario the pressure ratio is reduced to 3.5, leading to an efficiency of 53.7%.

Wet compression is used only in the scenario “Future II”. Staying with the old pressure ratio of 7.3, the efficiency is lower than in the previous case, reaching 51.9%. However, the power output rises to above 2.8 MW (+50% compared to the actual case), what would require at least a new design of the gear box and power generator.

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

In general, all those improvements require simple designs which are not a special technological challenge. The robustness of the original gas turbine can be preserved. Even the specific costs will not rise, as the increase in the power output will overwhelm eventual higher costs of e.g. expander blades for higher inlet temperature.

V. Levelized Cost of Electricity - LCOE

Usually the first criterion for comparison between different energy storage technologies is the round-trip efficiency. Finally everyone wants to keep the electricity losses induced by the storage at a minimum. However, it is also clear that the investment cost has to be acceptable in order to achieve the economic viability of the storage system. Some authors use the specific investment costs per one kWh of stored electricity, others prefer the specific investment costs per one kW of the input or output capacity. Comparisons based on such criteria give quite different results.

The most correct practice is to use the levelized cost of electricity (LCOE). It is an adaptation of the model that is used for electricity costs from power plants. The LCOE contains the capital expenditure (*CAPEX*) and the annual operational expenditure (*OPEX*), both referring to the energy output W_{el}. The interest rate i and the lifespan n in years are also included.

The LCOE has to be extended with the characteristics of energy storage systems. That results in the levelized cost of electricity storage (LCOES). It additionally contains the costs of the input electricity σ and the round trip efficiency η_{el}. The complete formula for the calculation of LCOES is given in equation (1):

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

This is the most objective value for comparing the energy storage technologies. However, for the correct comparison all technology details have to be known and be well analyzed. E.g. sometimes there is a difference between the nominal discharge capacity and the capacity which is achievable in praxis, as the full discharge cycles would mean a drastic reduction in the lifespan. Especially in the case of chemical batteries, the capacity is not the same at the beginning and at the end of their lifespan. In such cases the realistic pair of capacity and lifespan has to be taken into account.

With LCOES it is possible to analyze the whole complexity of the energy storage. In Fig. 6 two energy storage systems are compared:

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

- The other system has a round-trip efficiency of 40%, but the specific investment cost of just 500 €/kWh; due to further development the round-trip efficiency may be improved to 50% and 60%, retaining the same specific investment cost.

The presented curves show the change of storage cost LCOES (€/MWh) as a function of the input electricity cost, also in (€/MWh). With further development of the solar and wind generation technologies, that price will decrease, a tendency that has already been experienced in the last years. At the moment, the lowest recorded price of electricity generation from a photovoltaic system is 30 US$/MWh in California. Even some negative electricity prices are plotted, as with high penetration of intermittent renewable power generation it happens more and more often that the stock market prices are negative.

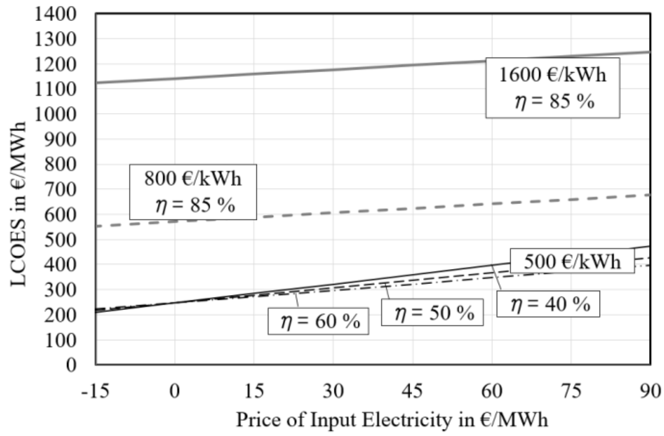

Fig. 6. Influence of specific investment, round-trip efficiency and price of input electricity on LCOES

The graph in Fig. 6 gives two important conclusions:

- 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.

The presented analysis indicates the direction in which the further improvements of HiTES should go. It means that the improvements in the efficiency must not be paid by increased investment cost. With an increased number of installed units, the specific investment costs would be further decreased.

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