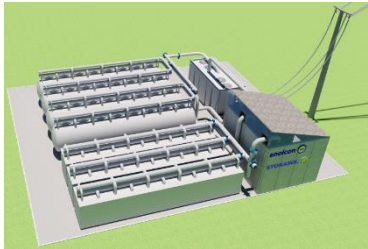


OPTES[®]-GT Battery

OPTimized Thermal Electricity Storage – Gas Turbine Battery

Path to the first demonstration plant OPTESDEMO of the novel CAPEX-optimized-Brayton-cycle-concept with P-VHTTES and HTTES

4th IWCB 2024: International Workshop on Carnot Batteries 2024



Supported by:

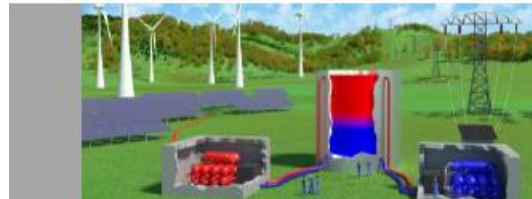


Federal Ministry
for Economic Affairs
and Climate Action



ZIM
Zentrales
Innovationsprogramm
Mittelstand

on the basis of a decision
by the German Bundestag



4th International Workshop on
Carnot Batteries
2024

Dr. Günter Schneider, 25th September 2024

CONTENT

1. Carnot Batteries under development of enolcon/STORASOL
2. OPTES[®]-GT-Battery concept
3. OPTES[®]-GT-Demonstration project - OPTESDEMO
4. P-VHTTES – the innovative core element
5. OPTES[®]-GT-Battery Outlook
6. Conclusion

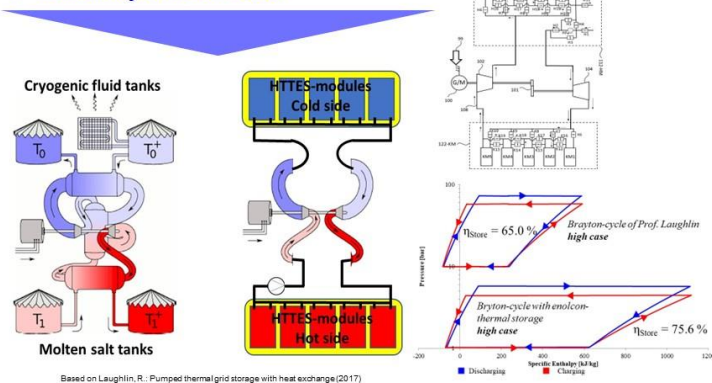
STORASOL and enolcon presented during IRES 2020 the OPTES®-Battery which is based on a closed Brayton-cycle. During the 3rd IWCB in year 2022 a Carnot Battery based on an open Brayton-cycle has been presented → OPTES®-GT Battery.



OPTES®-Battery Closed cycle

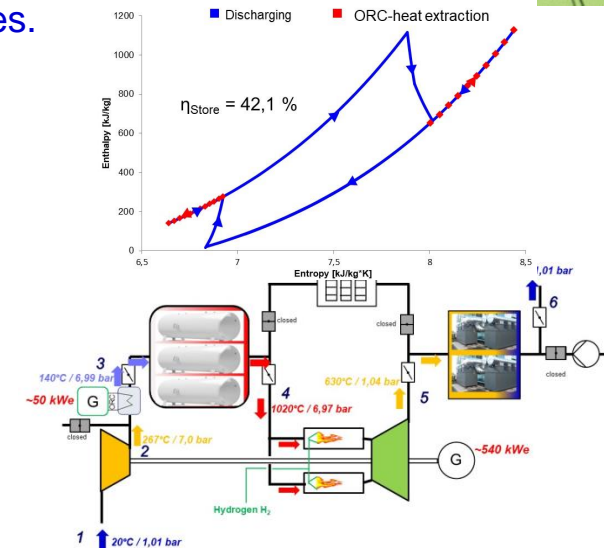
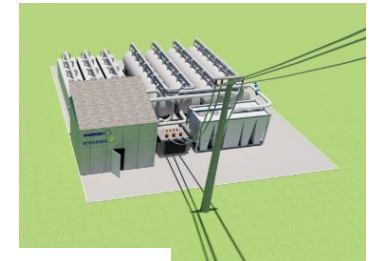
When the HTTES-technology of enolcon/STORASOL is applied there are several advantages:

- ✓ **No heat exchanger required** (but pressure vessel, at least on the hot side)
- ✓ **Temperature spread can be increased** (e.g. up to 700 - 800 °C on the hot side)
- ✓ **Lower pressure levels**
- ✓ **Operation is much easier, no risk of freezing, no large salt pumps etc.**
- ✓ **Efficiency is much better**

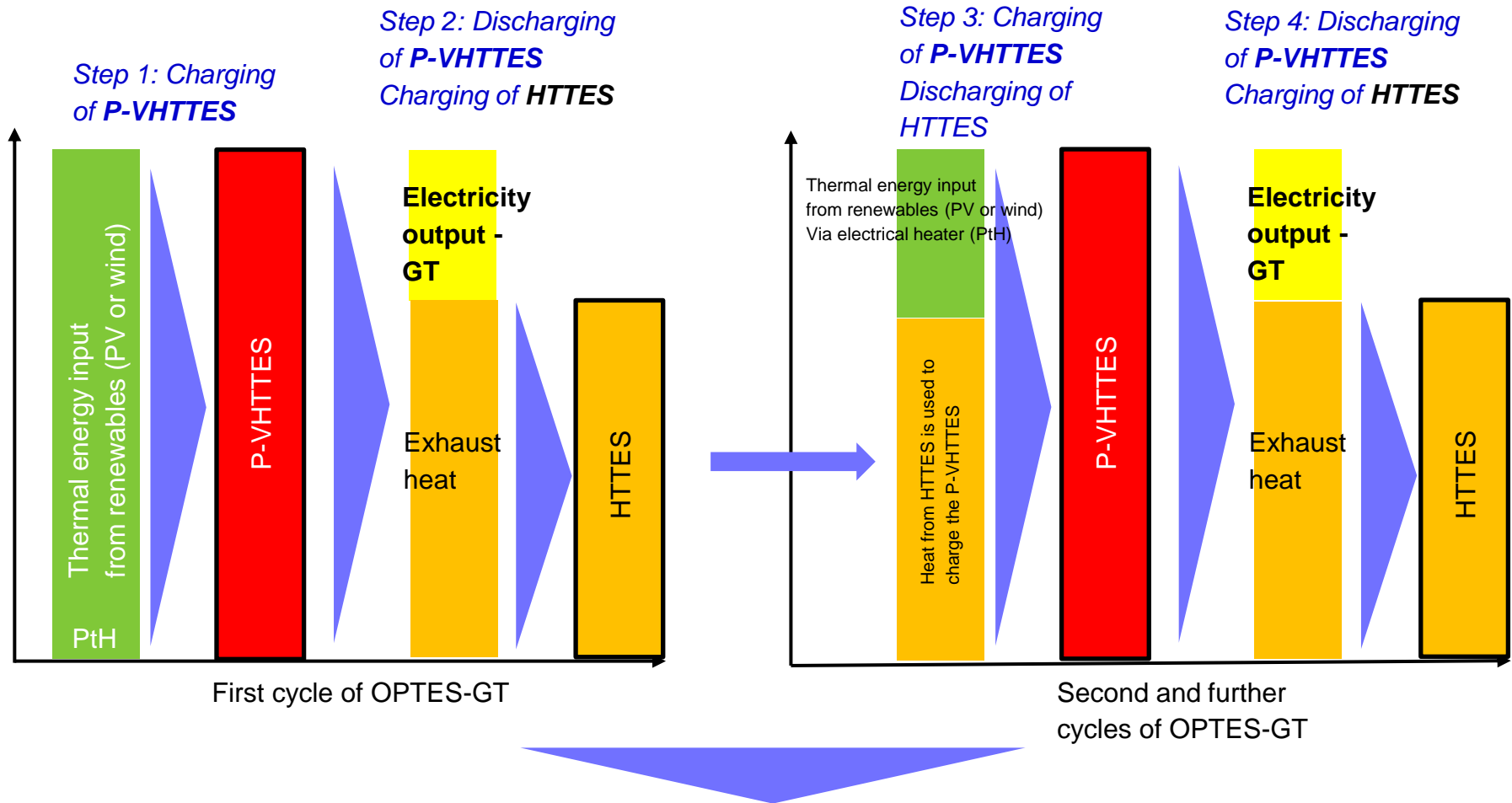


OPTES®-GT Battery Open cycle

Status of development is presented in the following slides.



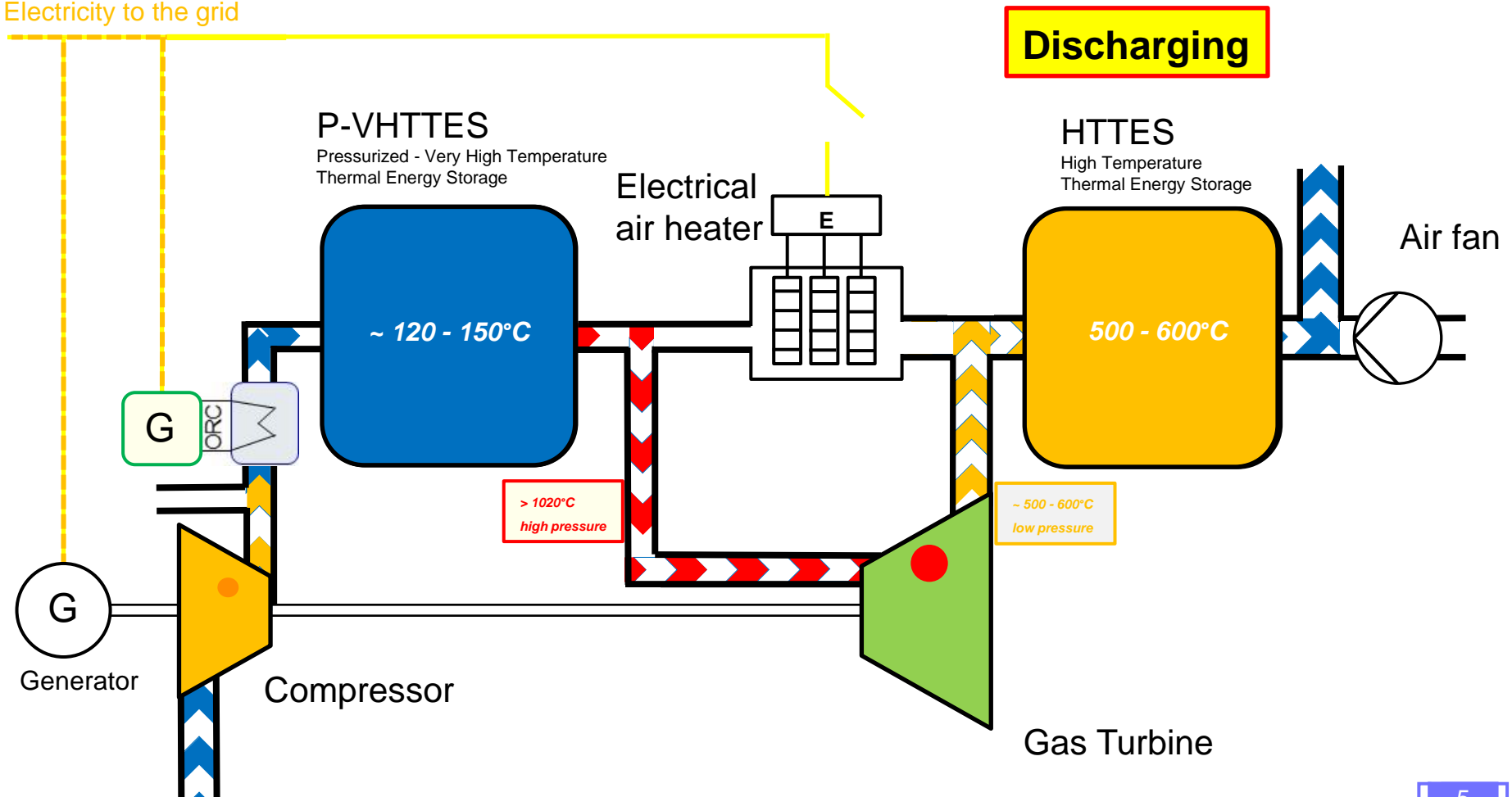
The general OPTES-GT concept (open cycle) is illustrated below:



The exhaust thermal energy is stored during discharging and re-used during charging of the P-VHTTES. As a consequence the amount of renewable energy to produce electricity is reduced → improving the roundtrip efficiency.

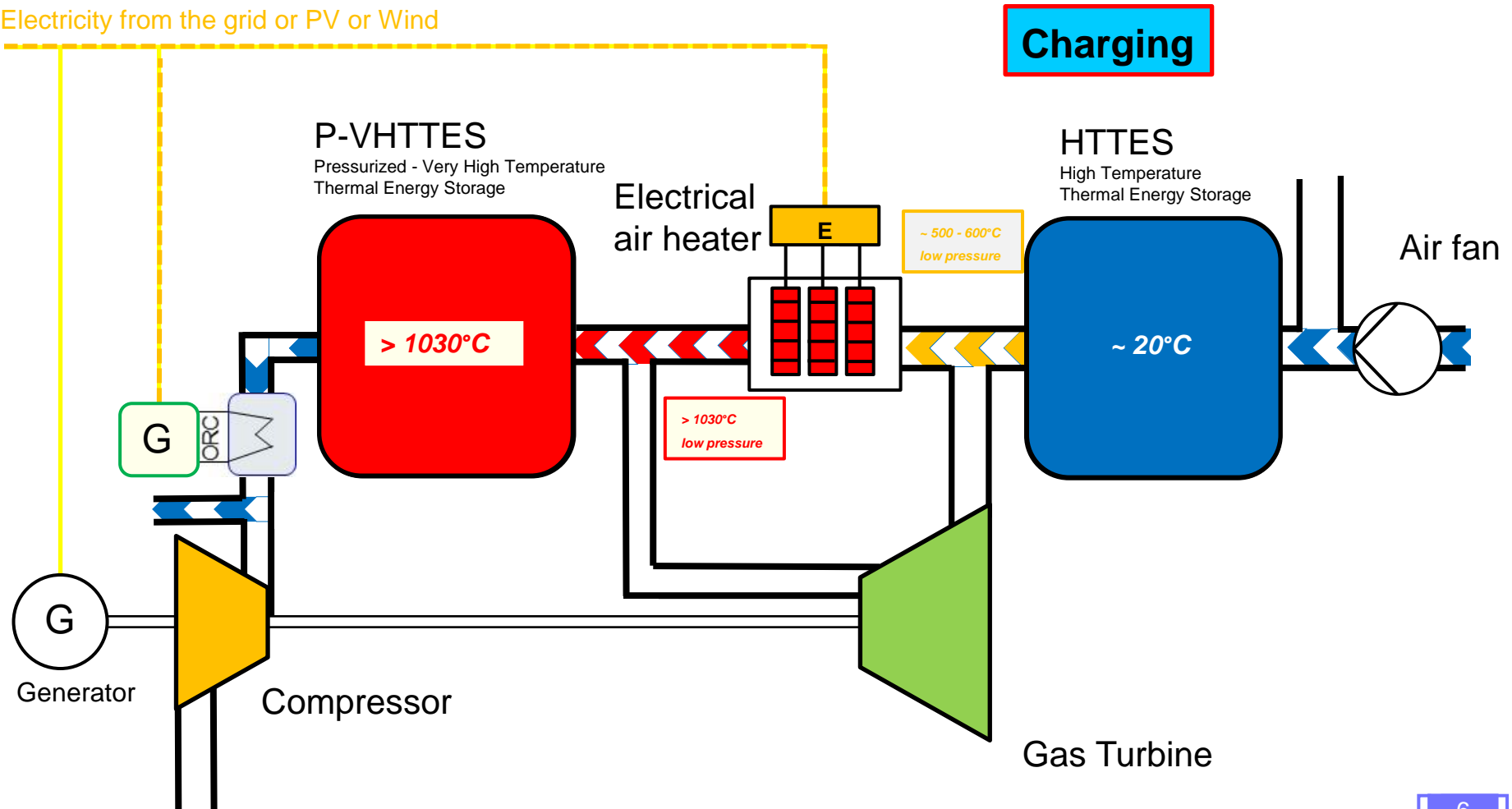
The general concept of the OPTES®-GT Battery is based on the idea that the renewable energy remains in the OPTES®-GT Battery system to a very large extent. That requires a pressurized very high temperature thermal energy storage (P-VHTTES) and a high temperature thermal energy storage (HTTES). The heat behind the Gas Turbine is stored in the HTTES. Illustration of the principle:

Electricity to the grid

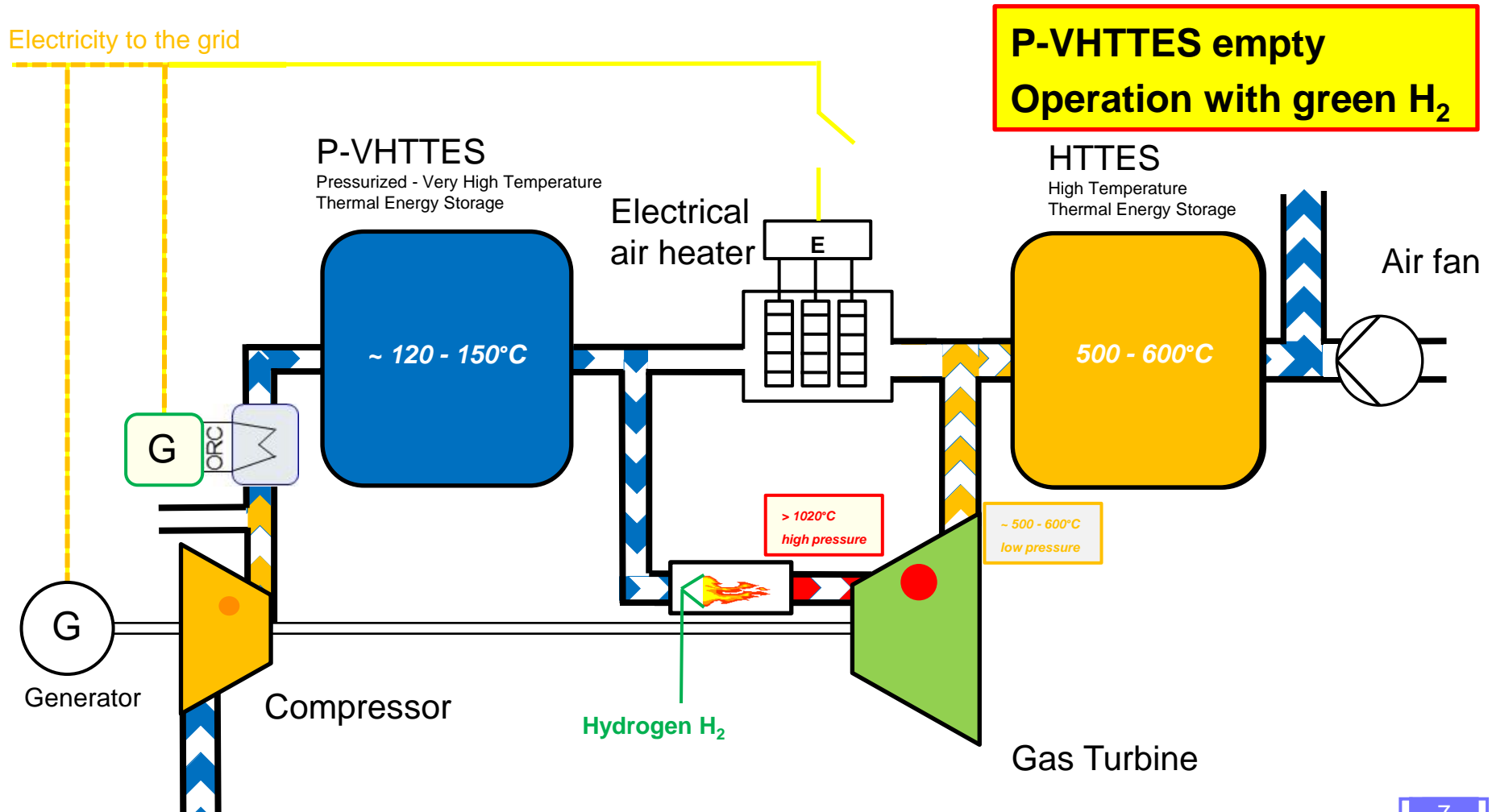


During charging the heat of the HTTES is used. The electrical heater has to deliver only the energy to heat up the air from the approx. 500 – 600°C to more than > 1030°C. The charging takes place on low pressure, slightly above ambient pressure to overcome pressure losses. Illustration of the principle:

Electricity from the grid or PV or Wind

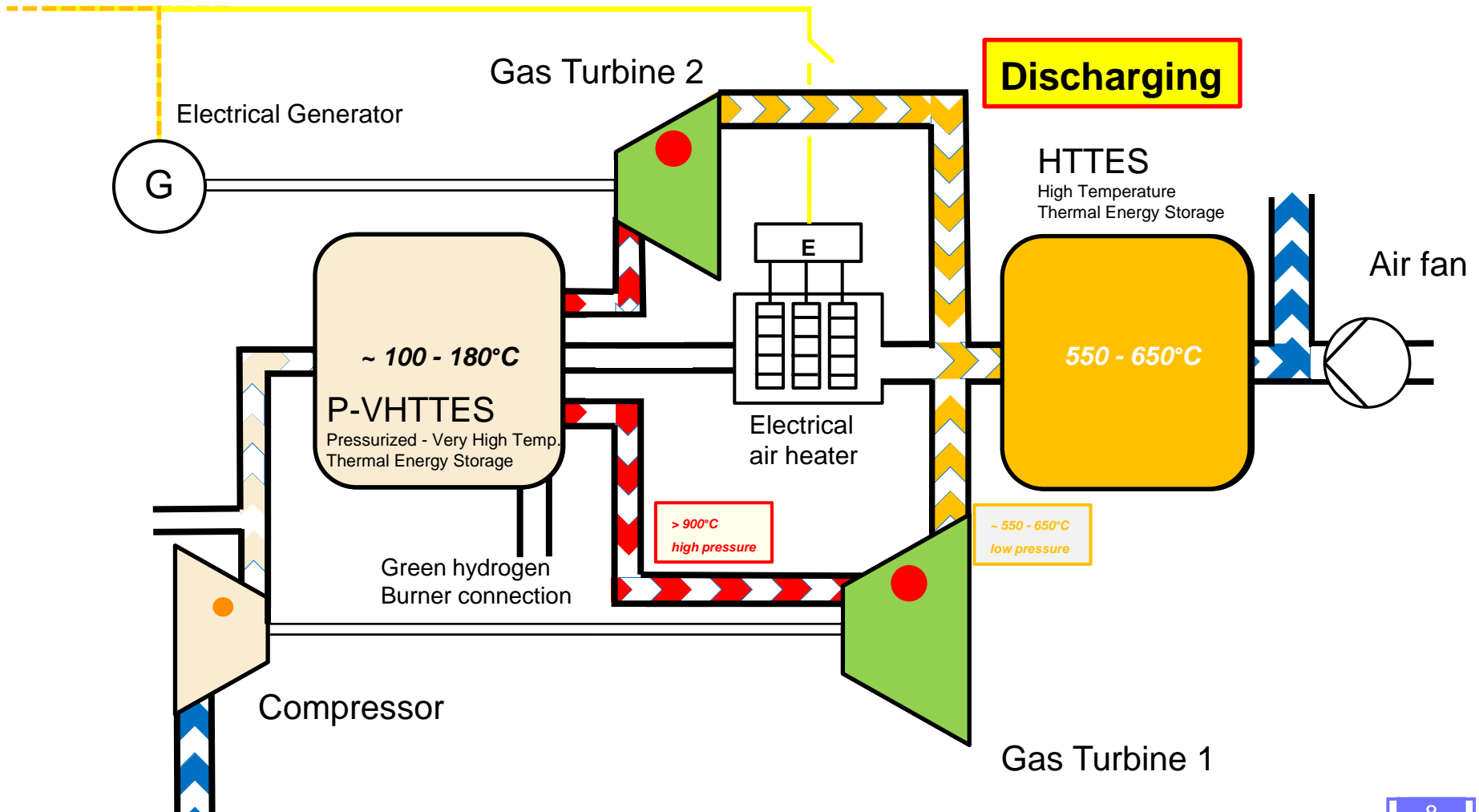


Such an **OPTES®-GT Battery** can also be operated for electricity production with **green Methane** or **green Hydrogen** if the P-VHTTES is completely discharged. It is also possible to use green hydrogen only as booster to increase the air temperature from the P-VHTTES and to improve the turbine efficiency.



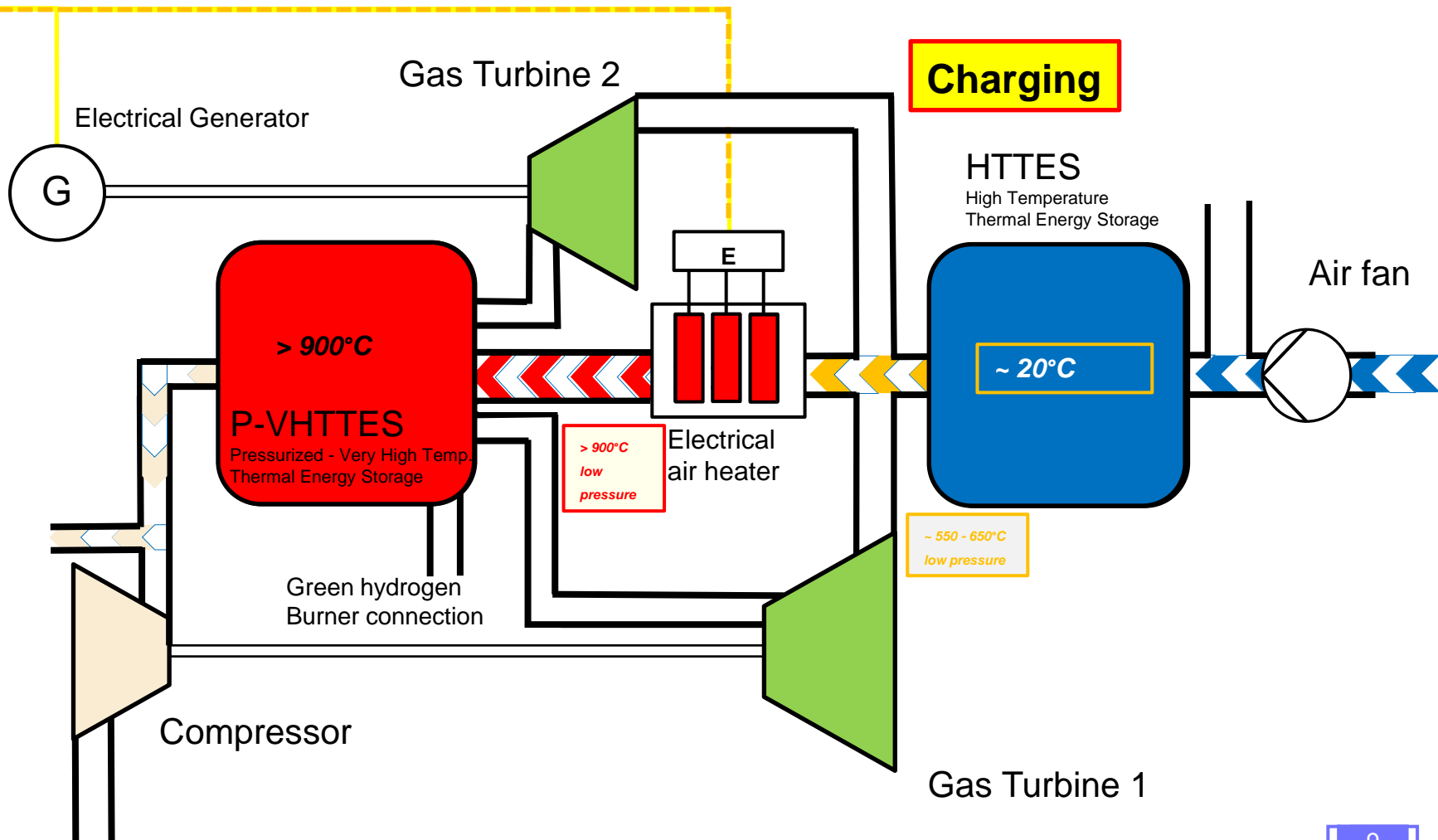
The **OPTESDEMO** is using two separate gas turbines operated with air, one turbine is driving the compressor, the other one is driving an electrical generator. The process looks as follows:

Electricity to consumer



The **OPTESDEMO** is using two separate gas turbines, one turbine is driving the compressor, the other one is driving an electrical generator. The general OPTESDEMO process looks as follows:

Electricity from the grid (PV, Wind)



The target of the actual works in the enolcon-laboratory is the construction and commissioning and testing of the **OPTES®-GT Battery** process. The name of the project is OPTESDEMO and it is supported by the German government with grants (ZIM).

The **OPTESDEMO-project** shall demonstrate:

- That it is possible to store **electricity** in a **thermal battery** with this type of Brayton-cycle.
- That the core elements (P-VHTTES, HTTES, turbines and compressor) are capable to fulfill their tasks.
- That fast start-ups and shut-downs are possible (much faster than Rankine-cycle processes).
- That the **OPTES®-GT Battery** process allows part load operations and **CHP-operations** (combined heat-and-power) when replacing the HTTES by a HRSG (Heat Recovery Steam Generator).
- That the **OPTES®-GT Battery** can also be operated with **green Hydrogen** (add-on).

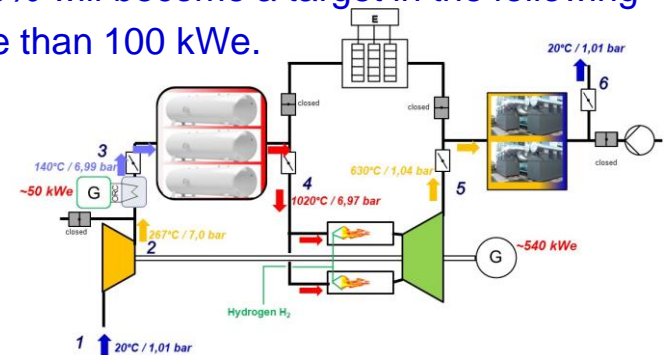
Since the OPTESDEMO is designed with small electrical capacities (electrical output during discharging is approx. 5 kWe) it is **not** intended to demonstrate high electricity roundtrip efficiencies.

The demonstration of electricity roundtrip efficiency of approx. 40 – 50% will become a target in the following **OPTES®-GT Battery** project with an electrical output capacity of more than 100 kWe.

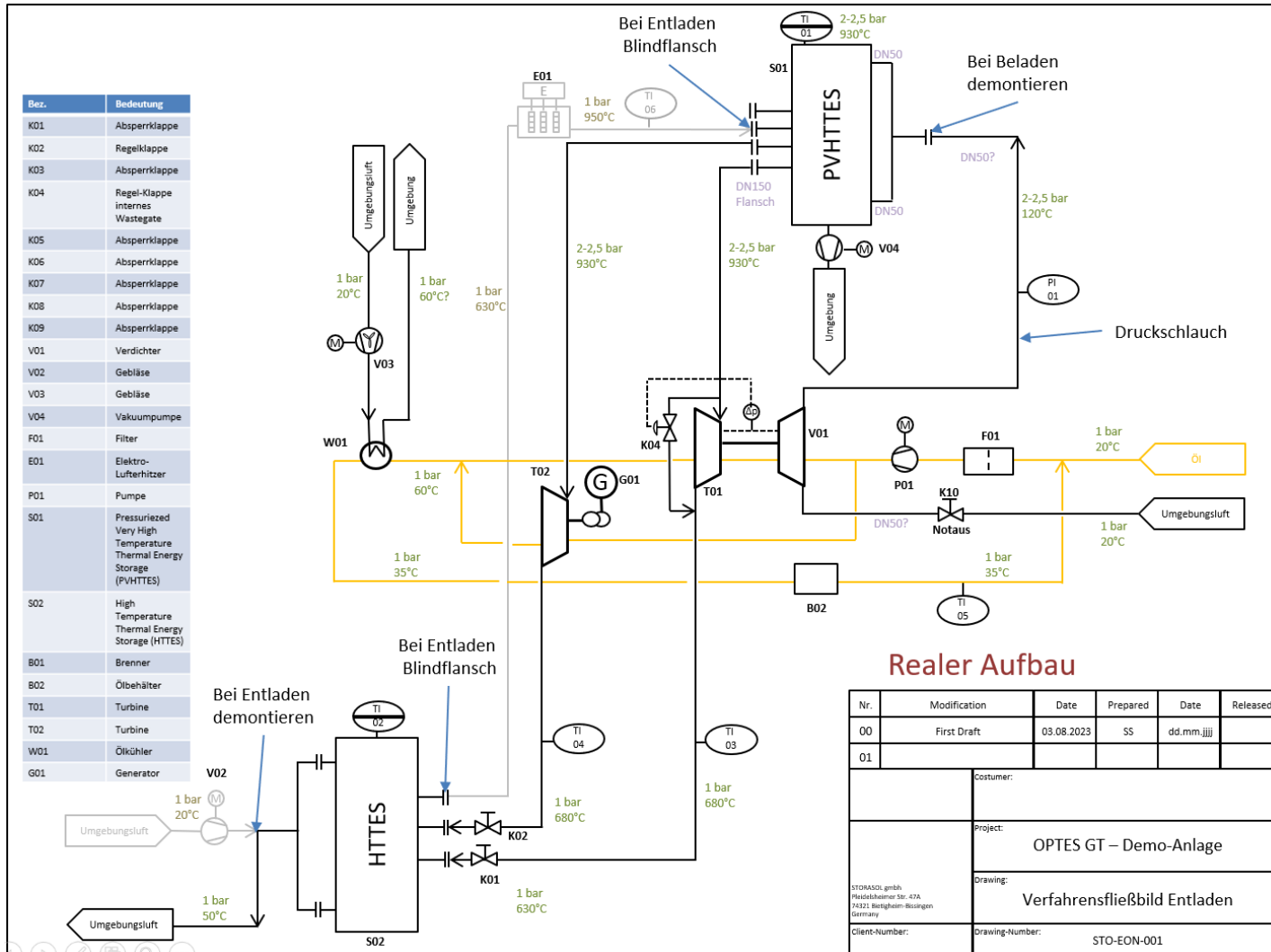
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by the German Bundestag



The **OPTESDEMO**-system which is under realization since June 2024 is designed with two gas turbines where one turbine has the task to drive the compressor and the second gas turbine shall drive the electrical generator.



Bez.	Bedeutung
K01	Absperrklappe
K02	Regelklappe
K03	Absperrklappe
K04	Regel-Klappe internes Wastegate
K05	Absperrklappe
K06	Absperrklappe
K07	Absperrklappe
K08	Absperrklappe
K09	Absperrklappe
V01	Verdichter
V02	Gebläse
V03	Gebläse
V04	Vakuumpumpe
F01	Filter
E01	Elektro-Lufterhitzer
P01	Pumpe
S01	Pressurized Very High Temperature Thermal Energy Storage (PVHTTES)
S02	High Temperature Thermal Energy Storage (HTTES)
B01	Brenner
B02	Ölbehälter
T01	Turbine
T02	Turbine
W01	Ölkühler
G01	Generator

What are the new elements in the OPTES®-GT Battery:

- a) Pressurized Very High Temperature Thermal Energy Storage (**P-VHTTES**) - **NEW**
- b) **Modified gas turbines** to be operated with hot air (instead burners)
- c) Optimized open Brayton-cycle via integration of ORC, or other heat consumer, between compressor and P-VHTTES (this is not part of the OPTESDEMO-project)

The **P-VHTTES** is a **new** element.

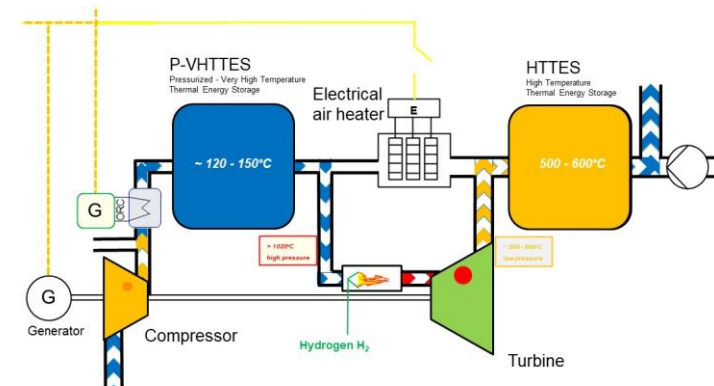


The HTTES-storage behind the gas turbine is **not** a **new** element since it has been commissioned in Bayreuth already in year 2015.



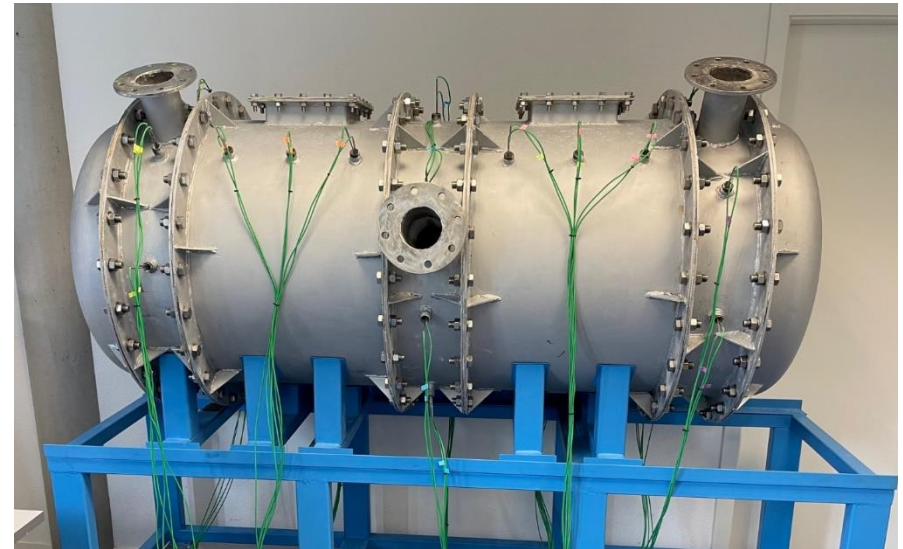
Advantages to some other concepts:

- ✓ No molten salt issues (freezing, large and expensive heat exchangers, cost of storage material)
- ✓ Fast starts possible (< 15 minutes) due to small masses e.g. compared to Rankine-cycles with water/steam.
- ✓ Fuel flexibility: Also Hydrogen or natural gas or another gas can be used as fuel (either supplementary or as the only heat source)
- ✓ Environmentally friendly: Sand, steel, insulation as main material.



New element is the P-VHTTES:

A pressurized thermal energy storage for very high temperatures (> 900°C) doesn't exist for such applications. Based on the proven HTTES-technology enolcon and STORASOL are developing such P-VHTTES. A first P-VHTTES-test module has been designed and built and commissioned in the enolcon laboratory in year 2023 with the support of a Master-student of DLR / University Stuttgart (Mr. Elias Alami).

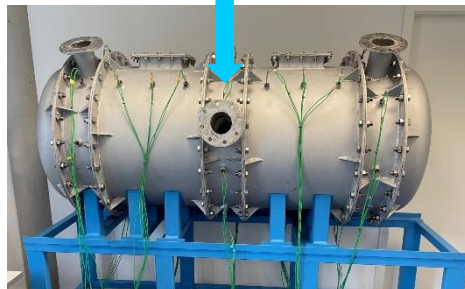


This new P-VHTTES was tested under several test conditions. The target of this P-VHTTES module (TESS3B) was to gather experience and design basis information for the P-VHTTES-module which shall become part of an OPTES-battery.

One important test feature is the temperature distribution especially between the storage material walls/layers, meaning that the temperature spread between the lowest and the highest temperature shall be very small.



Middle element of TESS3B (hot side)



DLR / University Stuttgart supported the further development with a Master degree study about the air flow and the temperature distribution in the middle element (Mrs. Annika Seidel).

The CFD-calculation was validated by the real temperature measurements in the TESS3B.

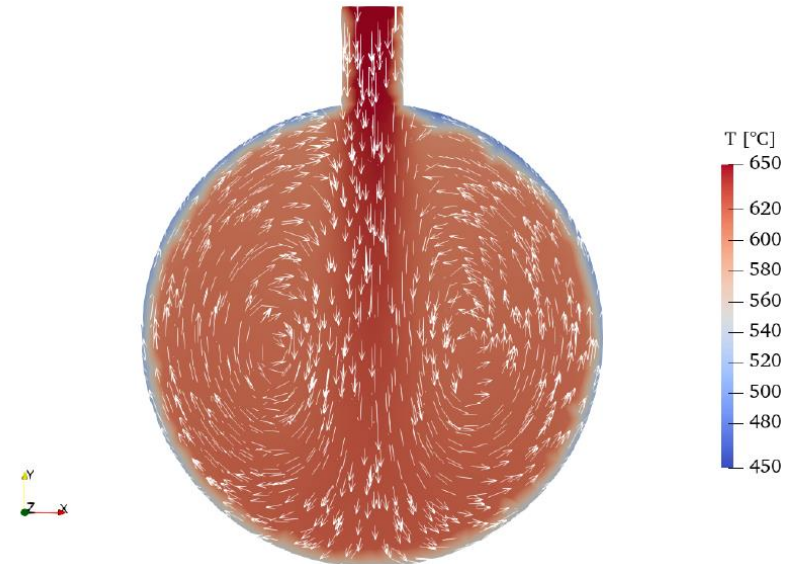


Figure 4.1: Cross-sectional view of the Type 0 temperature field along z-axis

The Master study has considered different concepts with regard to size and also with regard to different arrangements of the inlet. There is a large improvement potential to reduce the temperature spread.

The change of sizes/diameters and arrangement of inlet duct can achieve very small temperature spreads (e.g. from approx. 50 K to less than 5 K)

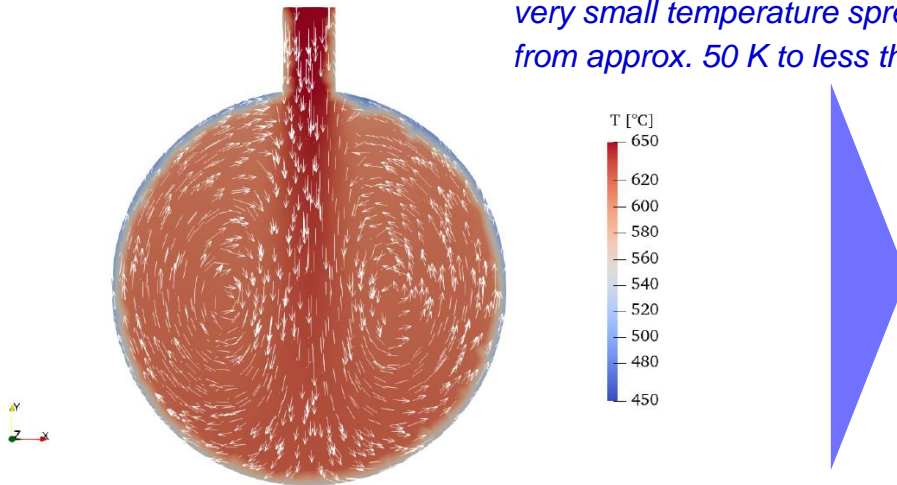


Figure 4.1: Cross-sectional view of the Type 0 temperature field along z-axis

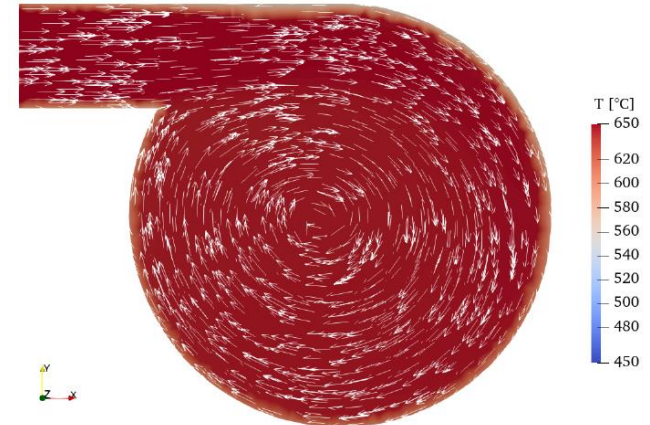


Figure 4.18: Cross-sectional view of the Type Ic temperature field along z-axis

There are also further improvements possible which are not considered in the Master study. An adjustment (confidential) inside the inlet area of the TESS3B between the storage material layers has improved the temperature spread dramatically:

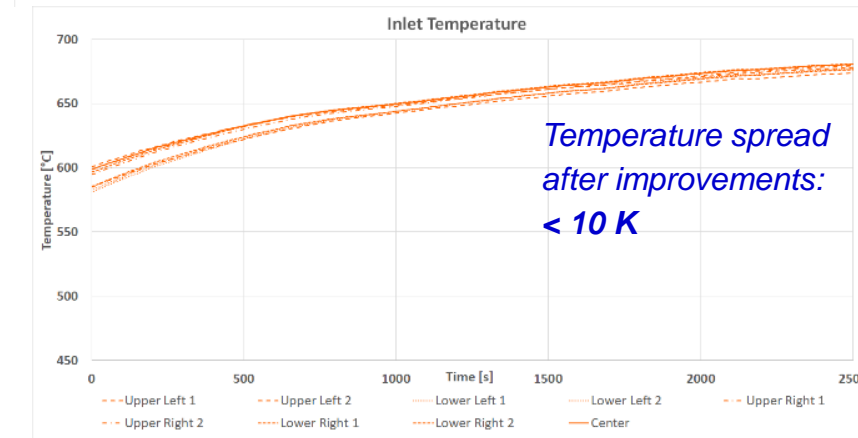
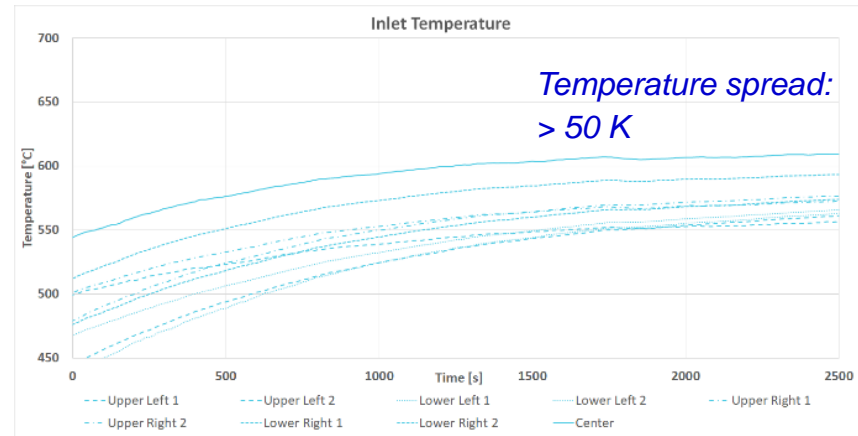
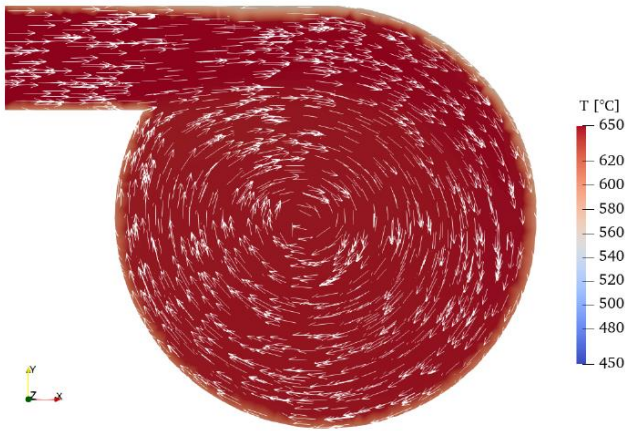


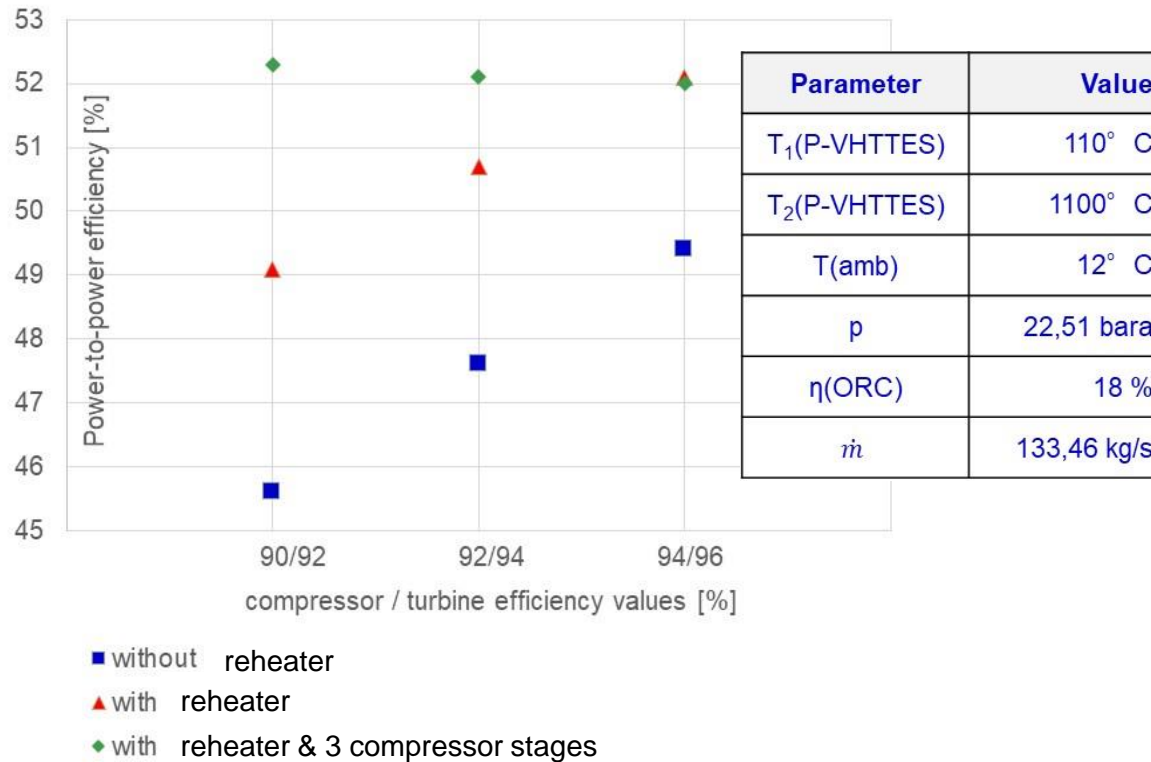
Figure 4.18: Cross-sectional view of the Type Ic temperature field along z-axis

For the OPTESDEMO-Project some improvements of the DLR-Master study will be implemented in the new P-VHTTES in combination with other improvements tested already in the TESS3B.

Measured values in the TESS3B inlet area before and after improvements

Roundtrip efficiency depends very much on compressor/turbine efficiency. From first studies with special developed equipment technically a **roundtrip efficiency** (electricity-to storage-to electricity) of up to **53 – 55%** can be achieved with an OPTES-GT process in large scale (see also our last presentation during the 3rd IWCB 2022).

Large potential for an economically attractive flexible electricity storage.



The **OPTES[®]-GT**-battery is an opportunity to store renewable energy in a **Carnot Battery** at economically attractive conditions and to support renewable energies.

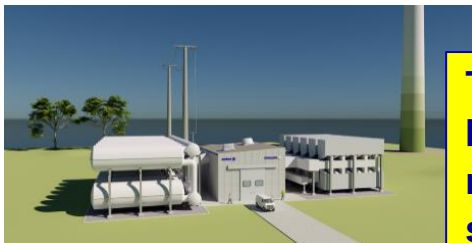
The **OPTES[®]-GT** development status is as follows:

- a) OPTES[®]-GT concept available. Further improvements still to be investigated/to be developed.
- b) Gas turbines with compressor are available. Modification for hot air –"firing" to be demonstrated. Discussion with several gas turbine suppliers started. OPTESDEMO is applying small standard gas turbines and compressor.
- c) HTTES commercially available.
- d) P-VHTTES not yet commercially available. The first P-VHTTES pilot plant (TESS3B) is available and commissioned. Tests form the basis for the P-VHTTES (TESS3C) for the OPTESDEMO-project.
- e) OPTESDEMO-project under realization, commissioning is scheduled for 2025 in the enolcon-laboratory.

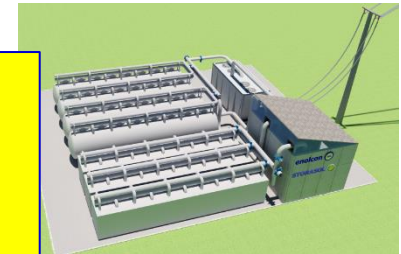
Next steps:

- OPTESDEMO demonstration plant in small scale to demonstrate **OPTES[®]-GT** process and to gather experience. Also operation with **green hydrogen** is planned to be demonstrated.
- A larger **OPTES[®]-GT plant** of approx. >100 – 1000 kWe to be built as next step, after OPTESDEMO was successful. Approaching partners from industry and research institutes for the next steps.
- Looking for a commercial partner to finance the commercial deployment.

OPTES[®]-Battery plant, closed Brayton-cycle



OPTES[®]-GT battery plant, open Brayton-cycle



The **OPTES[®]-GT** concept can provide a general boost for Carnot-battery deployment since the required financing for building first commercial sized **OPTES[®]-GT** batteries is relatively small.



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Back-up slides

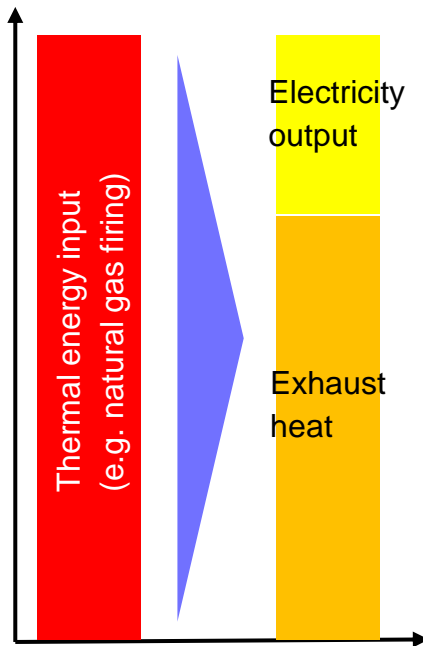
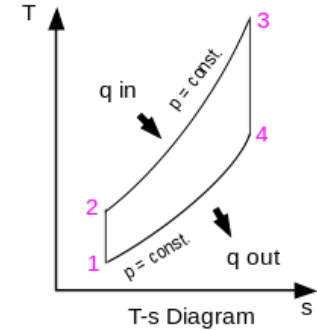
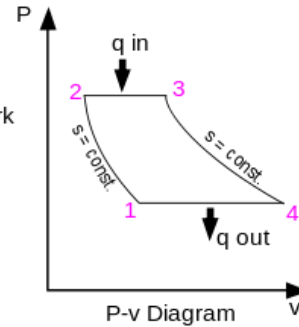
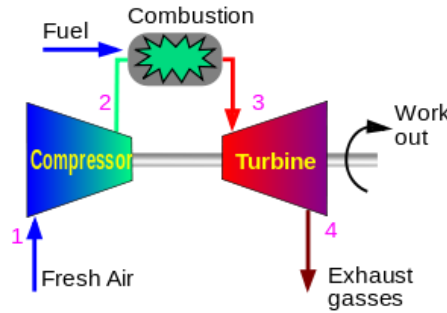
See also presentation slides shown during the 3rd IWCB 2022

Some basics: The classical open Brayton-cycle is applied in open gas turbines.

The temperatures after the combustion before the turbine part are normally high with $> 1000^{\circ}\text{C}$. The exhaust gases behind the gas turbine are normally at temperature levels of $450 - 600^{\circ}\text{C}$.

Therefore it makes sense to use this exhaust heat in a further process like a Rankine-cycle (CCGT-plant) or an ORC-process.

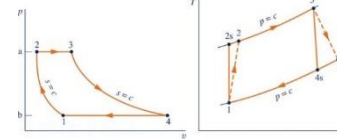
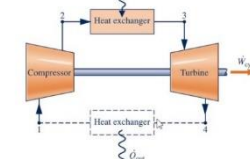
For the **OPTES[®]-GT Battery** the idea is to recover the heat and to keep it in the system.



“Classical GT-process”

Gas Turbines

- Smaller than vapor cycles
- Open or closed \dot{Q}_{in}

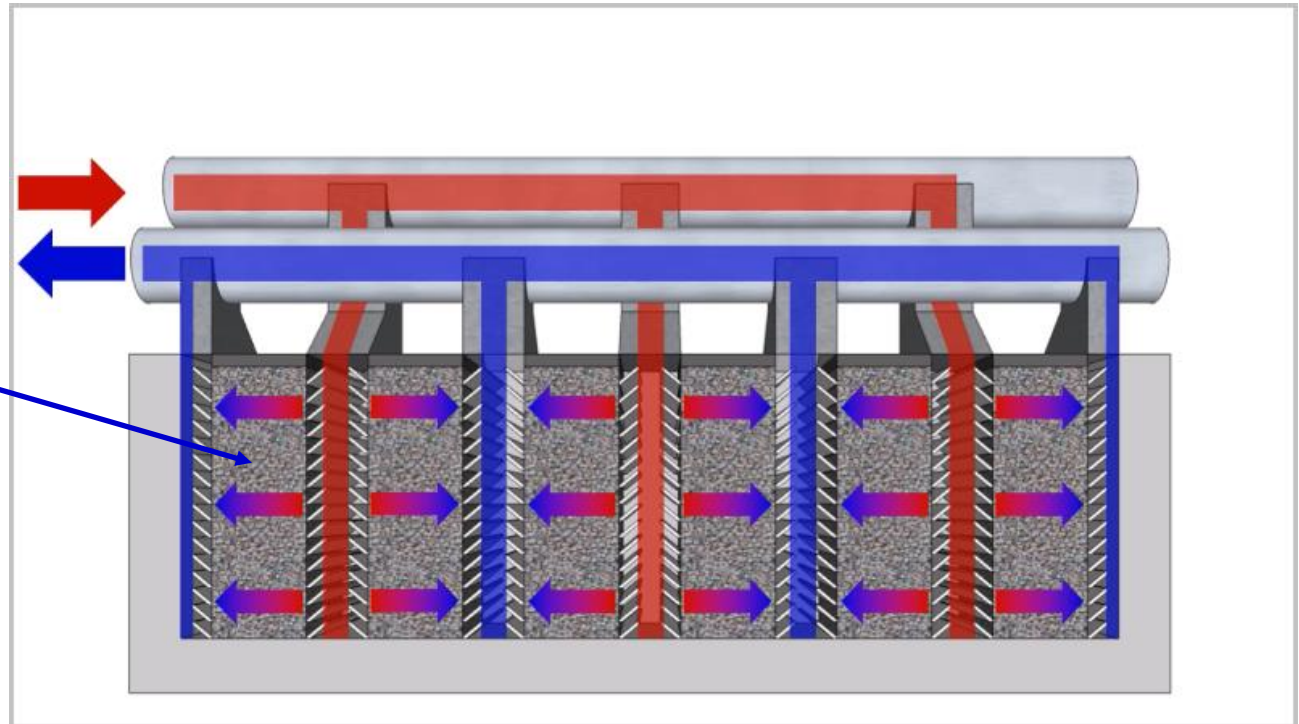


• Brayton Cycle

- Air-standard analysis (preferred)
 - $\dot{W}_c = \dot{m}(h_2 - h_1)$ $\dot{Q}_{in} = \dot{m}(h_3 - h_2)$
 - $\dot{W}_t = \dot{m}(h_3 - h_4)$ $\dot{Q}_{out} = \dot{m}(h_4 - h_1)$

The storage principle is based on several parallel layers containing the storage material (so called „storage material walls“). A horizontal air flow trough these walls is used for charging/discharging.

storage material
e.g. silica sand,
stones, gravel...



Advantages

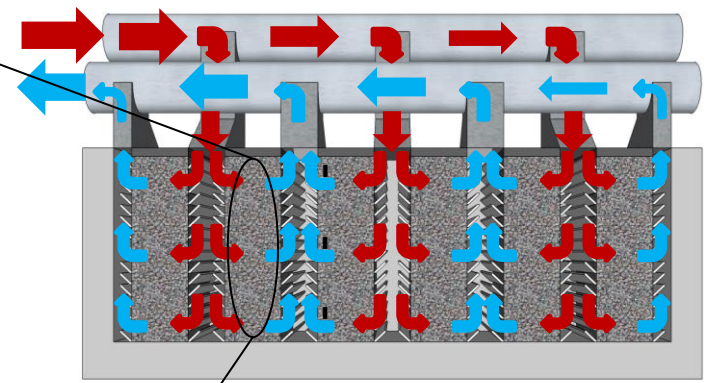
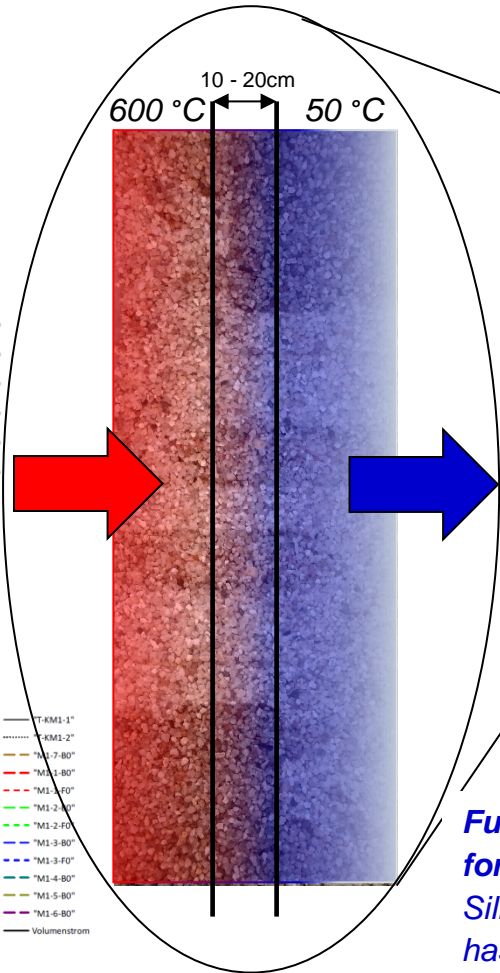
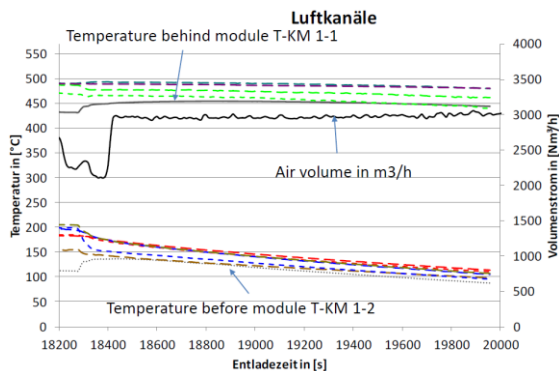
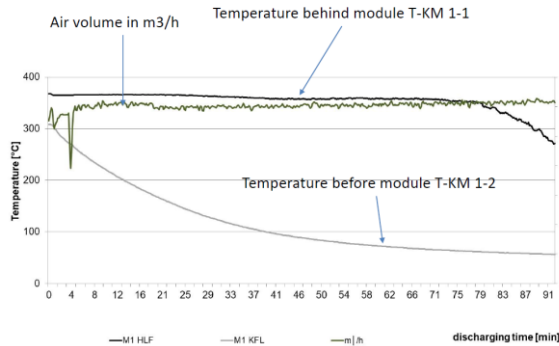
- flexible design of storage modules
- size of storage material walls adjustable
- use of different storage materials
- large charging/discharging capacities
- high local manufacturing portion



The use of fine-grained silica sand (e.g. 1 – 5 mm) allows for a small **THERMOCLINE**, meaning the distance between the hot part and the cold part during charging and discharging is very small (approx. 10 – 20 cm).

Advantage:

The temperature at the outlet remains very stable, see below excerpts of measured data.



Further advantage is the huge surface for heat transfer:
Silica sand with a particle size between 1 and 3 mm has a surface of approx. 2000 m²/m³ !

The main technical parameters for sensible heat energy storage are:

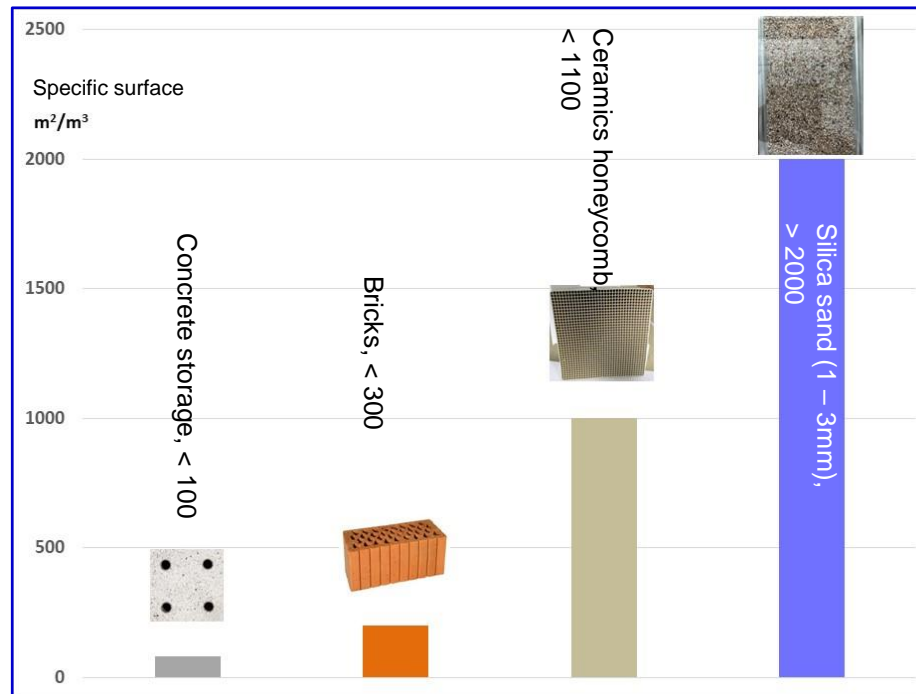
- **surface** for heat transfer between air/flue gas and storage material
- and
- **heat conductivity** of the storage material.

Example of storage material:

Silica sand with a particle size between 1 and 3 mm → large surface (approx. 2000 m²/m³)



To store the **same amount of heat in a fixed bed made from brick stones** or ceramics with fine channels, **12-18 times the volume** of a STORASOL-module is needed in order to create the same surface for heat transfer. The lower **heat conductivity of brick material is not taken into account.** → No large HTTES with perforated brick are existing.



The reason why STORASOL can apply silica sand with very large surface is the arrangement of the storage material → low pressure loss!

A large scale STORASOL-HTTES (> 1,5 MWh) is successful in operation at University of Bayreuth (Project name: ORCTES) since 2015:



The STORASOL-HTTES is undergoing the next steps to achieve very high temperatures (VHTTES) with 1000 °C and more for pressures of up to 1,5 bar_a and a storage module technology for very high temperatures of up to 1050 °C and operating pressure of up to 8 bar_a (P-VHTTES-modules).

2 HTTES-modules, ~1,5 MWh_{th}, 600 °C
Commissioning in year 2015, University Bayreuth



2 VHTTES-modules, 2 x 20 MWh_{th}, 1000 °C

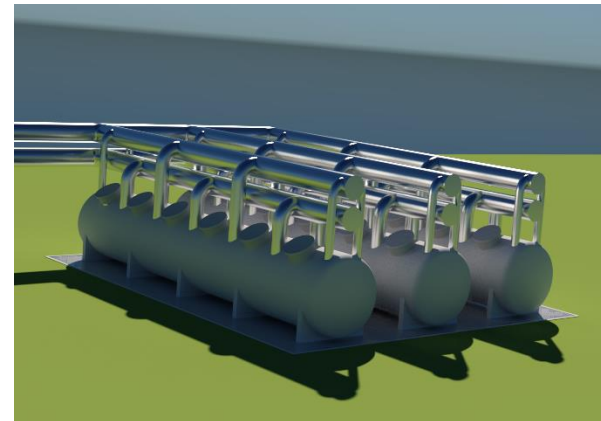


HTTES-test module TESS 3A, ~50 kWh_{th}, 650 °C
Commissioning in year 2020, enolcon laboratory and

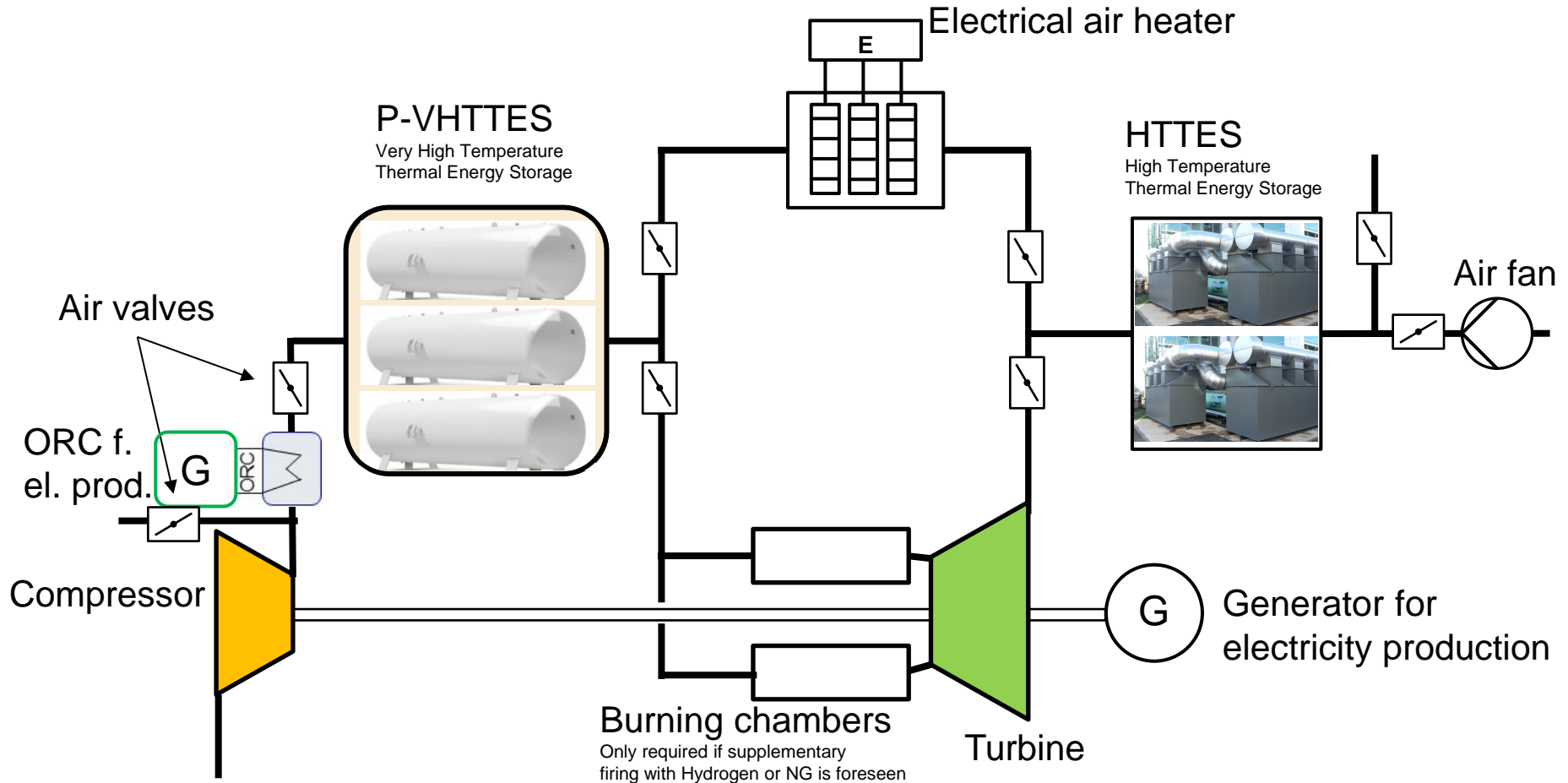
P-VHTTES-test module TESS 3B, ~100 kWh_{th}, 1000 °C
Commissioning in Q4/2022, enolcon laboratory



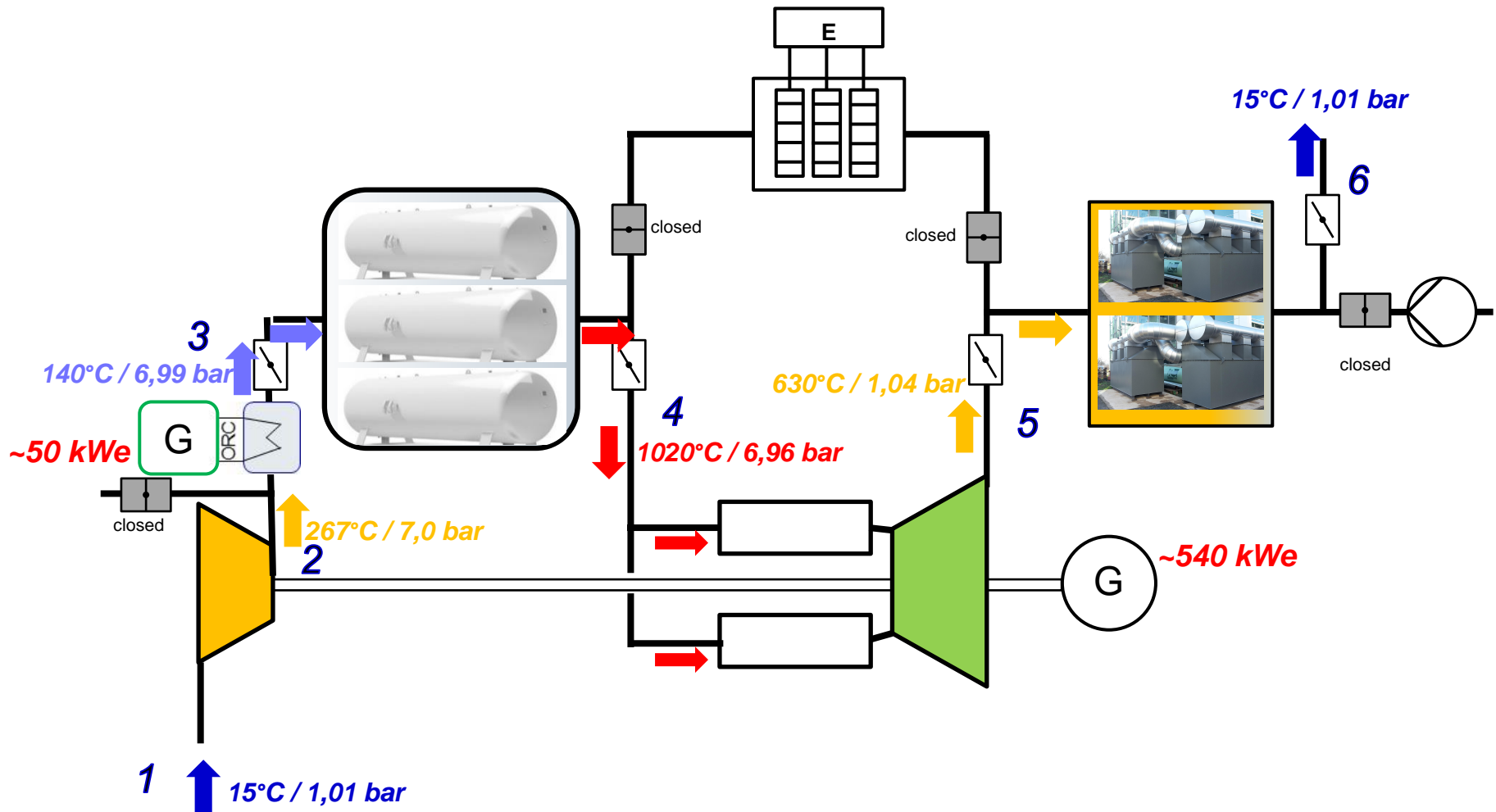
3 P-VHTTES-modules, 3 x 9 MWh_{th}, 1030 °C, ~8 bar_a



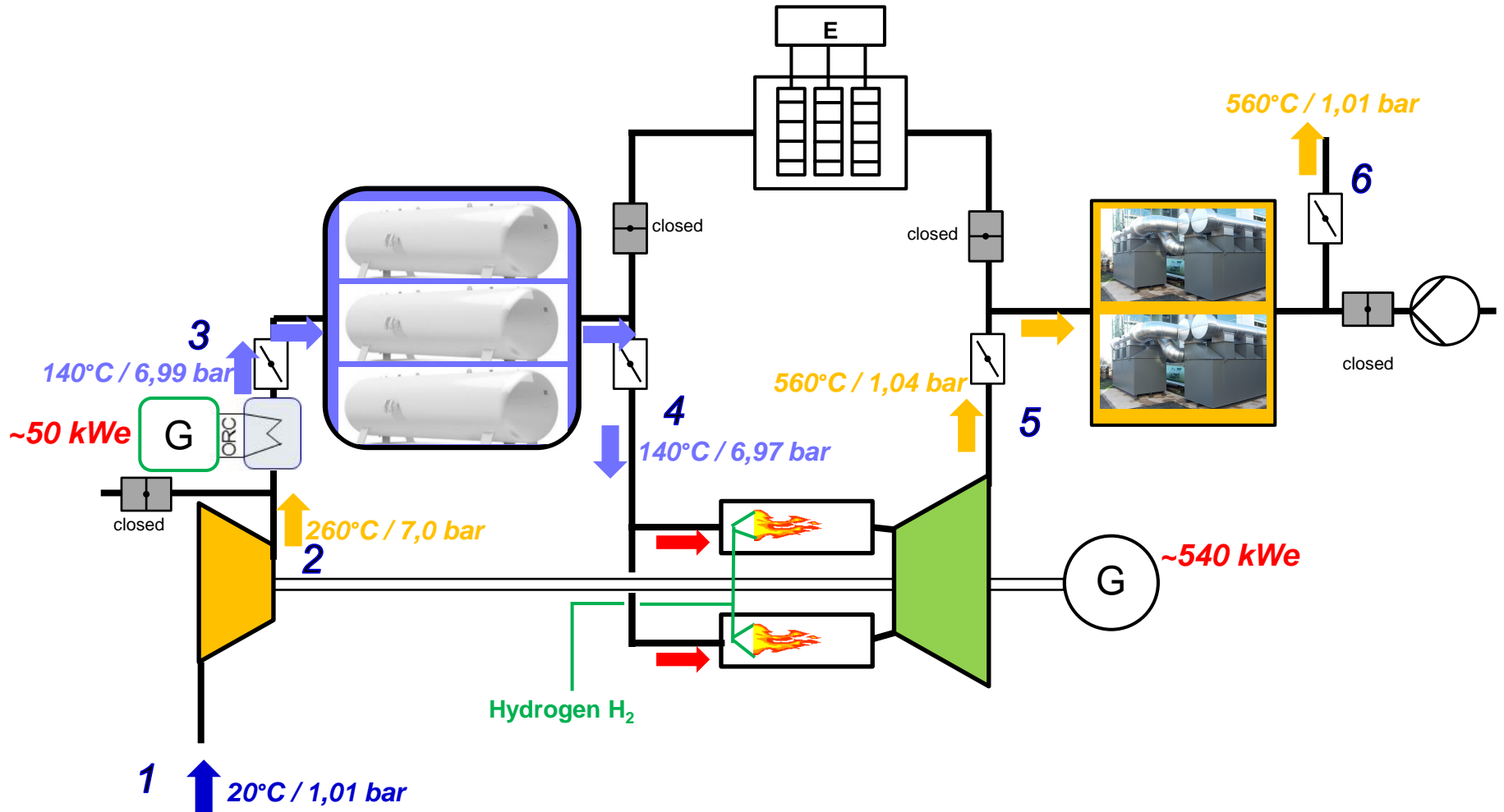
Process of OPTES[®]-GT Battery with real turbine data:



Process of OPTES[®]-GT Battery with real turbine data: **DISCHARGING:**



Process of **OPTES[®]-Open Battery** with real turbine data: **Green Hydrogen operation only** (e.g. in case P-VHTTES is discharged but still electricity required) :

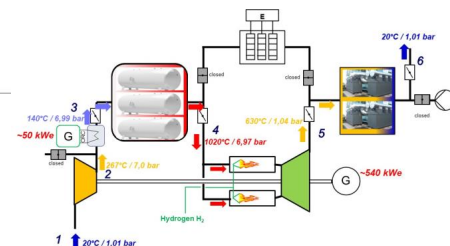
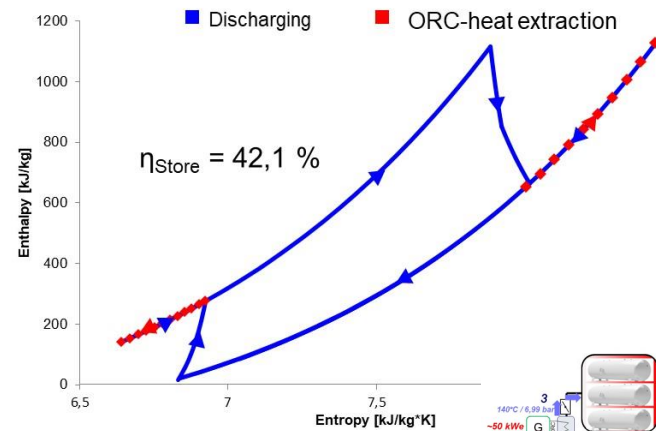
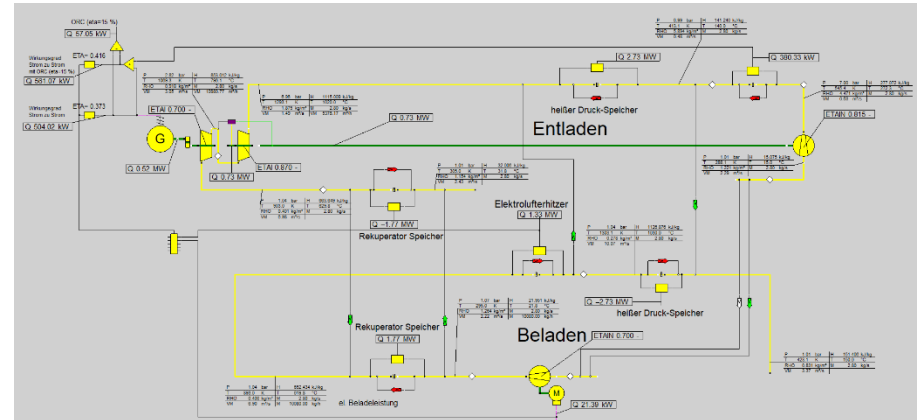


The **OPTES[®]-GT Battery** is an excellent tool for the transition into an energy supply based on renewable energies!

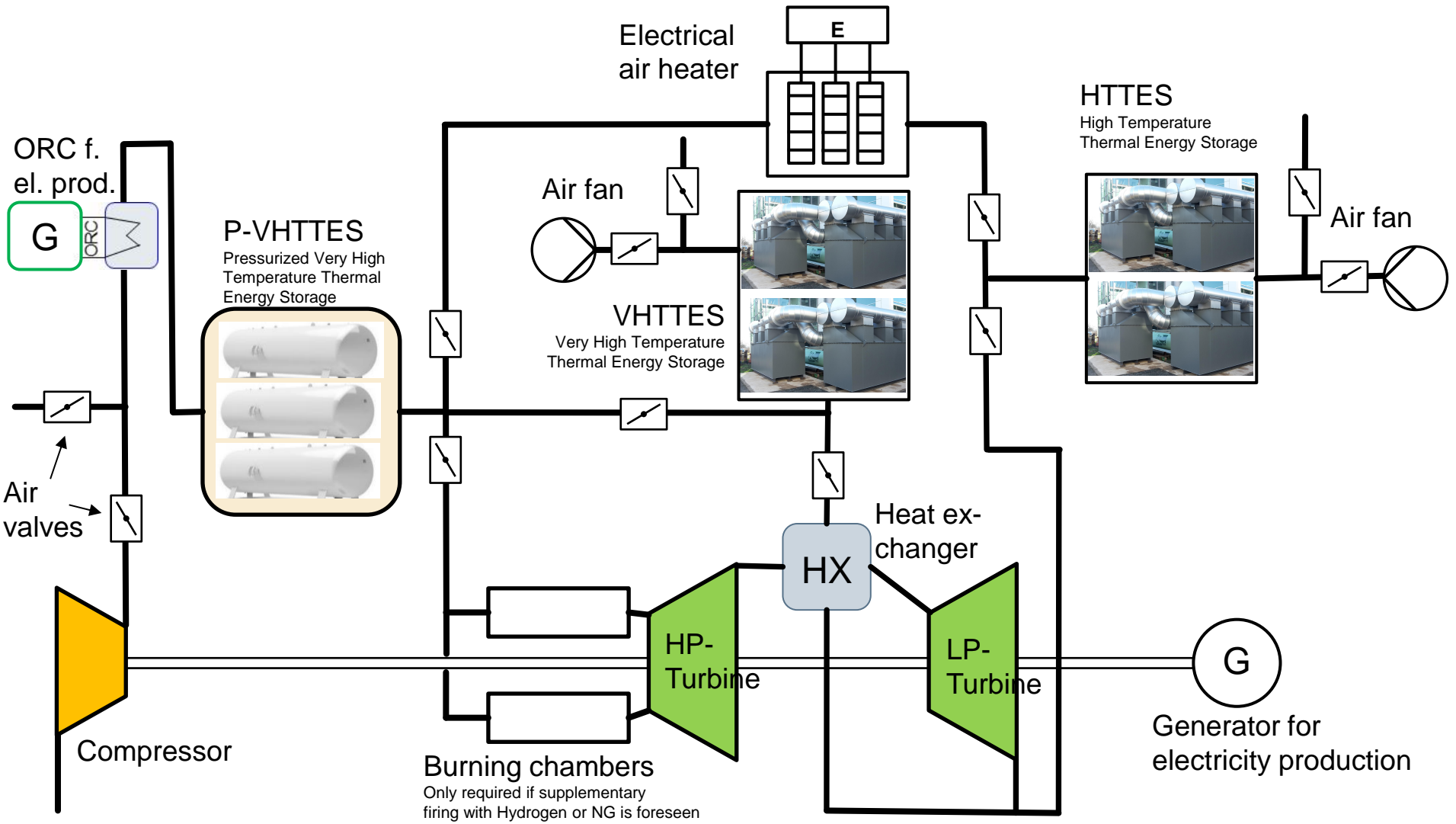
- ✓ Simple technical concept (Compressor+Turbine/Expander, air fan, electrical heater, HTTES-modules, ORC)
- ✓ Thermal storage parts of STORASOL
- ✓ High flexibility (renewable electricity can be used, but also green hydrogen or green methane), fully dispatchable when green hydrogen is available → Base load possible
- ✓ For energy transition period also natural gas could be used as back-up (in case “Dunkelflaute” is lasting too long).
- ✓ Storage capacity and also electrical capacity can be installed as market and space allows.

Technical data of OPTES[®]-GT Battery Model as presented in the slides are based on available gas turbine generator set.

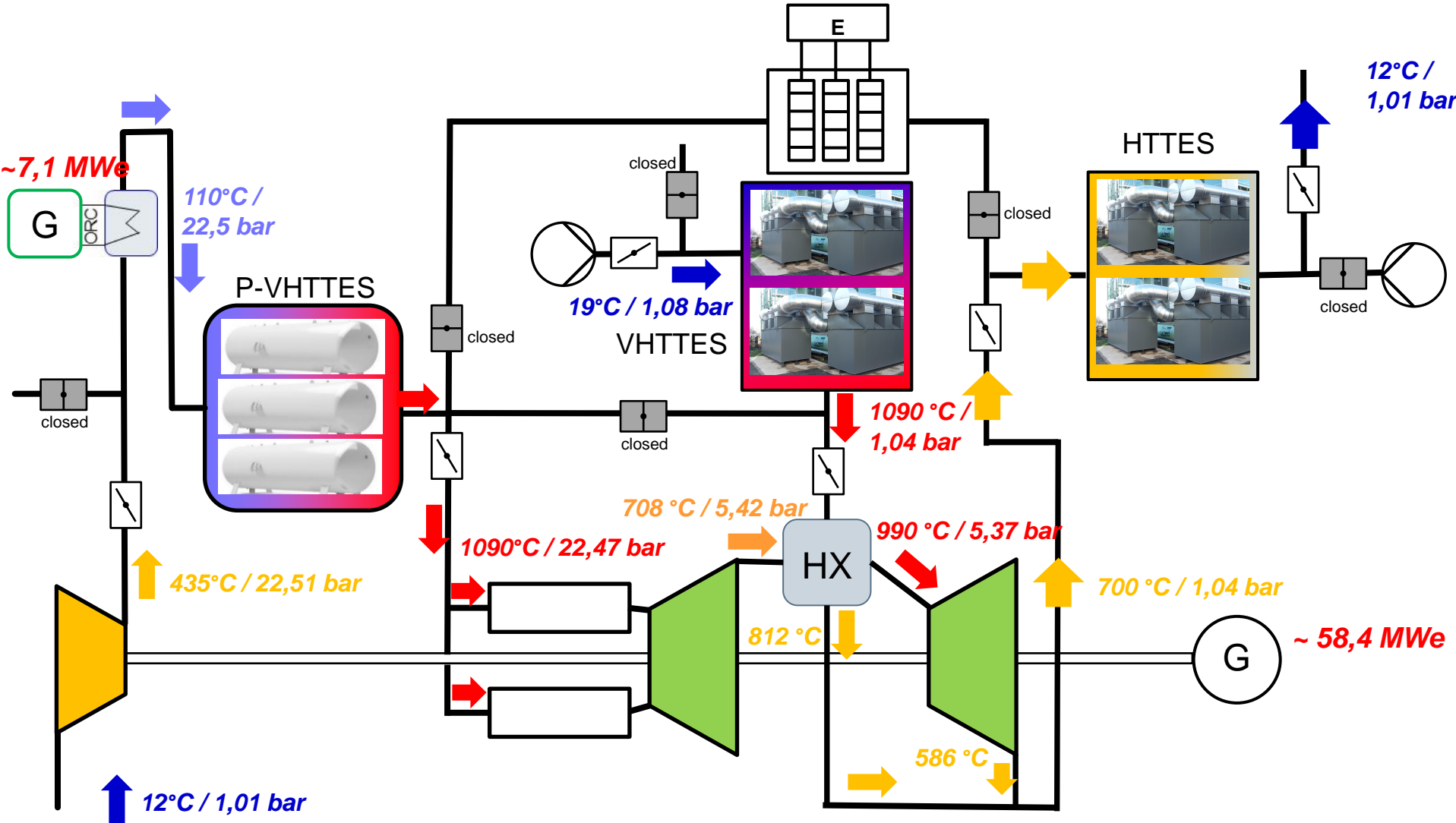
Roundtrip efficiency (el.-heat-el.) is > 40%, already for first generation.



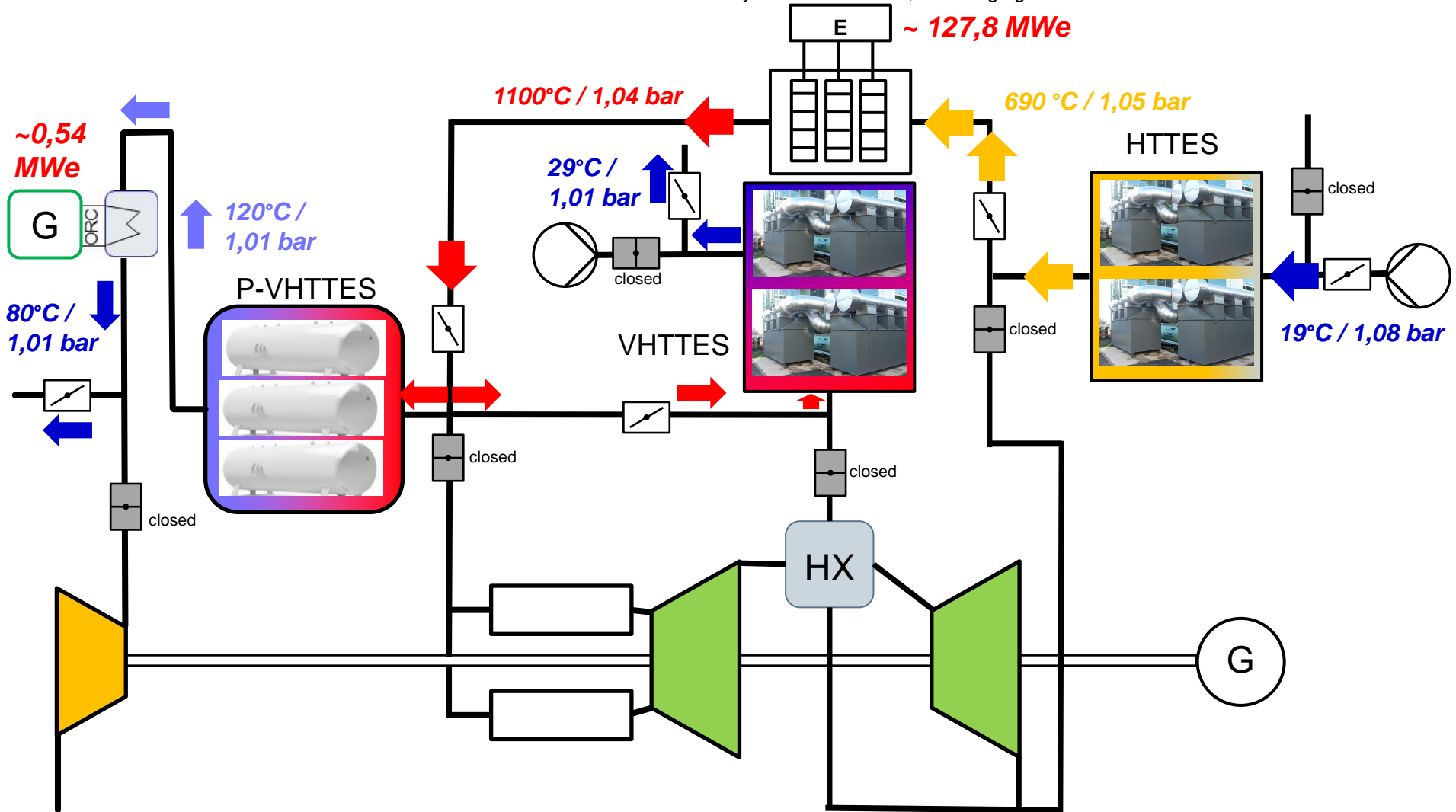
Process of OPTES®-GT Battery Model 2022 with reheater:



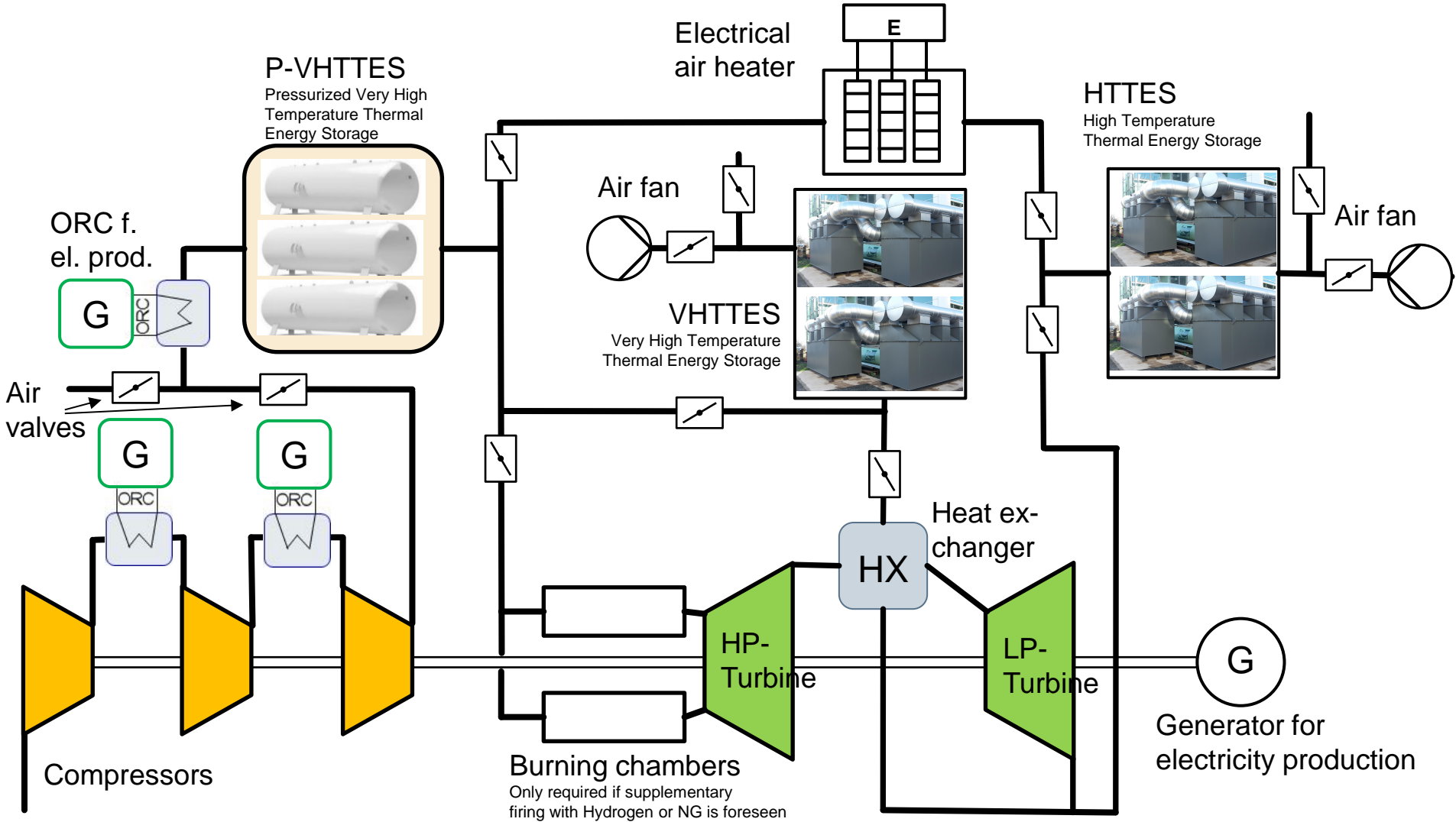
Process of OPTES[®]-GT Battery Model 2022 with reheater, **DISCHARGING:**



Process of OPTES[®]-GT Battery Model 2022 with reheater, **CHARGING:** Electricity from PV or Wind, for charging

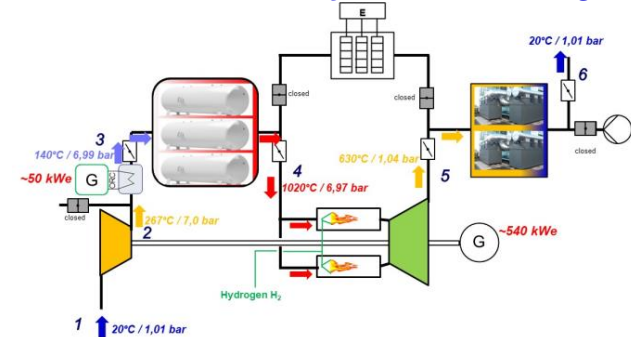


Process of OPTES®-GT Battery Model 2022 with reheater and 3 compressor stages:



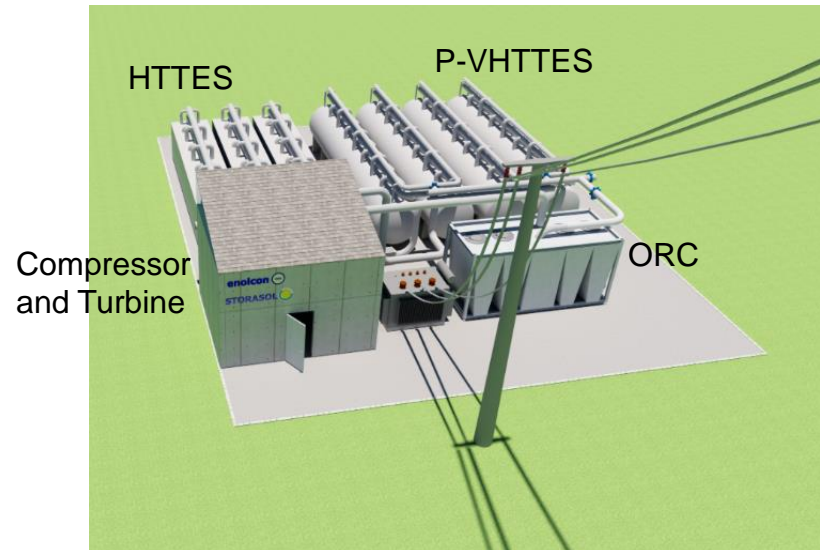
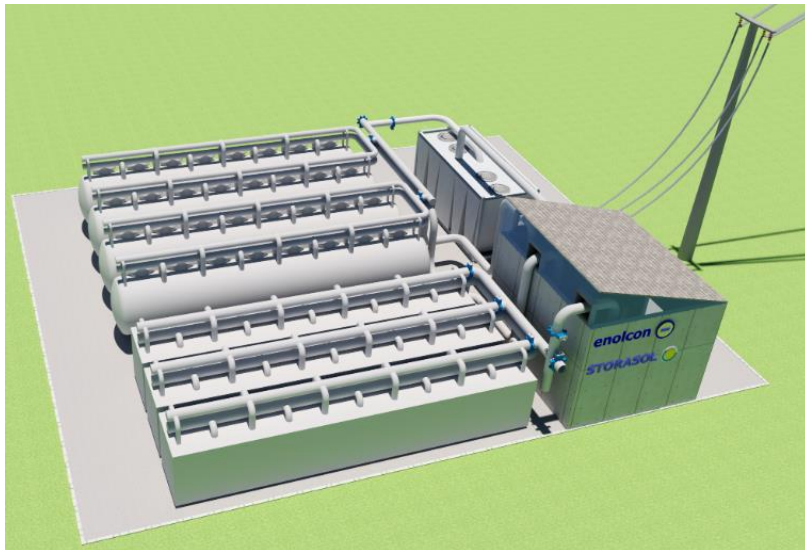
The following CAPEX-estimation on the next slide is based on an **OPTES®-GT Battery** with following data based on actual real turbine data:

- Charging time: 8 hours
- Charging power (electrical, net): 1,33 MWe (in: 10,64 MWh)
- Discharging time: 8 hours
- Discharging power (electrical, net): 0,56 MWe (out: 4,48 MWh)



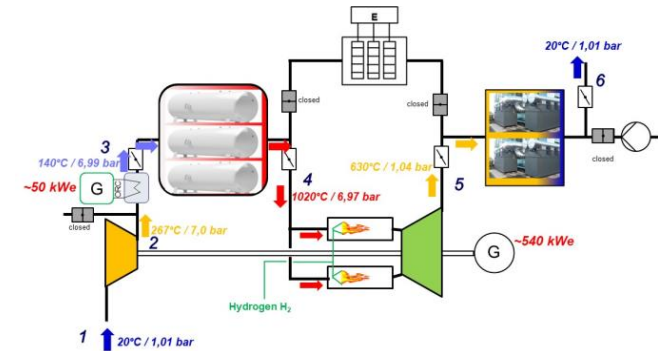
Note: Of course the OPTES-GT-process can also be applied in large scale.

An illustration shows how such small system for 8 hours could look like:



The **OPTES[®]-GT Battery** has a low **CAPEX** because of its simple and robust technical concept. The numbers are based on an amount of building approx. 10 **OPTES[®]-GT** batteries per year. In case of mass production and procurement in low-cost countries the numbers are expected to be even lower.

Storage capacity:	8 hours	12 hours
Air fan, el. fan power approx. 18 - 22 kWe		
Electrical heater for charging (approx. 1350 kWe), incl. electrical panels		
Compressor and Turbine, 560 kWe		
ORC-module (ca. 60-80 kWe)		
Air valves, with drives and electrical and control cabling		
Air ducts		
HTTES-modules, with silica sand as storage material		
P-VHTTES-modules, with silica sand as storage material		
Measurement equipment (pressure, temperature)		
PCS7 – control cabinet		
Concrete plates, small foundation		
Transportation costs of equipment		
Erection and mounting, installation		
Commissioning		
Documentation		
Engineering and Project Management		
Overhead, profit and risk		
Contingencies		
<i>Note: No gas firing included in this CAPEX estimation.</i>	800 - 920 T€	980 - 1.120 T€



Note: The specific CAPEX and OPEX will be reduced when installed capacity is increased (e.g. two gas turbines instead of one gas turbine set, or a larger gas turbine package).

These figures result in low specific electricity storage costs (related to the electrical input between 75 – 87 €/kWh_e for 8 hours and for 12 hours between 61 – 70 €/kWh_e), since the HTTES and the P-VHTTES are using very cheap storage material (silica sand).

OPEX: The OPEX of such fully automated OPTES-GT battery is also very low. Taking into consideration GT-inspections and GT-overhaul and also some maintenance works at the air valves and the fan, the **annual average OPEX** is at approx. **1,5 – 2,5%** of the CAPEX.

The HTTES-technology of enolcon /STORASOL is perfectly suited for an application in a **Thermal battery**. In such Thermal Battery electricity is stored in a way that it is during charging converted to thermal energy and stored in a thermal energy storage system. During discharging the thermal energy is converted back to electricity via a generator. The advantages of Thermal batteries compared to 'classical' batteries (like e.g. Li-Ion-batteries) are the much better economics, especially when applied with large storage capacities (> 4 hours).

A well-known thermodynamic cycle to produce electricity is the **Brayton-cycle**. The open Brayton-cycle is a typical gas turbine process with a compressor + burner + turbine. The **closed Brayton-cycle** has a cooler behind the turbine, and the gaseous working fluid is routed back to the entrance of the compressor.

STORASOL and enolcon already presented the **OPTES[®]**-battery during the IRES 2020 (International Renewable Energy Storage-conference). The **OPTES[®]**-battery is based on a **closed** Brayton-cycle where the hot storage and the cold storage are based on the STORASOL-HTTES-technology. The **OPTES[®]**-battery concept has the highest potential to achieve as realistic case electricity-to-heat-to-electricity **round-trip efficiencies of more than 65%**.

A further concept is the **OPTES[®]-GT**-battery: This concept is based on an **open** Brayton-cycle, whereby the heat behind the turbine is recovered. The **OPTES[®]-GT-battery** is less CAPEX-intensive than the **OPTES[®]**-battery and can also use **green Hydrogen** as back-up fuel or supplementary fuel. However, with regard to thermodynamics the realistic expected roundtrip efficiency is at **around 45% for a simple process and up to 55% in the OPTES-GT process with reheat stages**.