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Electricity Storage With a Solid Bed High Temperature Thermal Energy Storage System (HTTES) - A Methodical Approach to Improve the Pumped Thermal Grid Storage Concept

1st Dr.-Ing. Günter Schneider [a]
guenter.schneider@enolcon.com

2nd Dr.-Ing. Hartmut Maier [a]
hartmut.maier@enolcon.com

3rd Jonas Häcker [a]
jonas.haecker@enolcon.com

4th Simeon Siegele [a]
simeon.siegele@enolcon.com

[a] *enolcon gmbh* Pleidelsheimer Str. 47 A 74321 Bietigheim-Bissingen, Germany

***Abstract*—High Temperature Thermal Energy Storage (HTTES) systems offer a wide range of possible applications. Since electrical batteries such as Li-ion batteries suffer degradation and since complete battery-systems are expected not to fall to low cost levels (IEA-WEO report 2018 [1]) until 2040, it becomes economically more interesting to use thermal energy storage systems as 'Thermal Batteries' to store electrical energy. In this article an improved and optimized Thermal battery based on a closed Brayton-cycle is proposed (Carnot-battery). The improved electricity storage concept applies an efficient low-cost high temperature thermal energy storage technology for both, the hot- and the cold thermal storage. This concept not only allows for a bigger temperature spread and simplified operation, but also reduces CAPEX significantly. It is named enolcon-OPTES-Battery (Optimized Pumped Thermal Energy Storage - Battery).**

Keywords*—Electricity Storage, High Temperature Thermal Energy Storage, Brayton Cycle, Pumped thermal grid storage, Packed bed storage, Thermal Battery, HTTES, Pumped Thermal Energy Storage, Pumped Thermal Electricity Storage

I. INTRODUCTION

As more renewable energies are installed the need for economic and efficient energy storage facilities increases. Due to the fluctuation of renewables, the gap between electricity production and electricity demand is increasing. Energy storage is needed to close this gap and keep the grid stable. There is a demand for different time lines with short term storages ranging from minutes to several hours and long-term storages for a period of weeks or months.

For short term-storages, Batteries with Li-ion cells are the most commonly known system to the public. Their storage period is normally relatively short with an average of 1.6 hours due to economic constraints [1]. Currently the utility-scale battery costs are often too high for economical operation in the power grid, especially when applied for minute reserve where a storage capacity of 4 hours is required or for load shifting with storage capacities of 8 hours or more. Electrical Batteries like Li-ion batteries are far away from any economically interesting application when it comes to storage periods of more than 4 hours. Nevertheless, the pressure to install such electricity storage capacities is increasing as more renewable electricity generation capacities are installed. A further element which is coming up especially in smaller electricity grids where a lot of PV is installed, is the requirement of rotating masses for frequency stabilization in the grid. Moreover, there is no rotating mass in a Li-ion battery that stabilizes the grid frequency. So, there is an upcoming demand for electricity storage with storage capacities of 4 – 12 hours with low investment costs and low operating costs. In the best case such electricity storage systems provide also grid stabilization with rotating masses. A concept with a combination of a Thermal Battery combined with rotating mass has been proposed in [2].

When it comes to costs of electricity storage systems one must clearly distinguish between the costs of the complete system, including all equipment from the interface point to the electricity grid, and the battery cells. In general, the status in 2018 and 2019 was that the battery cells in a utility scale Li-ion-battery count for approx. 45 - 55% of the total costs. Taking into consideration that the other parts of such Li-ion-battery system count for the other approx. 45 - 55% and that there is no reason to assume that the costs of these parts (civil works, mounting, electrical cabinets, cables, HVAC-system, monitoring systems, fire protection, containers, engineering etc.) will fall, it can be easily understood why the IEA in its WEO report from November 2018 [1] has predicted a specific price of approx. 190 US$/kWh$_e$ in year 2040 (and approx. 210 US$/kWh$_e$ in year 2030) for an 8 hours LIB (Lithium-Ion-Battery)-system. However, it should be noted that the IEA has applied a cost of approx. 400 US$/kWhe as starting point in 2018 which can be considered as the very low end, or even too low when comparing with costs of real executed large Li-Ion-projects.

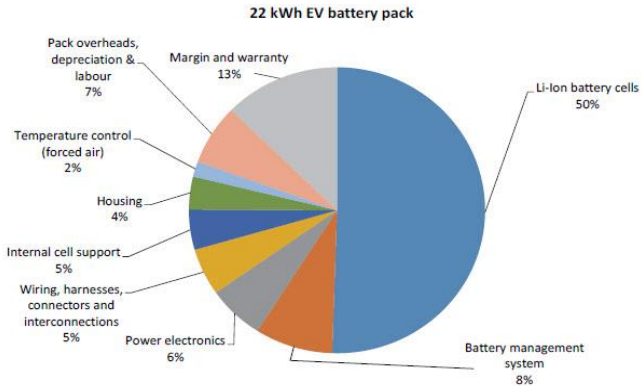

Fig. 1: Example cost breakdown of a Li-ion battery pack, source Global CCS institute 2018

To illustrate the real situation and despite several statements of battery companies and technology developers and research and marketing institutes, the **real costs** of a complete Li-Ion-utility scale electrical battery system in year 2018 was around or significantly higher than 450 €/kWhe in all commercial large scale Li-Ion-battery projects, see also [3], [4] and [5]. The most current large-scale Li-Ion-battery in Germany under construction is located in south-eastern Brandenburg, Germany and has a capacity of 53 MWh_e. The costs are 25 million € which result in a specific cost of 471 €/kWh_e or approx. 518 US$/$kWh_e$ [6], [7]. Since this project has ideal conditions with regard to site, grid connection and operation it can be seen as representative for the current cost level of large-scale Li-Ion-batteries. Another example in [6] is the 5 MWh_e Li-Ion-battery project ('*Kraftwerksbatterie*') located at the coal fired power plant in Heilbronn, Germany which has been built in year 2017. The specific costs of this Li-Ion-battery have been at a level of more than 800 €/kWh_e, approx. 880 US$/$kWh_e$. Furthermore, in Switzerland at Volketswil, see [8], the Li-Ion-batterie has a storage capacity of 7,5 MWh_e and the costs have been approx. 6 million SFR, or approx. 5,64 million €. The specific costs for this large-scale battery, which went into operation in year 2018, are at approx. 752 €/kWh_e. Again, all these numbers are total costs of **real** executed projects.

Applying these numbers and assuming that the Li-ion-cells will be provided free of charge to the market (0 €/kWhe) it becomes obvious that the IEA-report 2018 can still be considered as optimistic.

However, from today's point of view electrical batteries like Li-ion-battery systems will remain the first choice when it comes to short-term storage with storage capacities of less than 2 hours or primary response services. Especially when a fast reaction time for high capacity charging and discharging is required, thermal battery-systems will always have a disadvantage compared to Li-Ion batteries because of their thermal inertia.

Being aware of the weaknesses of electrical batteries such as Li-ion-batteries the research and development efforts of several companies and research institutes to find technical alternatives for longer storage periods at much lower costs have increased over the last years.

In the past years there were various developments for so called "Carnot batteries". Many of the concepts are based on state-of-the-art thermal electricity generation, e.g. with a Rankine cycle. Instead of burning fossil fuels, they use surplus electrical energy to generate heat which is then stored and used for electricity generation when needed, mostly with an offset of 1 - 24 hours. The most obvious concept is the use of a Rankine-cycle with steam generation from the stored heat. The Rankine-cycle is a highly optimized process that has been used for decades, e.g. in coal fired power plants or nuclear power plants. As an example, the company SIEMENS GAMESA estimates to reach an electricity-to-heat-to-electricity efficiency of approx. 45% [9] in future large-scale applications.

The relatively low efficiency compared to electrical batteries with its electricity-to-electricity efficiency of approx. 92 – 95% (new, without degradation) is outweighed by the much lower CAPEX of such Thermal Batteries and that there is no degradation in the efficiency even during very long operation periods (>20 years). Such **Rankine-cycles** operate a steam turbine with a generator and are therefore provide stability to the grid via its rotating masses.

A. *Pumped thermal grid storage using a Brayton Cycle*

In 2017, [10] Physics Nobel laureate Prof. Robert B. Laughlin proposed a Thermal Battery-process as "Pumped thermal grid storage with heat exchange" using a Brayton-Cycle to reach a round trip efficiency (electricity-to-electricity) of 72 %. The concept is based on well-known thermal storage components: molten salt-systems on the hot side and cryogenic systems on the cold side. The proposed process, however, requires large heat exchangers with very small temperature gradients which are uncommon in these capacities and specifications on the commercial market, and which are by far not available at a price level required to provide much cheaper Thermal Batteries than the price level predicted for electrical batteries. Prof. Laughlin has worked on an outlook of how design and costs for the required heat exchangers might be when produced as a mass product.

The Brayton cycle pumps heat from a low temperature level to a high temperature level when operated as a heat pump and vice versa when operated as a heat engine. Using a high- and a low-temperature storage as hot and "cold" reservoir, the cycle can be used to store and produce electric energy. For charging, gas is compressed in a compressor and thermal energy from the hot gas is transferred to a high temperature thermal energy storage. In a downstream turbine the cooled gas is expanded to the low-pressure level and cools down the low-temperature thermal energy storage. So, the gas gets to the compressor inlet temperature level again. During discharge, cooled gas from the cold storage is compressed before being heated in the high temperature thermal energy storage. After expansion in the turbine, the gas is cooled down in the cold storage unit again.

In [10] the Brayton Cycle is built with solar salt as storage medium for the high temperature energy storage and hexane for the low temperature storage. Both media are liquid within the temperature range of interest and the system is executed as a two-tank system. As working fluid Argon, or alternatively Nitrogen is used. Since the storage media is different from the process working fluid heat exchangers are necessary. One heat exchanger on the hot side (gas-molten salt) and one heat exchanger on the cold side (gas – liquid hexane), and a further process-internal heat exchanger (gas-gas).

When evaluating the proposed Brayton-cycle of Prof. Laughlin [10] and considering the real costs and actual technical constraints it turns out that a real executed Brayton-cycle with molten salt systems (e.g. temperature limitation of max. 565°C, high costs of molten salt and cryogenic fluid, large and expensive heat exchangers, electrical own consumption due to pressure losses in the heat exchangers and pipes etc.), has a real efficiency (mainly because of heat losses and temperature gradients in the heat exchangers) of not more than approx. 58 – 65% (see Table 1). The CAPEX of such large-scale Brayton-cycle [10] (for example 10 MW_e, 80 MWh_e) by far exceeds the CAPEX-numbers of approx. 22 - 24 million €, which lead to specific storage cost values of more than 275 – 300 €/kWh_e. The high-pressure level of approx. 40 – 70 bar (depending on the working fluid Ar or N2) in combination with the temperature level of up to 565°C is also a cost driver. Regarding the applied thermal storage systems it should be mentioned that the molten salt can only operate in a limited temperature range of approx. 240 – 565°C to avoid the risk of solidification of the salt. This leads to large volumes for the hot storage system. On the cold side there are also limitations on the upper temperature, therefore to maintain a high efficiency and to overcome operational constraints there is a third heat exchanger required to transfer heat internally inside the process. The expected advantage compared to electrical batteries is still there, but not as big as expected at a first glance.

Therefore, enolcon took the task to improve the proposed Brayton-cycle and has focused on the following key items:

- Increasing temperature spread between hot and cold side to improve efficiency (Carnot)
- Replacing the thermal storage systems by more simple and cheaper storage systems (reducing CAPEX)
- Reducing the expensive heat exchangers to one heat exchanger, or for the sake of economical optimization, eliminating all heat exchangers (improving efficiency and reducing CAPEX significantly)
- Simplification of operation and eliminating challenges and risks related to freezing of molten salt during start-up and shut-down

The key to achieve the mentioned improvements and to improve and optimize the proposed Pumped thermal grid storage is the application of another thermal storage technology.

B. *Enolcon HTTES-System*

In 2010 enolcon started developing a cost-effective **H**igh **T**emperature **T**hermal **E**nergy **S**torage system (HTTES) based on several packed bed layers arranged in parallel [11]. Small grained, natural and widely available silica sand, or alternatively iron based sand, or another material such as Basalt, is used as storage material [12]. Hot air is applied as heat transfer medium and directed horizontally through the packed bed layers. Since 2015 the large-scale demonstration plant ORCTES is in operation at the University of Bayreuth/Germany. With a thermal storage capacity of more than 1.5 MWh_{th}, charging power of up to 1.8 MW_{th} and temperatures of up to 600 °C, the system has already proved its performance in industrial scale, also see [13] and [14]. The ORCTES-plant is owned by the company STORASOL GmbH which is a partner of enolcon for the sales and implementation of HTTES-systems.

Fig. 2: HTTES-modules of the ORCTES-plant at University Bayreuth, STORASOL GmbH, built in year 2015

Instead of Salt and Hexane as liquid storage material, enolcon's HTTES-technology with its solid bed storage material is perfectly suited to the Brayton-cycle. The advantages are as follows:

- The enolcon-HTTES-storage can cover a temperature range from -100°C to +1000 °C and is therefore suitable for both, high temperature and low temperature storage applications.
- It can be designed as a pressurized thermal storage and thus the gaseous working fluid can flow directly through the storage material. This eliminates the need for large and costly heat exchangers.
- Since no phase change takes place in the solid bed storage material the whole process is easier to handle during start-up and shut-down (no risk of salt freezing or Hexane evaporation, no risk of damaging of valves or blocking of pipes and heat exchangers etc).
- Compared to Hexane and Salt the storage material has very low-costs, thus improving the economics of the whole storage system.

There are three main positive characteristics of the enolcon-solid bed HTTES-technology which qualifies it for an application in such Brayton-cycle:

- ✓ The small particle sizes (depending on the design it is between 0,5 – 8 mm) results in a large surface for the heat transfer from the working fluid N2 or Ar to the storage material. For example in the ORCTES-plant with particle sizes of 1-3 mm and a porosity of approx. 0,41 the surface per m3 is approx. 2000 m2. This huge surface leads to a slim thermocline (approx. 0,1 – 0,2 m) when charging or discharging the HTTES-modules.
- ✓ The disadvantage of small particles is a big pressure drop when gas is forced to flow through such solid bed. Due to the parallel arrangement of the solid bed storage material layers, the enolcon-HTTES-technology mitigates this disadvantage in providing a big inlet-flow-surface which reduces the gas velocity to very low figures (< 1 m/s) when the gas enters the

storage material. So, the electrical own consumption due to pressure losses is almost negligible.

- ✓ The temperature at the outlet of the HTTES remains very stable during charging, until the slim thermocline has reached the outlet. When discharged the same can be observed, the outlet-temperature remains very stable on a high level. The following graph shows measured data of the ORCTES-plant during discharging to illustrate this temperature behavior.

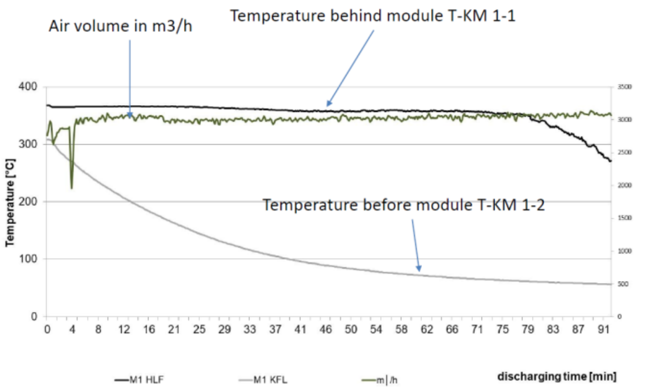

Fig. 3: Measured data as example for stable temperature level behind a enolcon-HTTES-module during discharging

II. Methodical Approach to Improve and to Optimize the Pumped Thermal Grid Storage Concept

As mentioned above Prof. Laughlin [10] proposed his concept with a round trip efficiency of 72 % (electricity-to-electricity) under almost ideal conditions. Enolcon has set-up the process according to [10] in the simulation software EBSILON Professional to verify this case. In Table 1 the theoretical case of [10] has been verified and extended by a high and a realistic case. The high case is applying optimistic parameters for example for gradients in the heat exchangers and low values for pressure drops etc. The realistic case is indicating figures which are achievable from enolcon's point of view when executing such a project. Background of the assumed parameters is the vast experience of enolcon and its core team in the design, execution and operation of many large-scale power plants and process facilities.

TABLE I. Evaluating the Proposed Brayton-Cycle of Prof. Laughlin [10] Under the Aspects of Actual Technical Constraints for a 10 MW_E Plant

	theo.	*high*	*realistic*
heat exchanger regeneration			
temperature difference	0 K	5 K	10 K
pressure drop	0 mbar	5 mbar	20 mbar
heat exchanger hot / cold storage tank			
temperature difference	0 K	2 K	3.75 K
pressure drop	0 mbar	5 mbar	20 mbar
Temperature salt (hot/cold tank)		823/495 K	
Temperature cryogenic (hot/cold tank)		300/180 K	
dumping temperature		300 K	
max. pressure p_H/p_L in bar	78/10	73/10	69/10
salt / cryogenic pumps			
power consumption each	0 kW	50 kW	100 kW
Generator / Motor			
efficiency	1	0.99	0.97
Expander			
isentropic efficiency	0.93	0.93	0.93
mechanical efficency	1	0.99	0.99
Turbine			
isentropic efficiency	0.91	0.91	0.91
mechanical efficency	1	0.99	0.99
Storage efficiency (power to power)	**75.0 %**	**65.0 %**	**57.7 %**

With the assumptions based on [10] the theoretical case shows a storage efficiency of 75 %. The reason for the deviation of 3 % to the efficiency of 72% mentioned in [10] are different material properties applied for the working fluid Nitrogen. Furthermore, it can be shown under ambitious conditions, especially for the heat exchangers a roundtrip efficiency of at least about 58 % can be achieved in the realistic case. However, the compressor and expander/turbine which is foreseen in [10] and also the heat exchangers are not (yet) standard equipment from the shelf. Actually, it is not foreseeable when the related compressors for such combination of **high temperature** (823K = 550°C) **plus high pressure** (level of approx. 70 bar) will be available on the market under normal commercial conditions.

With the principle set-up of the **closed Brayton-cycle** concept, but now applying the enolcon-**HTTES-technology** as storage systems on the hot side and the cold side, the following conceptual simplifications are possible:

- ✓ **No internal heat exchanger**: Because of the temperature limit of solar salt to avoid freezing in the concept of [10] an internal heat exchanger is necessary. With the wide operational temperature range of the HTTES and the working fluid (e.g. Nitrogen) there is no risk of freezing, so the working fluid can be cooled down in the hot storage during charging to the level of ambient temperature. This internal heat exchanger is no longer necessary. Therefore, the efficiency can be improved and CAPEX significantly reduced.
- ✓ **No heat exchanger between working fluid and hot storage or cold storage**: Also, there is no need for a heat exchanger at all, neither on the hot side nor on the cold side when applying the enolcon-HTTES-technology. The working fluid can flow directly through the storage material. The HTTES-modules can be designed as pressurized modules, which is required for the hot side in any case. In this study enolcon also evaluated the concept of applying heat exchangers between the working fluid and the hot- and cold storage system which allows to design them for ambient pressure conditions. Comparing this concept with heat exchangers with the concept with pressurized thermal storage modules, where the working fluid is flowing directly through the storage material in the storage modules, the result was very clear: Beside a better efficiency because of smaller temperature gradients between working fluid and storage medium, the CAPEX of the pressurized modules is much lower than applying large heat exchanger systems (approx. 30%).

✓ **Low pressure level**: The enolcon-HTTES-technology is allowing an optimization of the pressure levels. The design with regard to material and wall thicknesses and heat transfer is much simpler with a combination of **high temperature** (> 823K/550°C) **plus <u>low</u> pressure** (level of approx. 4 – 12 bar on the hot side and approx. 1,3 – 3 bar on the cold side). By lowering the total pressure levels of the whole electricity storage system, the total CAPEX can be reduced. So, the enolcon-HTTES-technology is opening the door for an easier optimization of the compressor + expander/turbine system, especially when higher temperatures shall be applied. So, the efficiency can be further improved and CAPEX significantly optimized/reduced. With Nitrogen as working fluid there is a cheap possibility for direct flow through the storage modules with no risk for health and safety.

With those simplifications and optimizations, the concept with enolcon HTTES-modules is designed as shown on the right in Figure 3.

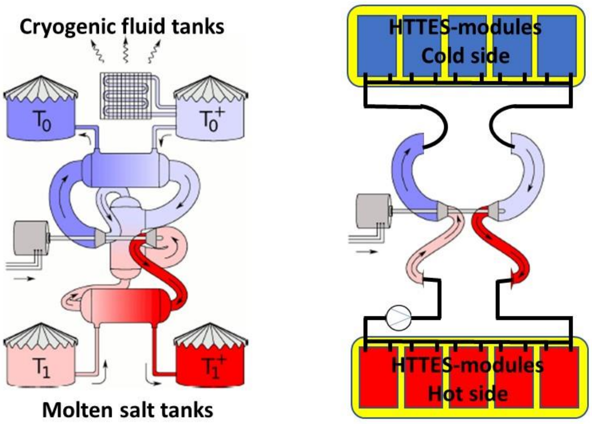

Fig. 4: Principle concepts, left the concept of Prof. Laughlin [10] with three heat exchangers, on the right the improved Brayton-cycle with enolcon-thermal storage, named OPTES-Battery

The concept of Laughlin [10] needs to dump heat energy on the cold side to allow stable process of charging and discharging. Like Laughlin [10] this improved enolcon-concept needs to dump also a small amount of energy, but unlike Laughlin [10] the energy is dumped after the hot storage part to cool the working fluid with an ambient cooler on the dumping temperature (see also Fig. 9 item 8). This cooler is necessary for the OPTES-Battery to maintain the process parameters at design conditions and at stable efficiency during steadily charging and discharging.

Equivalent to the procedure in *Table 1* for the Brayton cycle in *Table 2* the enolcon-OPTES-Battery concept is set up on a theoretical, a high and a realistic case. The results show an improved electricity-to-electricity efficiency of about 8 - 12 percentage points compared to the equivalent case of [10].

TABLE II. IMPROVED BRAYTON-CYCLE WITH ENOLCON-THERMAL STORAGE FOR A 10 MW_E PLANT, OPTES-BATTERY

	theo.	*high*	*realistic*
Hot HTTES			
chagring Temperature	1273 K	1273 K	988 K
temperature difference charge/discharge	0 K	5 K	10 K
pressure drop	0 mbar	20 mbar	30 mbar
Cold HTTES			
charging Temperature	208 K	205 K	201 K
temperature difference charge/discharge	0 K	5 K	10 K
pressure drop	0 mbar	20 mbar	30 mbar
dumping temperature	300 K	300 K	300 K
max. pressure p_H/p_L in bar	5.4/1.0	5.8/1.0	6.0/1.0
Generator / Motor Efficiency	1	0.97	0.97
Expander			
isentropic efficiency	0.93	0.93	0.93
mechanical efficency	1	0.99	0.99
Turbine			
isentropic efficiency	0.91	0.91	0.91
mechanical efficency	1	0.99	0.99
Storage efficiency (power to power)	**87.4 %**	**75.6 %**	**66.1 %**

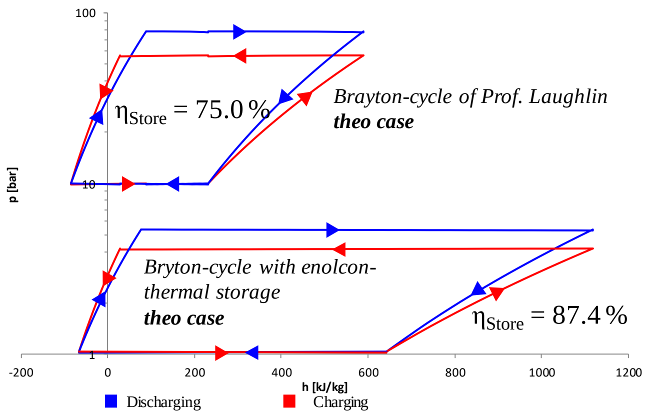

Fig. 5: Comparison of the Brayton-Cycles in the log p-h diagramm for the high case of Table I and II. On the bottom the improved Brayton-Cycle with enolcon HTTES; at the top the concept of Prof. Laughlin [10]

III. THE ENOLCON **OPTES**-BATTERY

In the previous chapters the general process of [10] and the principle improvements have been shown and indicated. In the following the enolcon-electricity storage based on a closed Brayton cycle is explained in more detail and also considered from the point-of-view of practical realization. There are two cases indicated: One case is an enolcon-OPTES-Battery which **can be built today** (March 2020), indicated as **actual case**. It consists of proven equipment which can be purchased at the markets on commercial basis (e.g. compressor + expander from company Atlas Copco Gas and Process; storage modules from STORASOL; valves, coolers electrical equipment etc. are offered from many suppliers.).

The **near future case** with its technical parameters is shown based on statements of suppliers of what can be delivered as equipment in **year 2023**.

The following figure shows the simulation model in EBSILON Professional of the improved Brayton-cycle.

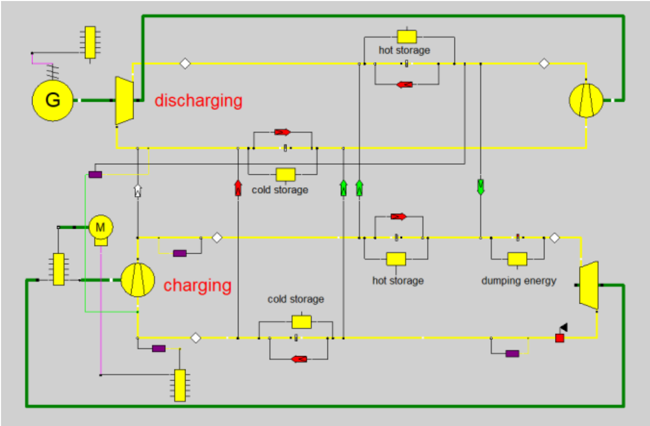

Fig. 6: Modeling the improved Brayton-Cycle with enolcon-thermal energy storage in Ebsilon Professional; bottom side: charging process; at the top: discharging process

The basic process with 5 storage modules (example) on the hot side (HM 1 – 5) and 5 storage modules on the cold side (KM 1 – 5) is indicated in *Fig. 4* where also the main valves are shown. In Fig. 4 there is no heat exchanger applied, the storage modules can be built as pressure vessels.

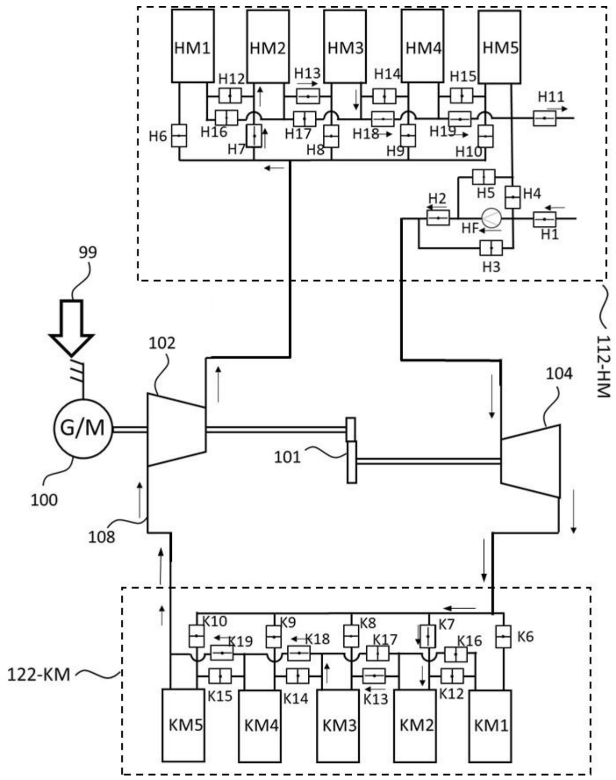

Fig. 7: Schematic enolcon-process of an improved Brayton-Cycle with enolcon-thermal energy storage modules, the arrows indicate charging of the system.

It should also be mentioned that different modifications of the OPTES-Battery have been evaluated, for example the installation of an electrical heater behind the compressor (see Fig. 9 item 6). This electrical heater heats up the working fluid to a higher temperature ('temperature booster') during charging. As result it might make sense to install a small electrical heater for that purpose from economic point of view, especially when the electricity for charging is very cheap or free of charge, but the total efficiency of electricity-to-electricity is reduced. Another positive effect of a small electrical heater is the possibility to control the temperature before the expander and therefore the efficiency of the process, especially during discharging the parameter can be kept in the level for optimized operation.

Another item which can currently be included to increase the total efficiency is an ORC-unit (Organic Rankine Cycle) behind the expander. This ORC-unit is operated during discharging and using the temperature difference of the Nitrogen directly behind the expander and the required process temperature before the Nitrogen is entering the cold storage modules (see Fig. 9 item 7).

Fig. 8 is a picture of an enolcon- OPTES-Battery with a storage capacity of 80 MWh_e and approx. 7,6 MW_e charging power. The **area** required for such 80 MWh_e-OPTES-Battery is with approx. 55m x 38m **much smaller** than the space occupied by the 53 MWh_e-Li-Ion-battery of [6],[7] with 110m x 62m, see [7].

Fig. 8: Picture of an **OPTES-Battery** with 7,6 MW_e and 80 MWh_e, the dimensions are approx. 55m x 38m and height of approx. 10m. On the left side the 'high' pressure hot thermal storage and on the right side the low pressure thermal cold storage.

With the support of company Atlas Copco Gas and Process the **actual concept** has been developed based on **standard Companders** (which combine Turbocompressor + Turboexpander functionalities) with Nitrogen as working fluid. The following graph is illustrating the process with process data developed together by enolcon and Atlas Copco. The total electrical efficiency without an ORC is between 40 – 43%. When applying an ORC as described above, the electrical efficiency is between 43 – 45%. It can be concluded that the closed Brayton-cycle when built **today**, already has an electrical efficiency number as **starting point**, which Thermal Batteries based on Rankine-cycles have as a maximum achievable **end point**. It should also be noted that the efficiency figures of the OPTES-Battery also consider electrical consumers such as the oil coolers, the process coolers, the Nitrogen-generator (to compensate Nitrogen losses at the companders) and further minor losses.

Currently the path is set to higher efficiencies of the OPTES-Battery with optimization of the pressure levels and the capability of compander-machines in a few years to handle temperatures above 715 °C. Such parameters will lead to practical electrical efficiencies electricity-to-heat/cold-to-electricity of approx. 63 – 67%.

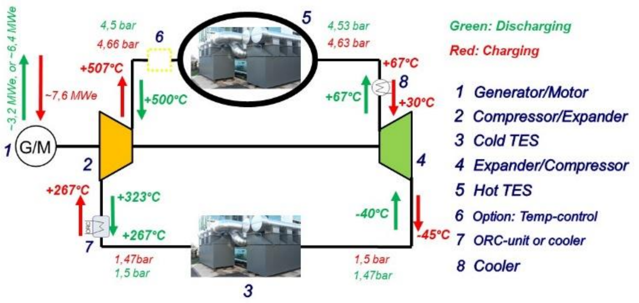

Fig. 9: Process of an **OPTES-Battery** with 7,6 MW_e as it can be build today (March2020).

IV. Costs

The costs for an electricity storage with an electrical storage power of 7,6 MW_e and 80 MWh_e based on the enolcon-Brayton-cycle (**actual case**) is at a level of approx. 16,0 – 20.0 million €, see also Table III (which is including an ORC-unit). The specific cost value per kWh_e is at a level of 200 – 250 €/kWh_e. If the storage volume is increased to larger amounts than 80 MWh_e the specific costs will be lower. If the same system is equipped with larger or more thermal storage modules which allow for a storage capacity of 100 MWh_e, then the specific costs will decrease to approx. 175 – 215 €/kWh_e.

When considering statements of equipment suppliers for compressors and expanders/turbines for future costs and parameters, then for the **near future case** (year 2023) the specific costs are expected to remain on the same level, but the electricity-to-electricity-efficiency is improved from a level of 40 - 45% to a level of 63 - 67%.

It should be mentioned that such a Thermal Battery like the OPTES-Battery is not subject to degradation or limitations of cycles or negative effects of DoD (Depth of Discharge) as with Li-Ion batteries. So, for economic considerations there is a useful technical lifetime of more than 25 years to be expected for an OPTES-Battery, with no replacement investments after a certain time (as it is the case with electrical batteries after a certain amount of cycles or approx. 10 years).

The operational costs (OPEX) are very low. There are some internal electrical consumers (e.g. for the Nitrogen-generator, the coolers, some HVAC-equipment) and there is some maintenance required for the compressors and the expanders/turbines. A very minor part of maintenance is for the air valves and balance of plant (BoP). In total as average annual OPEX an amount of approx. 0,5 – 1,0% of the CAPEX can be assumed.

With an actual '*can be built today*'-efficiency of 40 – 45% this improved Brayton-cycle process is already, and will remain, far ahead of electrical batteries for the next decade regarding economics when it comes to electricity storage periods of more than 4 hours.

In Table 3 a breakdown is shown of the key equipment and systems and its related costs based on current market prices. Since enolcon works in the project management, engineering and design of large technical facilities as part of its daily business (industrial power plants, process systems etc.), the shown CAPEX-data can be seen as reliable, based on actual market situation. The most important input data have been provided from companies like *Atlas Copco Gas and Process* (Turbocompressors and Turboexpanders) and STORASOL (Thermal storage).

TABLE III. CAPEX of an OPTES-Battery with enolcon-thermal storage for approx. 7,6 MW_E , 80 MWh_E - plant

HTTES (hot storage)	
Storage material	
Filling, erection, mounting	
Storage modules (14 pieces)	
gas ducts+collectors	
gas valves with motors	
Insulation+cladding	
Steel structure related to hot side	
Pressure vessel with inside steel plates and bars	
	4.884.200 €
LTTES (cold storage)	
Storage material	
Filling, erection, mounting	
Storage modules (12 pieces)	
gas ducts+collectors	
gas valves with motors	
Insulation+cladding	
Steel structure related to cold side	
	1.851.600 €
Compressor + Expander unit 1 (2 pcs), incl. Oilcooler etc.) (for charging)	
Compressor + Expander unit 2 (2 pcs), incl. Oilcooler etc.) (for discharging)	
Balance of Plant related to Compr.+Expanders	
Control system (e.g. PCS 7)	
measurement equipment	
BoP related to working fluid (N2),e.g. Nitrogen gen. and process (e.g. cooler)	
ORC-unit, approx. 300 -450 kWe	
Working fluid (N2)	
	9.748.000 €
Electrical equipment (for charging and discharging), Softstarter etc.	
Grid connection, incl. Tests	
Electrical BoP (cables, cable trays, etc, which is not incl. in the other items)	
	610.000 €
Civil works (concrete plates, foundation, small building)	
Erection and mounting works, not included in the other items	
Site costs (during construction)	
	988.000 €
Project Management	
Engineering (which is not included in the individual items)	
Commissioning	
Miscellaneous, contingency which is not included in other parts	
	1.823.636 €
Total costs of enolcon-OPTES-BATTERY	**19.905.436 €**

V. Summary and Conclusion

The tasks of this work has been to optimize the concept of a Thermal Battery based on a closed Brayton-cycle. Based on the works of [10], the key issues have been analyzed. To overcome these issues, which are mainly temperature spread limitations and CAPEX-burden because of the heat exchangers and the expensive thermal hot and cold storage (molten salt and Hexane) and the process disadvantages of the high-pressure levels, the solid bed-HTTES-technology of enolcon and STORASOL has been applied. This **new kind of Thermal Battery**, called **OPTES-Battery**, has much **lower CAPEX**-figures and **higher realistic efficiencies** and is opening the door for economically attractive electricity storage and supporting the implementation of renewable energies (Solar, Wind) and thus acting against climate change.

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