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D2.2 – Energy storage system design schematics

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Abstract	The deliverable reports on the preliminary designs of the thermal storages to be deployed at the demonstration sites	

REVISION HISTORY

Version	Date	Main Authors/Contributors	Description of changes
A	15/04/2022		Initial version
B	23/04/2022		Zorlu's comments
C	09/05/2022		TWI contribution, Naldeo comments
D	18/07/2022		Insheim TES predesign

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[1] Dissemination level security:

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Version: 1

Date: 3 September 2024

Summary

WP2 aims at doing the pre-design of the heat storage demonstrators that will be detailed designed, manufactured, installed and tested in respectively WP6 (Balmatt site at the beginning of the project, Insheim site after) and WP7 (Kizildere 1 site at the beginning of the project, Kizildere 2 site later). WP2 includes several Tasks such as the screening of suitable storage materials and alloys (Task 2.1), the development of design models (Task 2.3), the manufacture and test of the storage modules at a small scale (Task 2.4) and the study of the pre-installation on-site (Task 2.5 and 2.6). Task 2.2 called "Design of thermal energy storage system" is the main task and is detailed in this deliverable D2.2. The objective is to select the best technology for the geothermal sites, to find the best way to install it on-site and determine by the same way the operating conditions and limitations, and to size it in order to achieve specific energy and economic objectives. The three technologies that are envisaged are a pressurised thermocline, a steam accumulator or a Phase Change Material module. The objectives are to implement one demonstrator on the first site (Balmatt and Insheim) and two demonstrators on the second site (Kizildere 1 and Kizildere 2).

This Task has suffered several delays and extra non-scheduled activities, mainly because of the transfer of the demonstration activities to other sites. The pre-design started before the project suspension for the Balmatt and Kizildere 1 sites and ended after the suspension for the Insheim and Kizildere 2 sites.

Objectives Met

The following WP objectives that have been met are:

<u>For Balmatt site (Belgium, owner VITO):</u>

- Implementation of the storage system on the Balmatt site
- Predesign of the pressurised thermocline storage system
- Sensitivity analysis concerning the extension of the District Heating demand and the addition of an ORC
- Interest in the storage system in case of a restart at a lower flowrate and power

These studies were conducted during the first period of the project, until the decision of not restarting the Balmatt site and transferring the activity to the Insheim site in Germany after the project suspension.

<u>For the Kizildere 1 site (Turkey, owner Zorlu):</u>

- Implementation of the heat storage modules on the Kizildere 1 site including some modifications of the site
- Predesign of the steam accumulator
- Strategies to mitigate the effect of CO_2 on the steam accumulator
- Predesign of the PCM module

These studies were conducted during the first period of the project, until the decision of transferring the activity from Kizildere 1 to Kizildere 2 (same owner Zorlu) after the project suspension.

<u>For the Kizildere 2 site (Turkey, owner Zorlu):</u>

- Implementation of the heat storage modules on the Kizildere 2 site including some modifications of the site (new IP separator)
- Predesign of the steam accumulator
- Strategies to mitigate the effect of CO_2 on the steam accumulator
- Predesign of the PCM module with 2 PCM (adipic acid and HITEC salt) with hydraulic inserts
- Predesign of the PCM module (HITEC salt) without hydraulic inserts but the addition of aluminium profiles
- Choice of the PCM module installation on the site, after the HP separator is preferred to after the new IP separator

- Procedures to clean the PCM module and selection of the 5th one (more mature and less expensive)
- Energetic impact of the rinsing step of this cleaning procedure evaluated and mitigated by rinsing with hot water from the steam accumulator

These studies were conducted after the suspension that lasted from June 2020 to February 2021 and were achieved end of January 2022.

<u>For the Insheim site (Germany, owner VNI):</u>

- Objectives for the TES for the new Insheim site configuration connected to the Landau DH network
- Implementation of the storage system on the Insheim site
- Predesign of the pressurized thermocline storage system

These studies were conducted after the suspension that lasted from June 2020 to February 2021 and were achieved end of July 2022.

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1. INTRODUCTION

The objective of Task 2.2 is to select suitable heat storage technologies for each industrial site, and to dimension them according to a specific objective.

Among all the existing technologies, a pressurised thermocline water storage is well adapted to the Balmatt site because the level of temperature is rather low and the storage plugged on clean waterside. The objective is to shave the peak demand of the District Heating network and to decrease the natural gas consumption. The situation is similar for the Insheim site.

For Kizildere I and II, which produce directly steam and electricity, the objective is the flexibility of the electricity production. A steam accumulator is a mature technology that is suitable for steam storage, the latent heat of condensation is stored in the liquid water sensible heat. A more innovative solution is also developed at smaller scale, a phase change material storage module. In this module, the brine sensible heat will be stored in the latent heat of melting of the PCM media. This technology is less mature and will require more research activities that are done also in WP2 (see Task 2.1 and D2.1, Task 2.3 and D2.3, Task 2.4).

2. BALMATT SITE

2.1 Site characteristics

The Geothermal Balmatt (Figure 1) process includes 3 cascaded loops, brine loop, primary water loop or Balmatt substation and secondary water loop or DH network, connected by 2 heat-exchangers (Brine HX and DH HX). It delivers heat to a District Heating (DH) and to an Organic Rankine Cycle (ORC). The DH heat-exchanger is designed for a maximal power of 9.9 MW even if the geothermal field power is lower (6.7 to 7.2 MW).

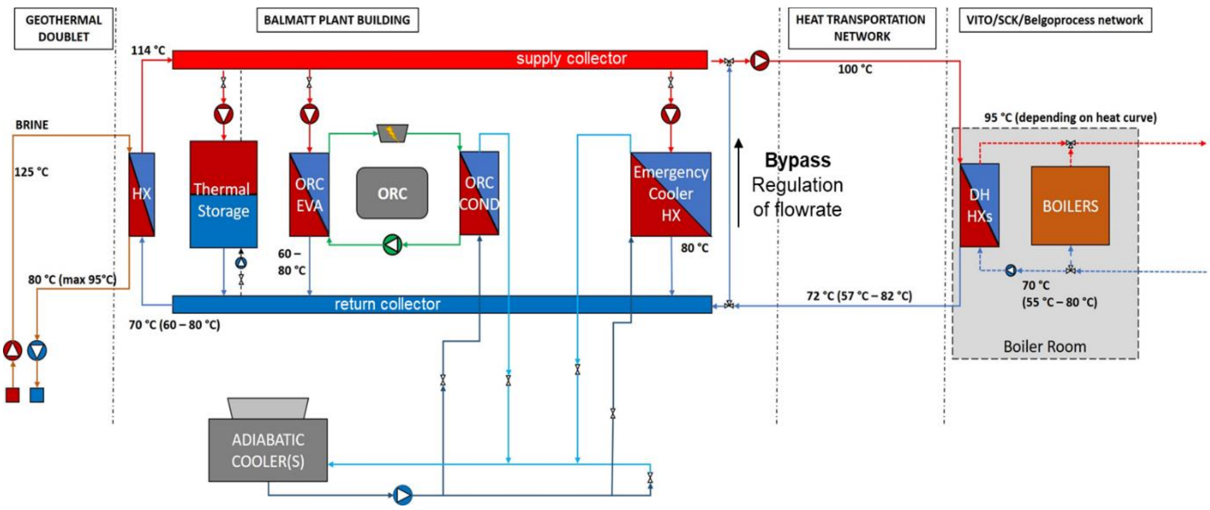


Figure 1. Simplified P&ID of the BALMATT existing system including the thermal energy storage module

The ORC system is plugged on the water Balmatt loop between the supply collector at 114°C and the return collector at 70°C. It includes an organic fluid Rankine Cycle that produces electricity, a water/organic fluid evaporator (ORC EVA) and a glycol water/organic fluid condenser (ORC COND), the glycol water being cooled thanks to an air cooler (ADIABATIC COOLER). Up to now, there is one single ORC unit at Balmatt, with the project to add a second one in the future. The maximum power of 2 ORC units will be 5.8 MW.

The departure toward the DH network is somehow different. The supply temperature is lowered to 100 °C thanks to a mixing valve between the supply collector at 114 °C and the return collector at 72°C. This water is sent in the transportation network on a distance of 2.5 km to the DH heat-exchanger (DH HX) and comes back at a temperature of 72°C. The VITO/SCK/Belgoprocess network delivers heat at 95°C, a natural gas boiler is plugged in parallel to the DH HX to supply the peak demands that are not covered by the geothermal heat.

One of the objectives of the GeoSmart project is to install a thermal energy storage in parallel to the production well (Figure 1) in order to:

- Ensure the District Heating's needs are met with geothermal energy with a minimal use of natural gas.
- Increase the economic gain linked to the production of electricity with the ORC (increase production and sell electricity at highest price).

This deliverable describes the methodology for the sizing and pre-design of the storage module.

2.2 Heat storage module pre-design

A qualitative analysis of the heat demand on Balmatt site allows to understand the interest and limit of a storage system.

VITO provided the variable heat demand of the District heating for 2 full years, 2016 and 2018, with a hourly resolution. For these two reference years, the nominal geothermal power was 6.71 MW, except during a 3 weeks period in summer during which the geothermal plant was shutdown for maintenance. The DH demand is plotted versus time in Figure 2, together with the well production and the DH heat-exchanger maximal power.

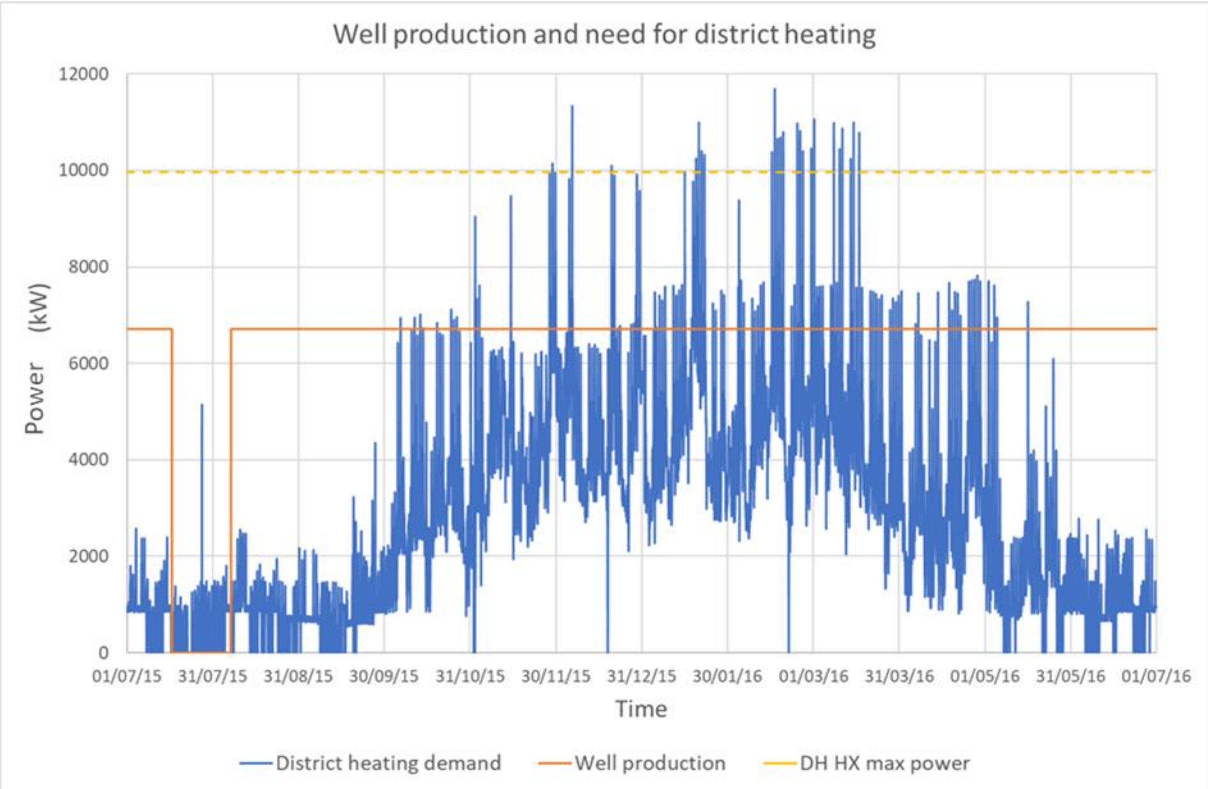


Figure 2. Well production and district heating demand (year 2016)

The well production has a nominal power of 6.71 MW, which represents an annual energy of 55600 MWh. The cumulated DH demand represents an energy of 24200 MWh per year, 44% of the well production.

In wintertime, the district heating demand can be higher than the well production. During this period, the energy for DH not available from the geothermal well is 260 MWh, which represents **1.1%** of the DH demand. We expect that this energy could be supplied by a storage system. However there is another limitation coming from the DH heat exchanger, which has a maximum power of 9.9 MW, the energy demand above this value requires an energy need of 16 MWh that can be supplied only by the natural gas boiler.

In summertime, the well production is stopped for three weeks, which requires an energy need of 252 MWh from natural gas, we can point out that this need has the same order of magnitude as the total DH energy that is not covered by the well during wintertime.

In conclusion, the DH energy demand that is not available from the well and that is covered by natural gas is 512 MWh, which is theoretically the maximal cumulated energy content of the storage system on a whole year. In reality, a part of the demand cannot be covered by a storage because of the DH HX limitation (16 MWh) and the summer demand is not a daily demand and is therefore not adapted to a daily storage (252 MWh). In the end, the storage system could cover in the best case 244 MWh, which is 58% of the total consumption of natural gas.

If we sum the DH demand and the 2 ORC units power (5.8 MW) as depicted in Figure 3, we can see that 2 ORC units are useful in summertime because the DH demand is very low. The well production is even sometimes too high, this lost energy represents 609 MWh that must be removed by the emergency cooler. An alternative is to increase the return collector temperature and to reduce the well power during this summer period. During wintertime, the well production can never cover the DH demand plus 2 ORCs, the priority is given to the District heating.

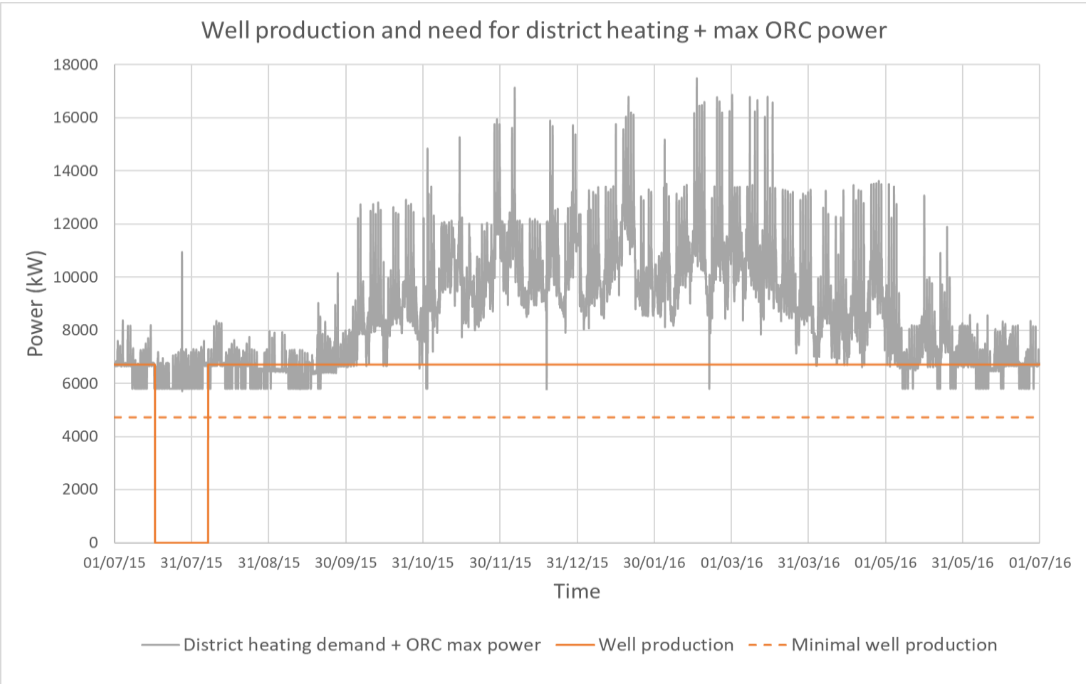


Figure 3. District heating demands + ORC maximum power compared to well power (Year 2016)

From this preliminary analysis, we can conclude that there is a need for a storage module during winter time for the DH needs but that the storage will not allow turning off the natural gas consumption because nearly half of this consumption is done during the summer plant shutdown. This effect can be better visualised in Figure 4, which gives the minimal stored energy that would be necessary along the year to bring the natural gas consumption to zero. Apart from the first huge peak of 250 MWh corresponding to the summer break, the other peaks are all under 35 MWh, and most of them under 15 MWh.

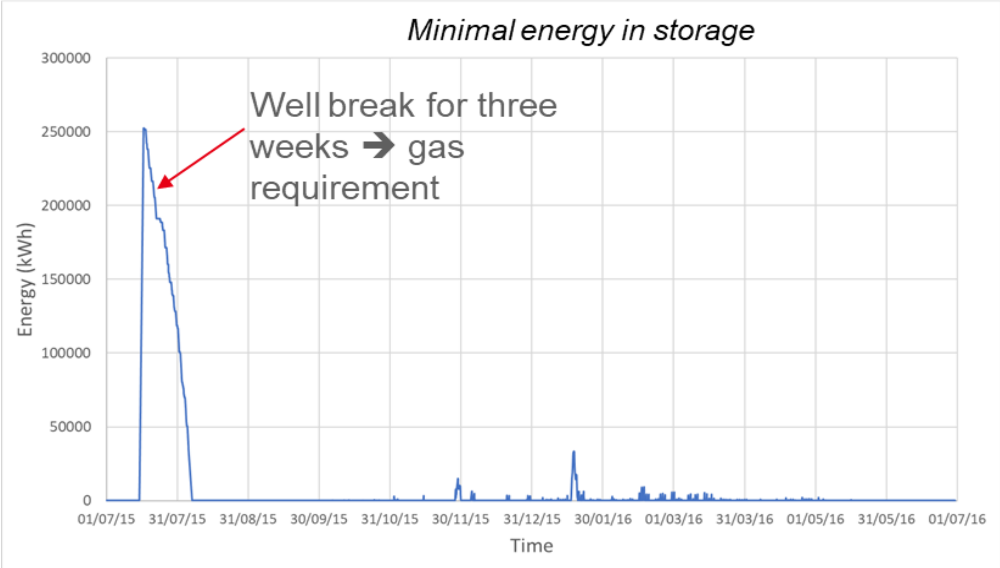
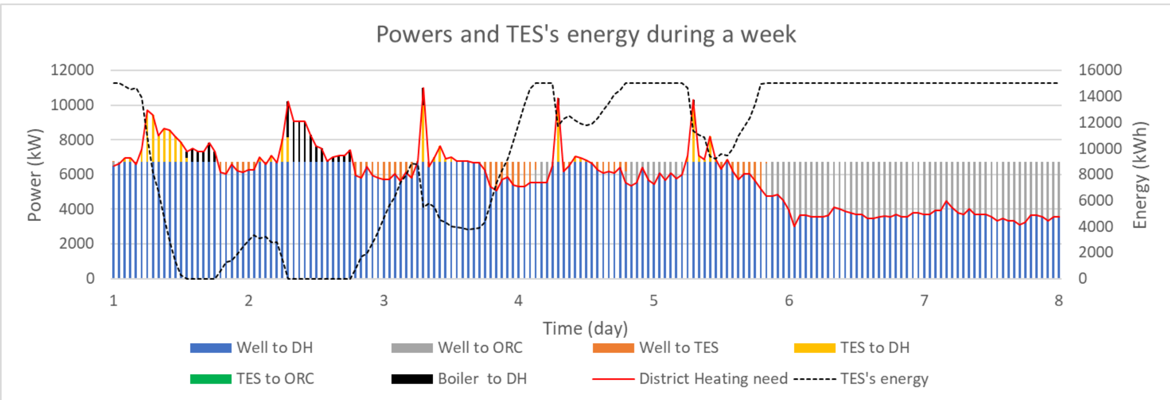


Figure 4. Minimal energy in TES to fulfil DH demand

We need now to have a more precise idea of the storage size by a closer analysis of system, hour by hour. In such a system including 3 main components (DH, ORC and storage), we need to define a regulation strategy that could be implemented on site. Two different strategies were proposed, the first one is very simple but not very performant as will be seen later, the storage is charged when the well power is higher than the DH demand and the ORC is supplied when the storage is full. In the second strategy, the storage charge is similar, but the ORC supply starts as soon as there is enough heat in the storage to ensure the future DH demand.

If we compare the 2 strategies for a same week (18-23 January 2016) and storage capacity (15 MWh), the well supplies the ORC more often and the storage is less full in the strategy 2 (Figure 5):



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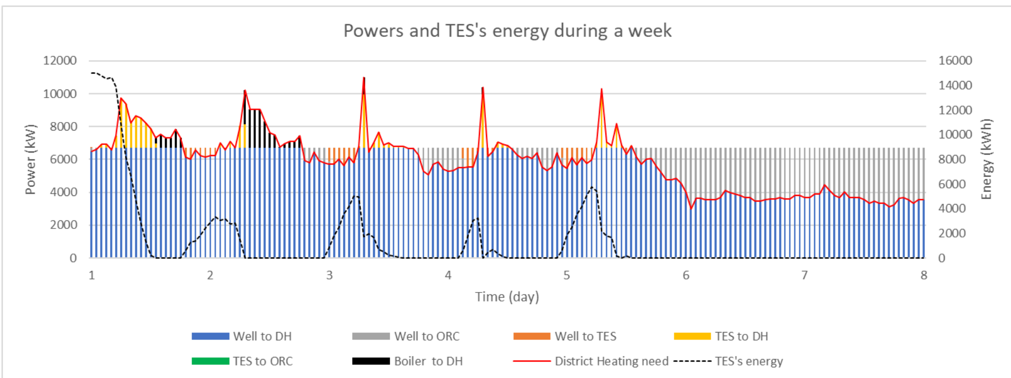

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Figure 5: System behaviour using Strategy 1 (a) or Strategy 2 (b) (18-23/01/2016 and a storage capacity of 15 MWh (about 300 m3))

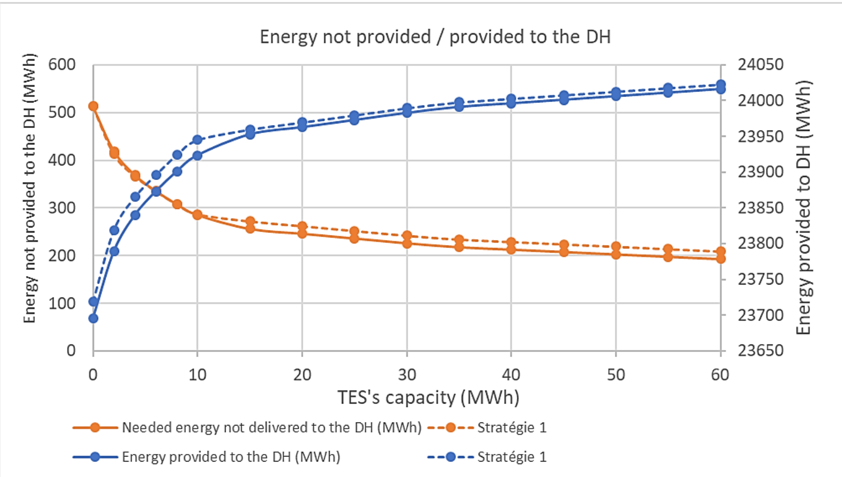
If we compare the 2 strategies for various storage capacities, we can conclude:

- The energy sent to the DH is similar for the 2 strategies (Figure 6a), it increases fast at the beginning then has an asymptotic tendency after 10-15 MWh.
- The energy delivered by the ORC is higher for the strategy 2 (Figure 6b)
- The storage module is often full in Stategy 1 (Figure 6c), and empty in Strategy 2,
- The cumulative number of full charges is higher in Strategy 2, even if it remains low (Figure 6d). This indicator is important because it impacts the Return on Investment (ROI) of the storage module.

As the district heating may be extended in the future, we will study the impact of such extensions on the storage requirement before finding the optimal size of the storage module.

Compared to the existing situation (0MWh added), we can increase the DH Demand by 17% (+ 4000 MWh) or 40% (+10 000 MWh) or add a third ORC.

The DH extension leads to an increase of the natural gas consumption, which not acceptable. A storage system allows to decrease this consumption, the absolute reduction is higher for the larger extension, which means that the storage is more solicited (Figure 7). This tendency is confirmed by the number of equivalent full charges that increase for a given capacity (Figure 8).



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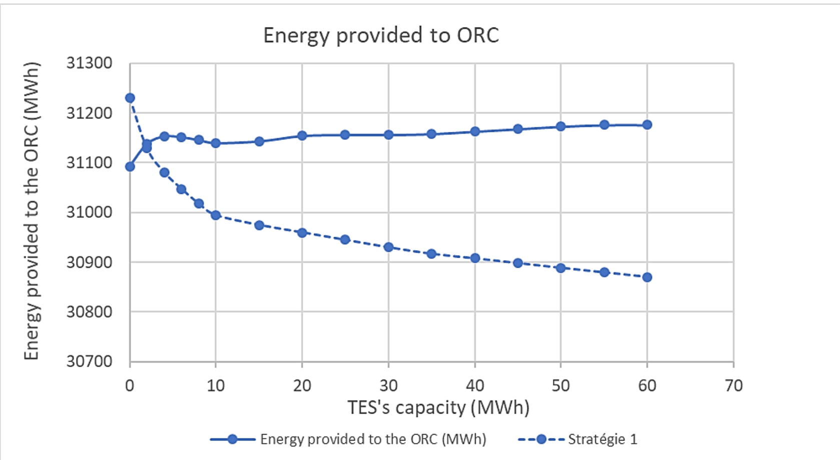

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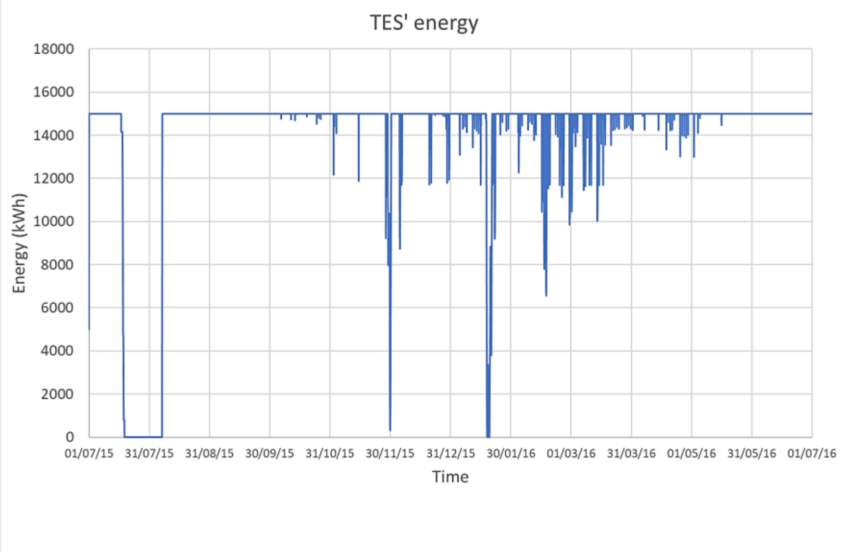

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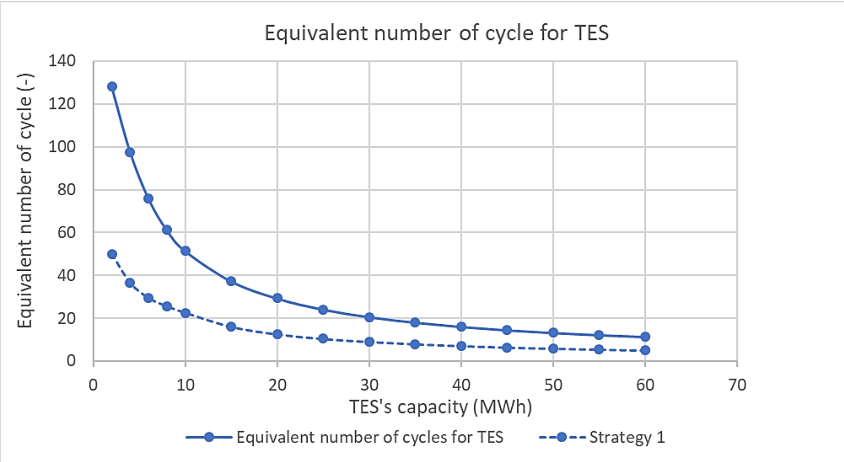


d/

Figure 6. Energy to DH (a), to ORC (b), TES energy (c), Equivalent full charges (d) for various TES capacities and 2 Strategies (1: dot line, 2 full line)

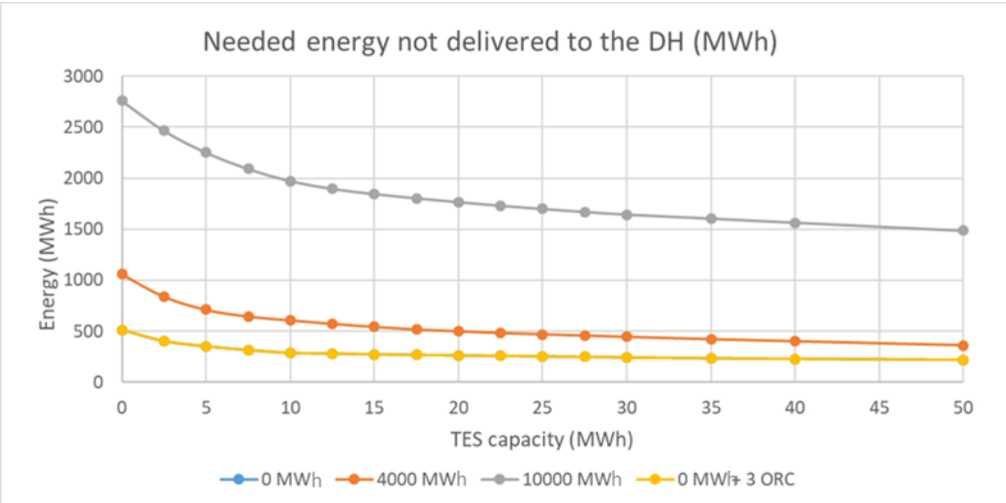


Figure 7. Needed energy not delivered to the DH (strategy 2, Year 2016)

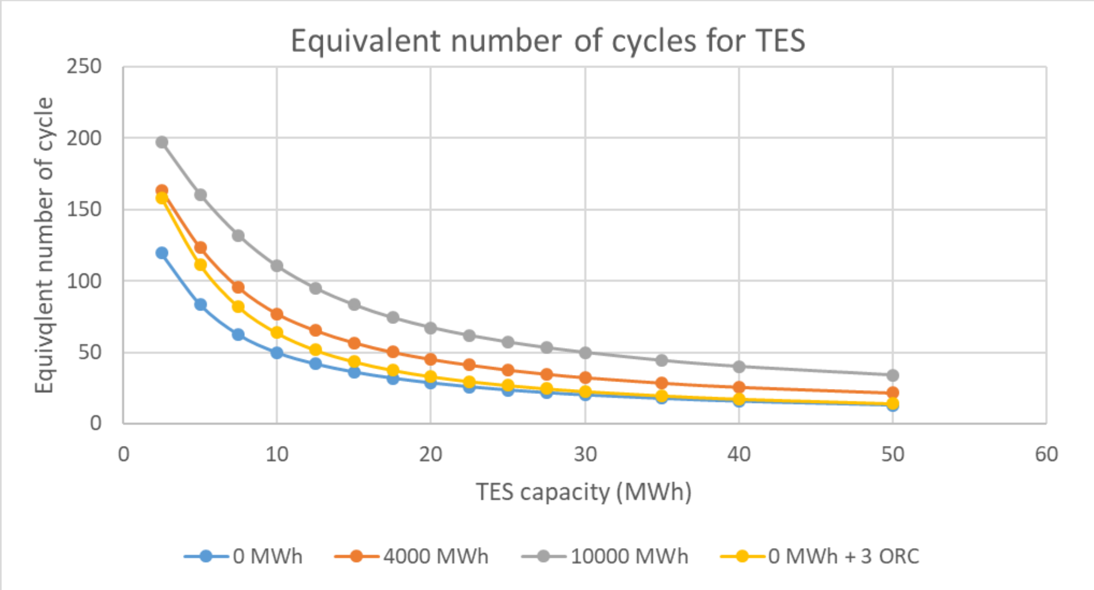


Figure 8. Equivalent number of full-charge cycles (strategy 2, year 2016)

The ORC production is directly impacted by the DH demand extension, and there is no increase of production with the addition of a third ORC, which is clearly useless (Figure 9).

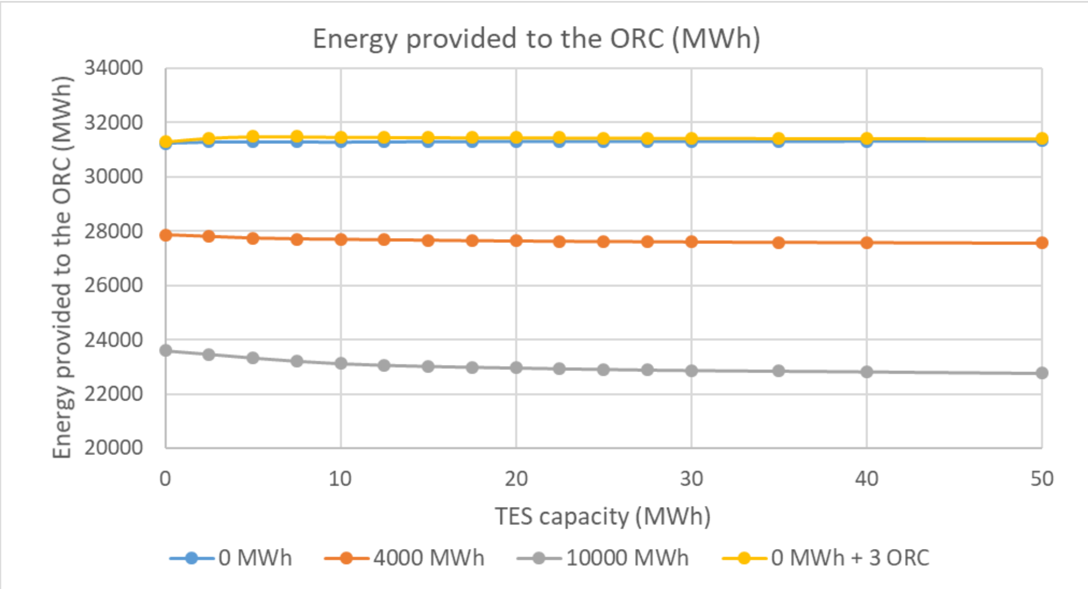


Figure 9. Energy provided to the ORC (strategy 2, year 2016)

Bertin Technologies has performed the same analysis, from an economic point of view and comes to the same conclusions. Increased demand from the heating network makes it possible to increase the rate of use of the storage and therefore its profitability. It also increases the boiler demand. Figure 10 shows economies made thanks to storage and the additional cost associated with boiler back-up according to the evolution of the need.

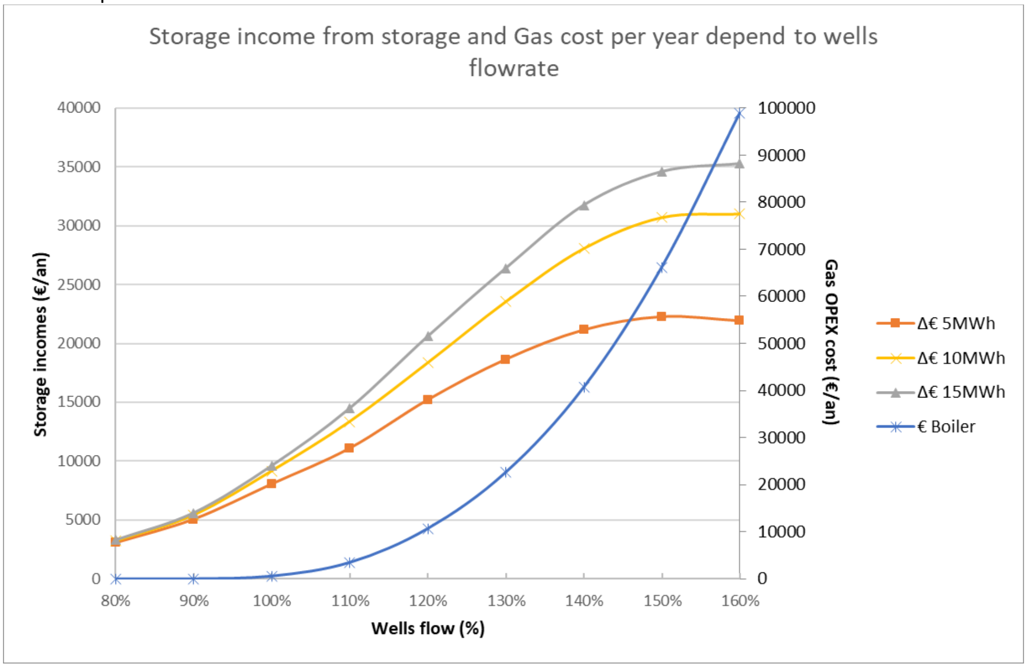


Figure 10. Impact of storage on savings made according to its capacity and the changing needs of the heating network

Bertin Technologies has combined these analyses with storage costs (based on the state of the art) to define the optimal size of storage under Balmatt conditions (Figure 11):

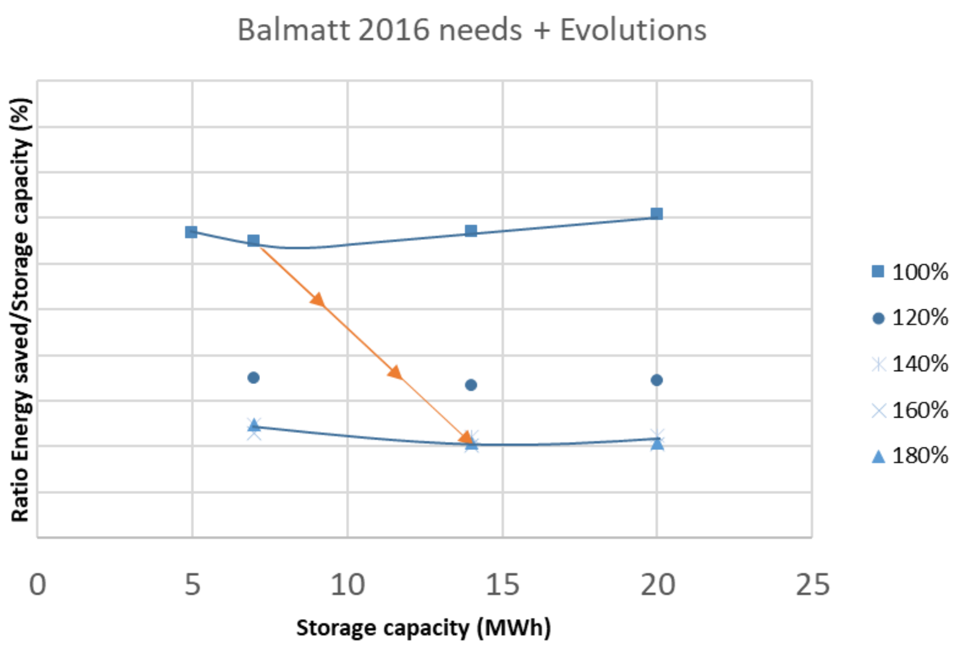


Figure 11. Storage efficiency analysis

Figure shows that to date the optimal size is **6.8 MWh** for the existing District Heating**.** If DH needs increase by 40%, the optimal capacity can reach 13 MWh.

2.3 Storage module design

Once the energy and the power requirements are known for the Thermal Energy Storage (TES) of the Balmatt site, the next step is to define the design of the tank to respect these needs. The design will depend on regulatory constraints, space constraints, and costs. For a given tank geometry, the effective storage capacity depends on:

- The constraints of the thermohydraulic system: what temperature from the storage is acceptable for the system during charging and discharging?
- The flow in the tank: there is indeed the formation of a thermocline zone which reduces the capacity of storage due to the system constraint temperatures.

VITO has defined strict acceptable temperature constraints, similar to those already applied for the other components of the system. CEA developed a thermocline storage model (Figure 12) to study the impact of these temperature constraints on the effective rate of use of the storage in nominal conditions. This 1D model (Dymola) will also be included in a whole system model (Dymola) in order to study the system during a long period (from a week to a season for example). This allows also to study the impact of partial charges and partial discharges on the effective rate of use in real conditions and to test several strategies to optimise it.

A key point for the flow in the tank, and in particular the thickness of the thermocline zone, is the mixing zone around each distributor (top and bottom). CEA has started a CFD study (ANSYS/Fluent) of the distributors and the tank in order to define the best geometry for the distributors and to define the associated mixing zones. A radial circular diffusor was chosen.

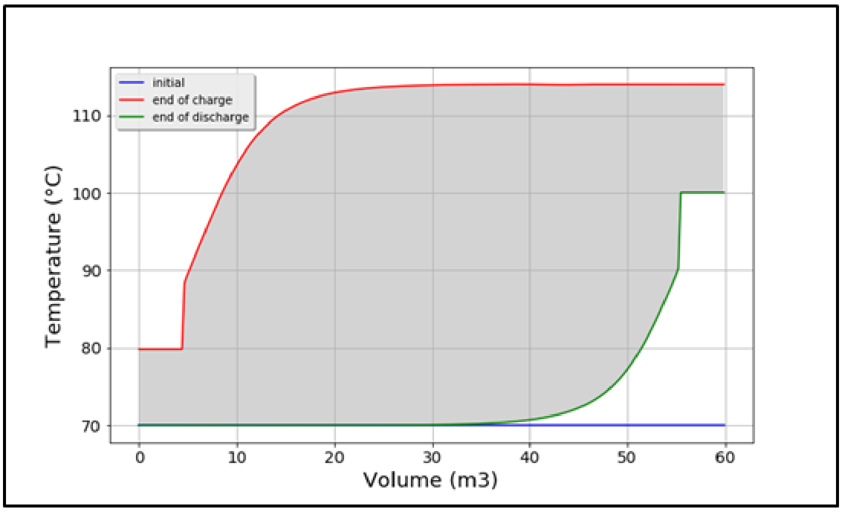


Figure 12. Example of effective use rate (80%) of one tank in nominal conditions with the temperature constraints defined by VITO and mixing zone of 4.4 m³ around top and bottom diffusor (diameter : 3.6m , volume 58 m3) (CEA 1D-modelling tool).

Concerning the location on Balmatt plant, two options are considered (Figure 13):

- In the existing building (Zone 1);
- Outdoor on a new concrete floor specifically created (Zone 2).

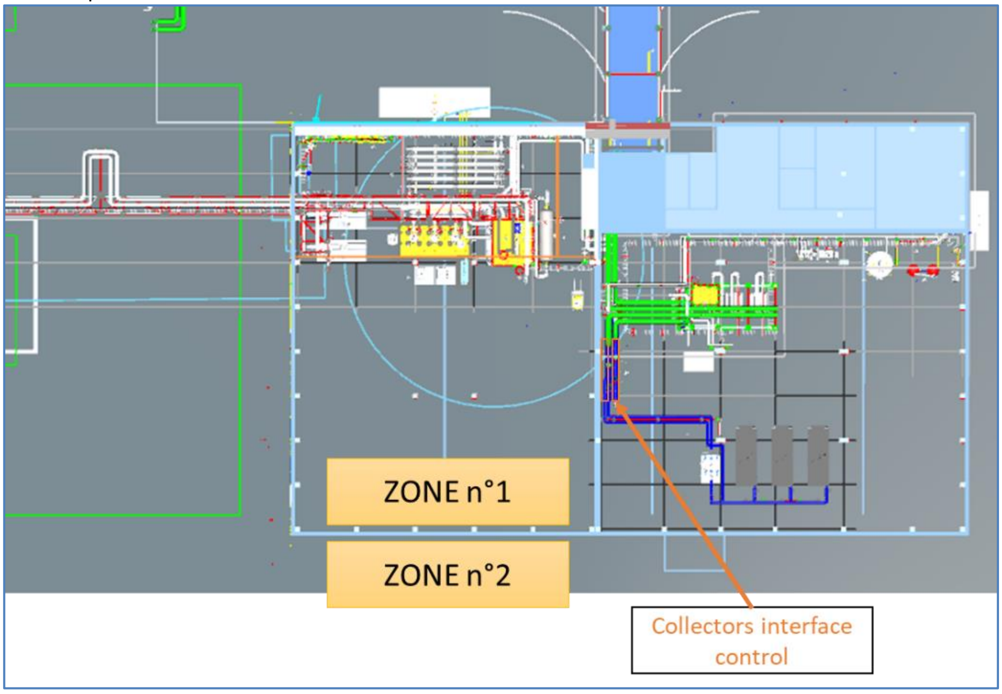


Figure 13. Storages area layout in Balmatt plant

To assess the surface area required, Bertin Technologies therefore pre-sized the storage thanks to the operating conditions of the power plant. The main input data are listed below (Table 1)**:**

Table 1. Thermocline thermohydraulic design conditions

Criteria	Level
Total capacity (MWh)	6.8 MWh
Charging temperature (°C)	114 °C
Return temperature (°C)	70 °C
Design temperature (°C)	150 °C
Design pressure (°C)	10 barg
Fluid	Water

Table 2 details the defined constraints necessary to limit the study:

Table 2. Thermocline Geometric design constraints

Criteria	Level
Maximal diameter (mm)	3 600
Maximal height (mm)	24 000
Maximal storage speed (mm/s)	2
Maximal collector speed (m/s)	2
Type of storage end	elliptical
Material	P265 GH
Corrosion thickness (mm)	2
Type of Support	Skirt
Maximal building height (m)	10
Maximal storage Height (m)	8
Design storage time (h)	3

Figure 14 visualises the design for a thermocline storage tank. Layout constraints may require several modular tanks in parallel to ensure sufficient capacity.

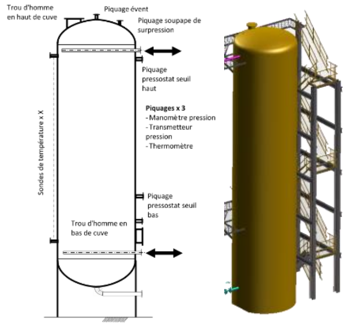


Figure 14. 3D design storage example for Balmatt plant

With all of these data, Bertin Technologies has calculated the useful volume and sized different compatible configurations for installation inside the building or outside the building (Table 3).

Table 3. Tanks number and size for outside or inside the building

	Outside of the building (Zone no.2)			Inside the building (Zone no.1)		
Case no.	1	2	3	4	5	6
Tank diameter (mm)	2 000	2 600	3 600	2 000	2 600	3 600
Height (mm)	11 700	16 600	10 000	8 000	8 000	8 000
L/D	5,9	6,4	2,8	4,0	3,1	2,2
Number of tanks	5	2	2	8	5	3
Total steel weight (kg)	30 000	24 600	29 400	36 000	33 000	31 800
Storage flowrate (mm/s)	0,8	1,2	0,6	0,5	0,5	0,4

Vito decided in the end to install the modules inside the building (zone 2). Case n°6 is in that case is more interesting because the cost of modules is directly related to its weight.

Bertin Technologies has also analysed the influence of the final position of the storage on the distribution system (Figure)

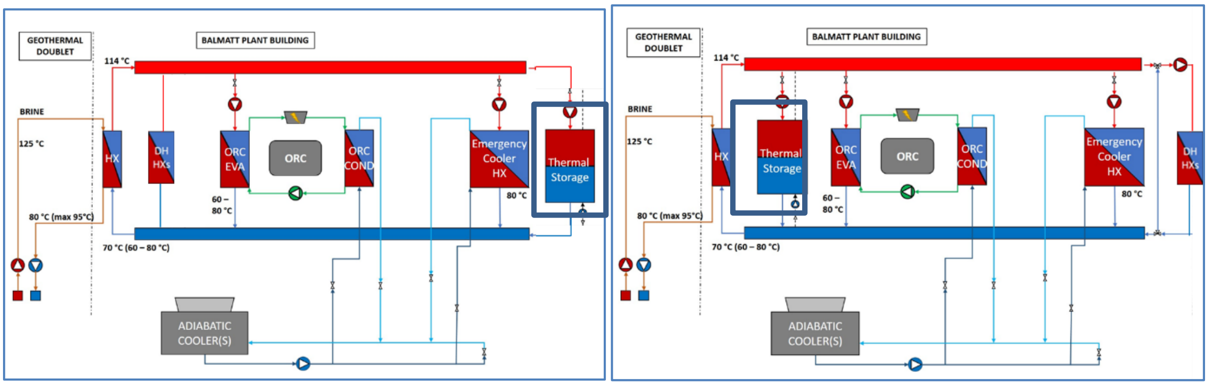


Figure 15. Schemes of two different position for the thermal energy storage (at the end (left) or at the beginning (right) of the hot collector)

The position is important during discharge phases and must be in accordance with consumers' need (temperature). Thermal energy storage at the beginning of the hot collector (Figure 15, right) induces cold flows during discharge. The network (district heating) needs 100°C, there is no problem of temperature. But the ORC will absorb a mixture of flow at 114°C (brine HEX) and flow at lower temperature (from thermal energy storage discharge). There is an impact on the ORC efficiency. Therefore, it should be better to install the TES at the end of the hot collector (Figure 15, left). However, all equipment (except the storage) is already installed on the Balmatt site. The only free position is at the beginning of the hot distribution collector. Despite a slight reduction in ORC performance at the end of discharge, Vito decided to keep this position for storage.

2.4 Balmatt plant re-start at low flowrate / power

Before the final shutdown following detection of earthquakes during operation of the power plant, it was foreseen to re-start the Balmatt geothermal power plant at partial charge for a certain period. Bertin Technologies has therefore studied the impact of this partial load on storage in order to guarantee optimised operation of the solution. Different load rates were analysed between 14% and 100% of the nominal, retaining the same design as before (ORC 5.8 MW; Storage "Heat network + ORC" 7MWh; Boilers 2x 6MW).

To better visualise the influence of the reduction in the flowrate of the well, Bertin Technologies has made a financial analysis to see the operating costs (Figure 16).

Three main hypotheses are considered:

- Boiler efficiency 90%
- Average gas price 28.5 € / MWh
- Average price of electricity 96.7 € / MWh

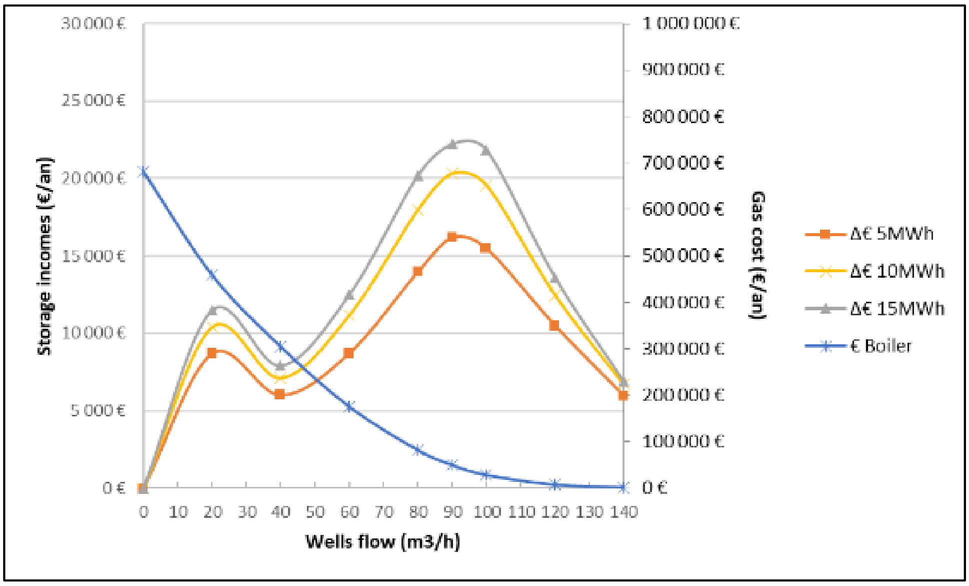


Figure 16. Balmatt plant main OPEX analysis results

This analysis concludes that:

- Boiler gas OPEX will be very high with a small well flowrate;
- Decreasing well flowrate will not have a negative economic effect on the storage. Indeed there is an optimum close to a well flow of 100 m3/h (nominal 140 m3/h).
- The return on investment of the storage is dependent on the well load evolution.

2.5 Conclusion

At the end of the first period, the storage system was designed on the basis of technical and economic optimisation. Its size was smaller than pre-calculated by VITO because the optimum does not correspond to the complete suppression of natural gas consumption. The system was formed by 3 pressurised water thermocline modules operating between 70 and 104°C for a total stored energy of 6.8 MWh corresponding to 135 m^3. Each reservoir had a total height of 8 m and a diameter of 3.6 m. The volumes were installed inside the Balmatt process building and connected after the brine heat exchanger. The remaining actions that were not achieved because of the shutdown of the plant were:

- The regulation modes of the modules (3 reservoirs, possible in series, in parallel),
- The exact geometry of the water diffusors at the top and bottom of each tank,
- The instrumentation of the system.

The detailed design (WP6) had not started.

3. KIZILDERE 1 SITE

3.1 Site characteristics

Kizildere 1 geothermal plant uses directly the brine energy to produce electricity. The brine emerging from 5 production wells is sent to a single separator, and the steam exiting the separator is turbined in a single stage turbine. The brine is sent to Kizildere 2 site. For this site, the main objective is thus to store the steam in order to optimise the electricity income and also compensate the peak loads in the electricity distribution grid. Zorlu wishes also to store the heat from the brine in a second TES module.

PVald has developed an EES tool representing the entire site from the wells to the turbine and making it possible to determine the operating points of the system. Figure 17 shows an example of the system without storage.

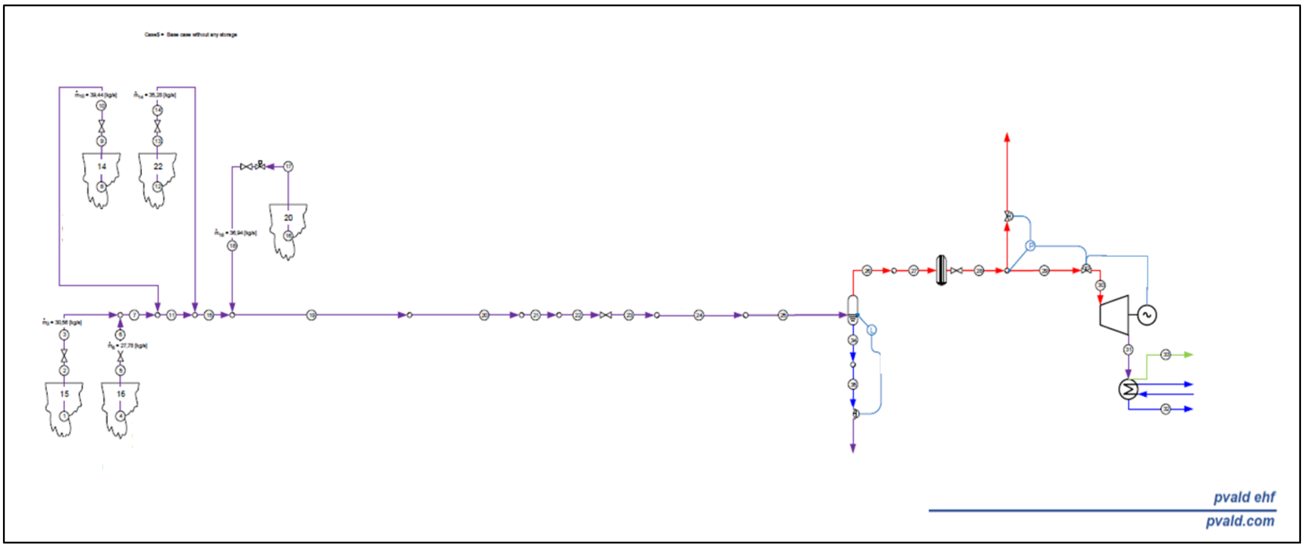


Figure 17. Example of system represented by the tool developed by PVald. On the left, five wells, one separator in the middle and one turbine on the right.

3.2 Steam accumulator predesign

The easiest and more mature technology for steam storage is up to now a steam accumulator. Figure 18 shows the configuration initially planned in the specifications. The storage of a capacity of 5MWh positioned after the separator should make it possible to stabilise the operation of the turbine and to restore this energy when the price of electricity is more favourable and grid has the highest peak loads simultaneously. With the characteristics of the brine from the wells, the pressure at the separator is approximately 4 barg. The operating pressure of the turbine is 3.2 barg. This small pressure gap (less than 1 bar) is not favourable for storing energy. Even if the presence of non-condensable gases is not taken into consideration, we need to supply 6 tanks of 23 m long and 4.5m diameter to successfully store the 5 MWh target, which is not realistic from an economic point of view.

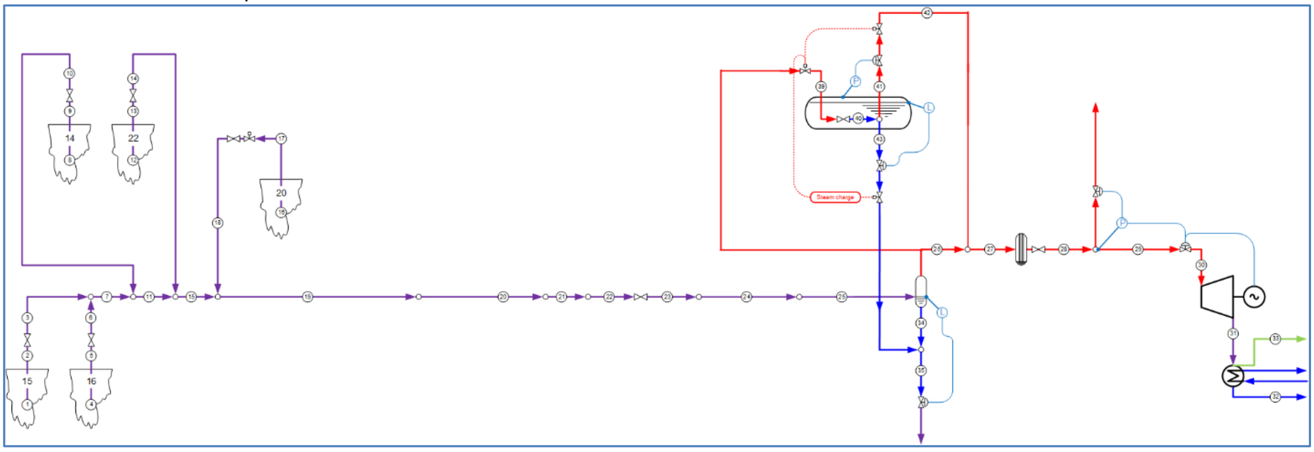


Figure 18. Initial steam accumulator position

In order to solve this very low difference of pressure that is detrimental for the steam accumulator design, the consortium has investigated KZD I to find the well with the highest pressure. Table 4 gives the wells characteristics, well n°20 has the highest pressure of 6.9 barg.

Table 4. Kizildere 1 wells characteristics

Well n°	Drilling date	Deep (m)	Elevation [m]	Temperature [oC]	Enthalpy [kj/kg]	Well head pressure (barg)	Well head temperature [oC]	Steam Flow (t/h)	Total flow (t/h)
KD-14	29.12.1970	597	197.02	186	789	4.9	151	23.4	142
KD-15	31.05.1971	510	211.05	187	794	4.4	147	18.3	110
KD-16	9.06.1973	666.5	199.05	188	798	4.8	150	16.9	100
KD-20	27.01.1986	810	194.6	193	820	6.9	164	22.6	127
KD-22	27.07.1985	887.5	193.35	189	802	6.1	159	22.7	133

The consortium has proposed a modification of Kizildere 1 site, with the addition of a new separator at the outlet of well n°20 and the steam accumulator connected on the steam outlet of this new separator (Figure 19).

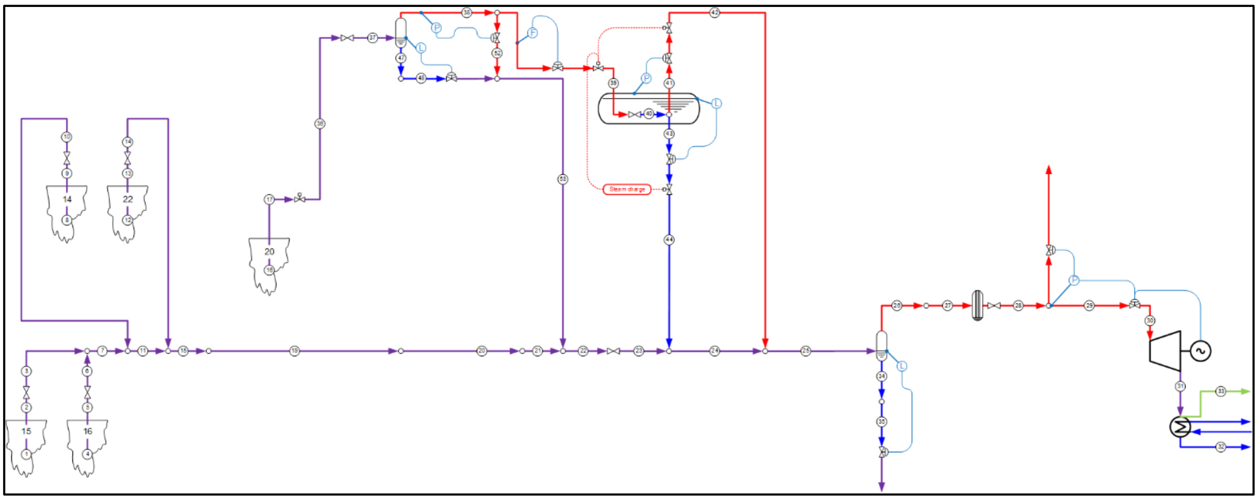


Figure 19. New position for steam accumulator on well n°20

This larger difference of pressure between charge and discharge (3.5-6.5 barg effective with pressure drops) leads to a much smaller volume, a single reservoir with a diameter of 4.5 m and a length of 23 m.

Another difficulty of geothermal plants is the presence of non-condensable gases in the steam. CEA had to develop a steam accumulator model (Dymola) taking into account the effect of the presence of non-condensable gases. The precise proportion of non-condensable gas present in the vapour of well N°20 is not known. However, feedback from Zorlu and the various partners tends to show that there would be around 10% of non-condensable gas in the vapour, which leads to a reduction in capacity by 65%. (Figure 20).

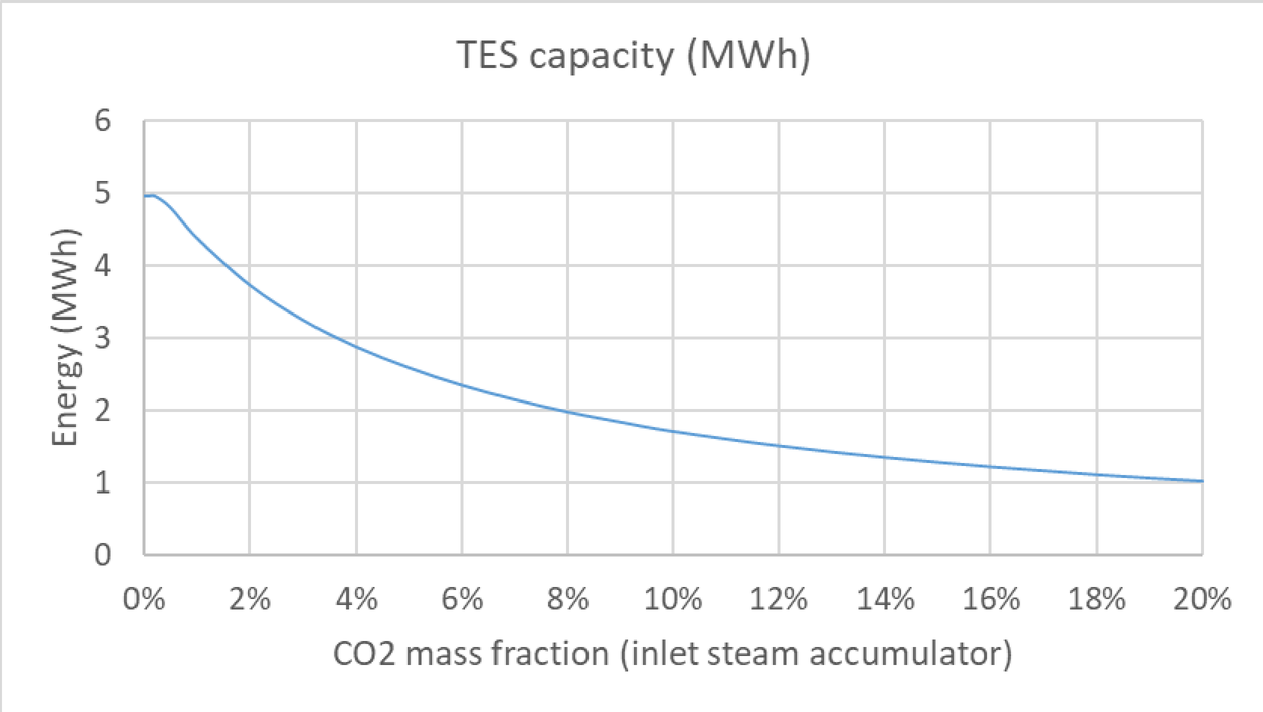
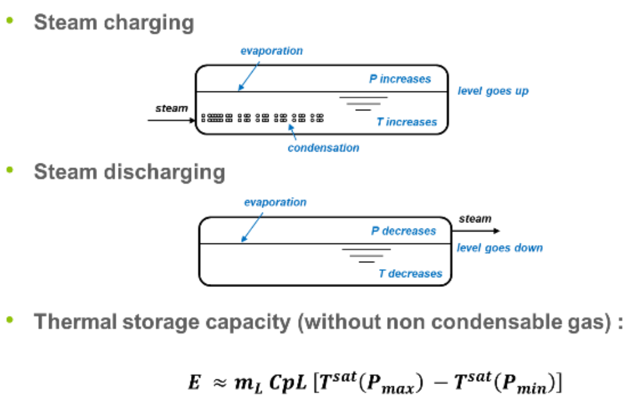
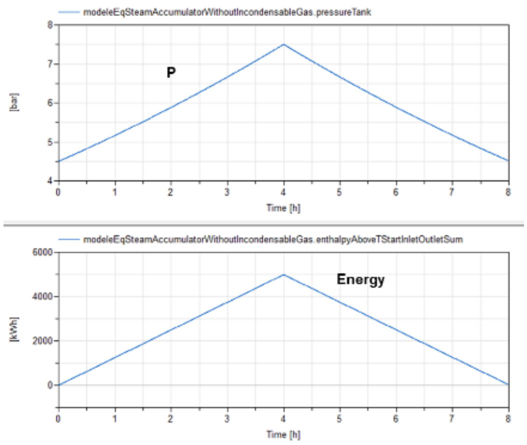


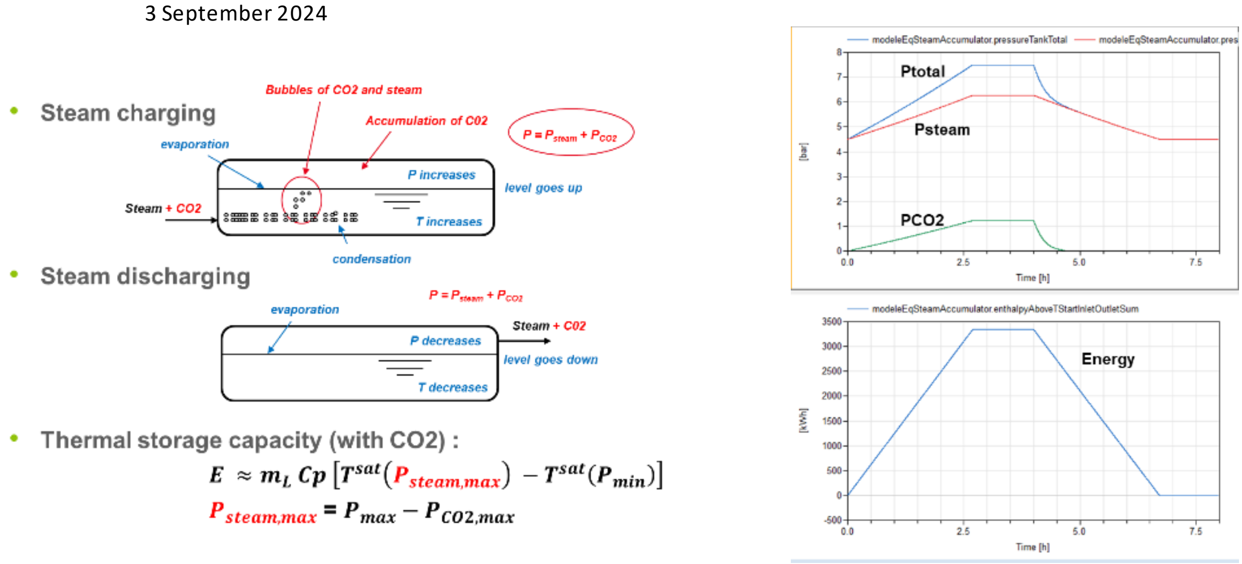
Figure 20. Storage capacity regarding the CO2 mass fraction

This reduction comes from the accumulation of the CO_2 in the gas sky of the steam accumulator, leading to a reduced partial pressure of steam, and a reduced water temperature at the end of charge, the water being at saturation, as depicted in Figure 21.





a/



b/

Figure 21. Evolution of pressure (top) and energy (bottom) in a steam accumulator with the Kizildere I site conditions without non-condensable gas (a) and with 2.8% w of non-condensable gases (b) (charge during 4 hours and discharge during 4 hours).

Five strategies have started to be assessed in order to limit the impact of non-condensable gases and to define the optimal one (Figure 22):

- Increase the inlet gas flowrate and extract gas continuously (strategy 1) or by periods (strategy 2) during charging,
- Sweeping sky and extract gas continuously (strategy 3) or by periods (strategy 4) during charging,
- Add a second separator and connect the steam accumulator at the outlet of the second separator (strategy 5).

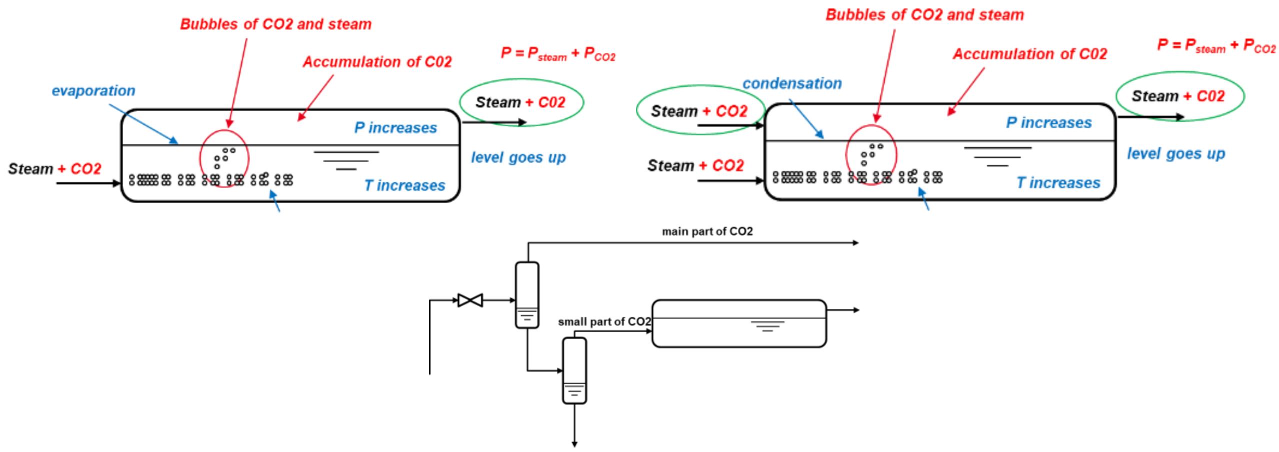


Figure 22. Strategies to reduce the impact of non-condensable gases on steam accumulator capacity (strategies 1 and 2 on the top left, strategies 3 and 4 on the top right, strategy 5 bottom).

3.3 Brine heat storage

The steam accumulator stores the steam coming from the new separator, but it seems interesting also to store the heat from the brine exiting this new separator, it is a second way to increase the electricity production. As it is not optimal to store directly the brine because of its high loading in minerals and risks of deposits, PVald and CEA have proposed to install a PCM module on the brine flow as depicted in Figure 23:

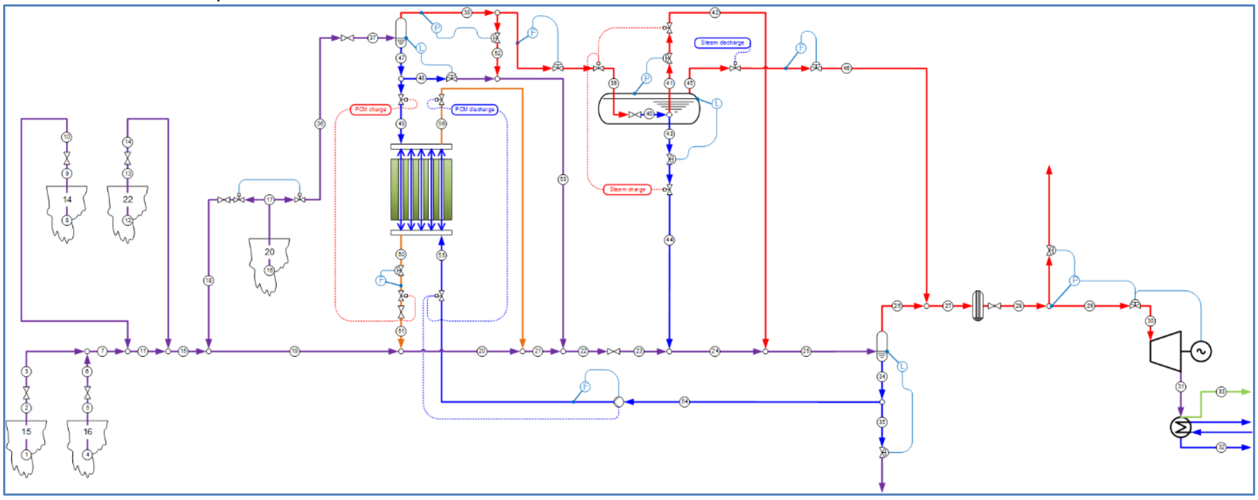


Figure 23. Kizildere 1 site final implementation with a new separator, steam accumulator and PCM module.

PCM modules are less mature than steam accumulators, the envisaged capacity was 2 MWh, which is higher than any demonstrator already built. CEA started to design the module, the proposed technology is a shell and tubes heat-exchanger with a single pass on the tubes side to ease cleaning. As most PCMs have a very low thermal conductivity, the tubes will have fins on PCM side in order to enhance this conductivity (Figure 24).

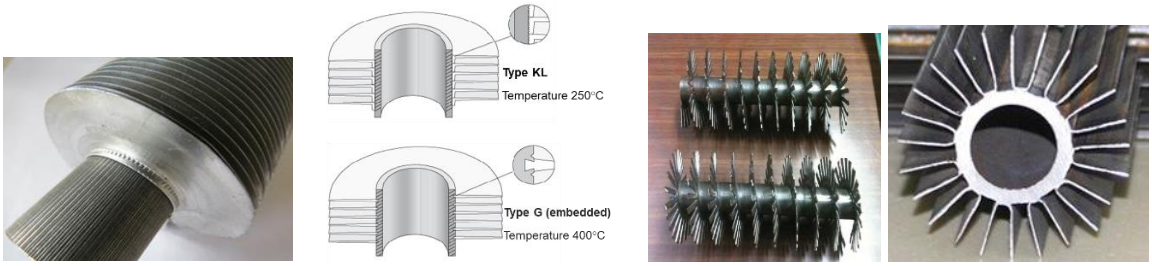


Figure 24. Some examples of tubes with fins

The first step is to identify a suitable PCM. In the case of Kizildere 1, the first selection was done in the melting temperature range of 110-150°C, well adapted for the existing separator conditions, and had to be done again in the range 140-170°C when it was decided to add a new separator operating at higher pressure and temperature. This preliminary activity was still in progress when Zorlu decided to temporarily shutdown Kizildere 1 in May 2020 and to transfer the demonstration activities to Kizildere 2. The PCM module was therefore not designed yet at the end of this period.

However, CEA had developed a PCM storage model using Dymola software. This model combines 0D to 2D sub-modules. The upper and lower collectors are 0D components. The tubes bundle is axially meshed and the PCM region is moreover radially meshed. This region is divided in 3 zones that have a different thermal conductivity, i.e. the tube wall, the PCM and fins, and the free PCM. The model can select various heat transfer coefficients on the brine side according to the fluid Reynolds and Grashoff.

3.4 Conclusion

Kizildere 1 is a single flash plant and had to be adapted to receive a steam storage. The consortium proposed the addition of a new separator on the higher pressure well and the installation of two heat storage modules, a steam accumulator of 5MWh on the steam flow, and a PCM module of 2MWh on the brine side.

The steam accumulator pre-design was achieved at the end of the period. CEA highlighted the impact of non-condensable gases on the design of the steam accumulator and proposed 5 strategies of mitigation of this effect.

The PCM module was still in the procedure of PCM selection.

Most of these activities could be transferred to Kizildere 2 site. The idea to add a new separator was re-used, but for different reasons. The model of a steam accumulator with non-condensable gases and the model of the PCM module could be re-used. In addition, the selection of PCMs could go on because the operating conditions of Kizildere 2 were compatible with the range of Kizildere 1 (140-170°C).

4. KIZILDERE 2 SITE

Kizildere 2 is a commercial geothermal plant producing electricity with 3 flash separators feeding 3 stages of a turbine at high, intermediate and low pressure (HP, IP and LP). This architecture is an advantage compared to Kizildere 1 for the implementation of a steam accumulator because a higher variation of pressure is existing in the process. However, the steam contains a high percentage of CO_2 after the HP separator, which reduces significantly the stored energy. The consortium proposed an innovative solution by adding a new intermediate pressure separator, the idea was to produce enough steam for the steam accumulator at a maximal pressure with a lower CO_2 content. Compared to Kizildere 1, the PCM module is plugged at the outlet of the HP separator, which guaranties the maximal range of temperature (107-165°C) for the PCM selection and an independent operation of the two storage systems. The general simplified PFD for Kizildere 2 including the 2 storage modules becomes (Figure 25):

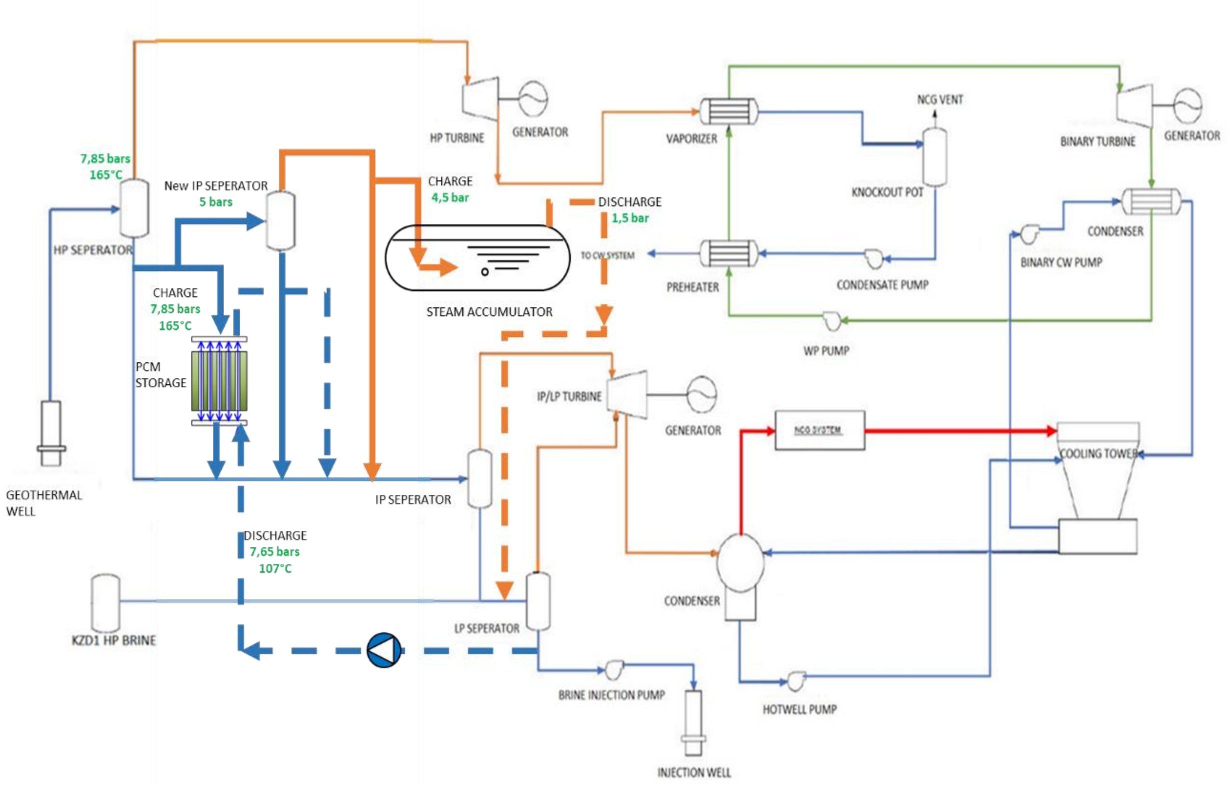


Figure 25. Simplified PFD for Kızıldere 2 site with the addition of the thermal energy storage demonstrators and the new IP separator (charge straight lines, discharge dotted lines)

The maximal brine flowrate that can be sampled at maximum at the outlet of the HP separator is 200 t/h, 150 t/h is devoted to the steam accumulator and 50 t/h to the PCM module.

4.1 Predesign of the steam accumulator (SA) and new IP separator

The first step is to design the new IP separator. It must provide enough steam to charge a 5 MWh steam accumulator in 3 hours and the operation pressure must be as high as possible to have the smaller reservoir and smaller cost.

Zorlu estimated the CO_2 content in the steam behind the new IP separator, it depends on the separator operating pressure (Figure 26):

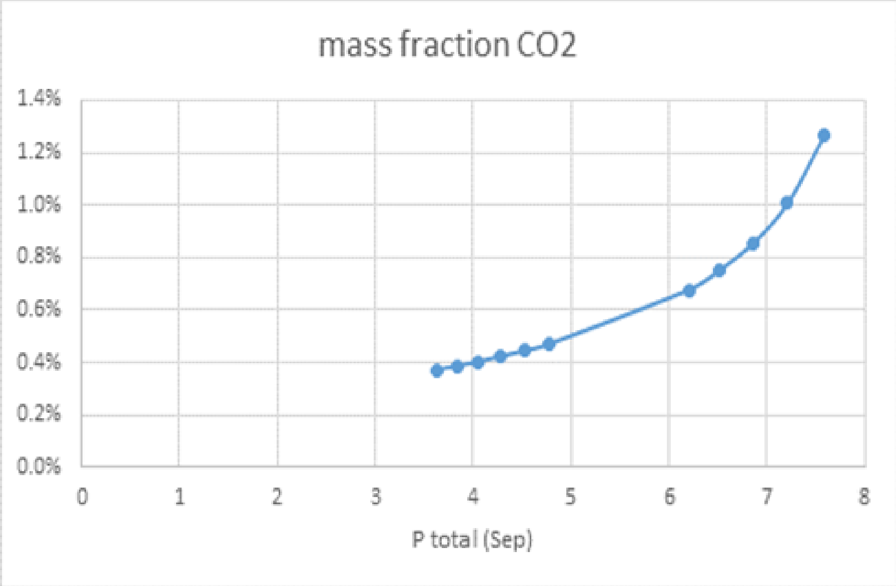


Figure 26. CO_2 content in steam behind the new IP separator versus pressure

For a pressure of 5 bara, the CO_2 content is approximatively 0.5%w. This value is only an estimation and has a large uncertainty of +-100%. Thanks to the model developed for Kizildere 1, it is possible to take into account the effect of the non-condensable gases on the design of the steam accumulator. The strategies remain basically the same as for Kizildere 1, either increase of the steam accumulator size, or operation strategies such as sky sweeping to mitigate the accumulation of CO_2 in the SA sky.

The first step is to determine the operating pressure of the new IP separator and the size of the steam accumulator. If the pressure is too high, there will not be enough steam produced for the steam accumulator charging, and if it is too low, the SA will be bigger and more expensive. Apart from the operating conditions of pressure and temperature, it is important to know the pressure drops between the new IP separator and the SA, and between the SA and le LP separator. At this stage of the project, the values are indicative, but it will be important to have precise values for the SA final design when the PID of the process is done.

The assumptions for calculation are:

- Stored energy: 5 MWh
- 3h of steam accumulation
- Operating conditions:
  - 7,85 bar / 165°C in existing HP separator
  - 4,15 bar / 144,9°C for existing MP separator
  - 1,2 bar / 104,8 °C for existing LP separator
- Brine flowrate at the inlet of new IP separator: 150 t/h
- Pressure drop of 0,5 bar upstream of steam accumulator (new IP separator to accumulator, 0.2 bar in pipes, 0.3 bar in injectors),
- Pressure drop of 0,2 bar downstream of SA (accumulator to LP separator), le minimal discharging pressure is therefore 1.4 bar,
- CO_2 content: as depicted in Figure 26

The following Figure gives the steam accumulator volume versus the new IP separator pressure, the curve in grey corresponds to steam without any CO_2, and the curve in blue gives the effect of CO_2 on the SA size. The maximal pressure for the new IP separator is 5.5 bar, above which there is not enough steam to obtain 5MWh in 3 hours. The curve in orange corresponds to a sweeping strategy where all the remaining steam that is produced at the outlet of the new IP separator is used to decrease the CO_2 content in the SA sky. This sweeping strategy is very efficient if the separator operates below 5.4 bar because the SA volume is close to the condition without any CO_2 in the steam. To have a small margin, we can propose a new IP separator operating pressure of 5.2 bar, and a steam accumulator volume between 150 and 180 m3.

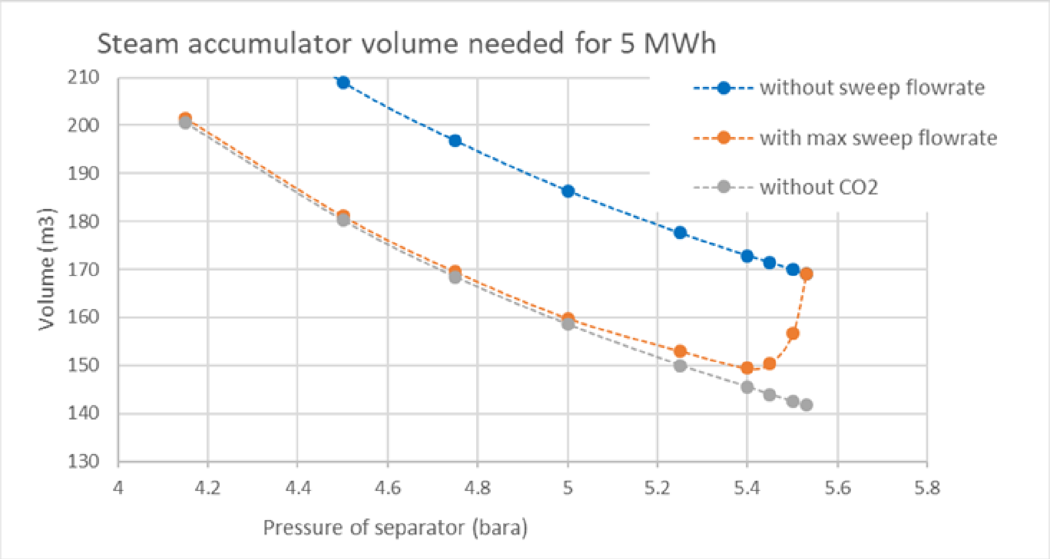


Figure 27. Steam accumulator volume vs new IP separator pressure

The pressure drops upstream and downstream of the steam accumulator have a major impact on the size, as depicted in the Figure 28, especially the pressure drop upstream of the steam accumulator. This is why the steam accumulator size should be confirmed when the circuits are fully designed.

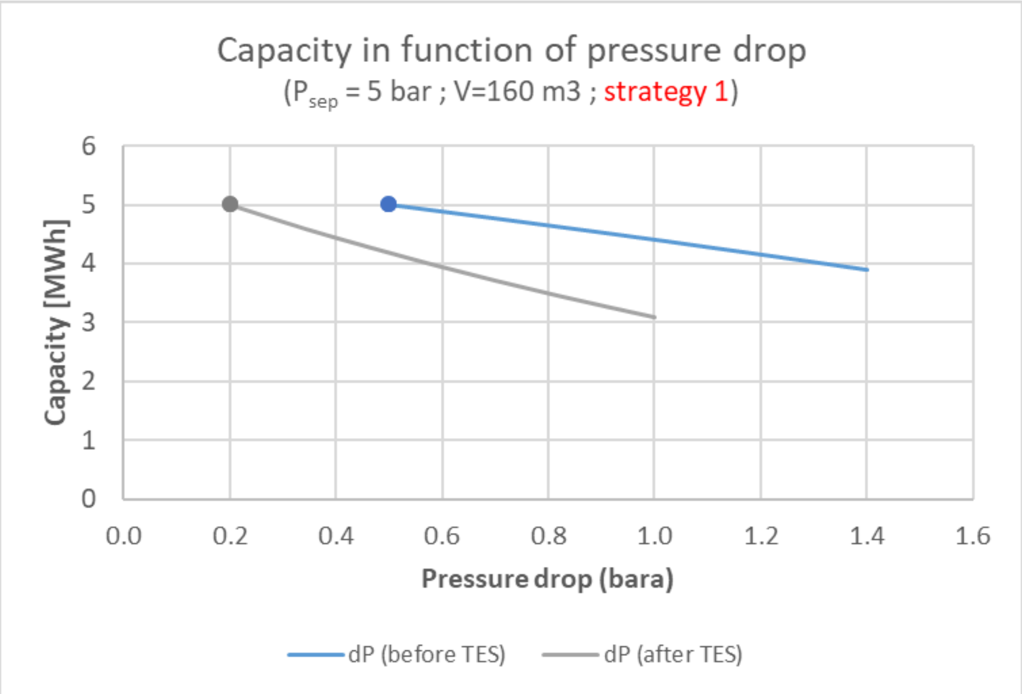


Figure 28. Effect of pressure drops upstream and downstream the steam accumulator on the stored energy (separator pressure of 5 bar, SA volume of 160 m3 and sweeping strategy n°1)

The energy capacity is also affected by the initial volume of liquid in the tank (Figure 29), the nominal level is 66.7%

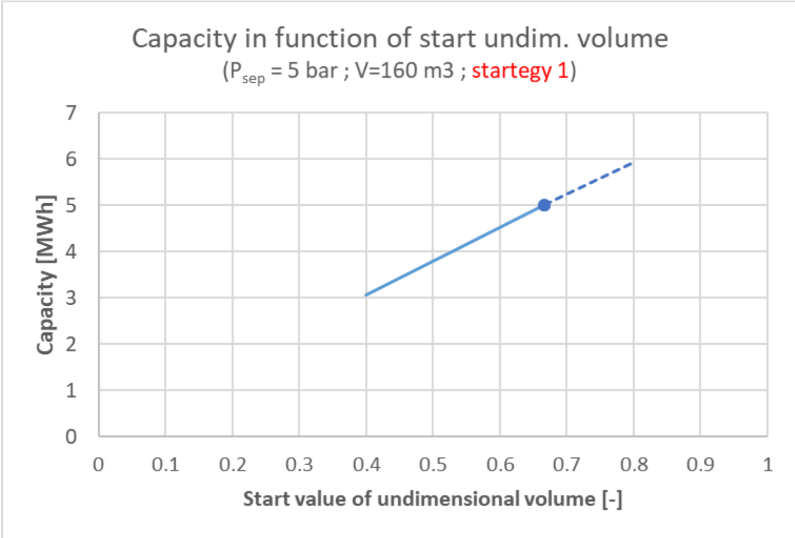


Figure 29. Effect of initial water level on the stored energy (separator pressure of 5 bar, SA volume of 160 m3 and sweeping strategy n°1)

Naldeo has done a similar analysis, but without the effect of CO_2, and including some geometry constraints, the idea is to have an economic optimum.

The study is done for a fixed diameter of 3.6 m. The accumulator length can vary but is limited to 19 m.

Table 5. Synthesis of steam accumulator geometry, performance and cost

Configuration n°	F1	F2	F2	F3	F3	F4	F5	F6	F7
Charge time (h)	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
ΔP before accumulator (barg)	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
ΔP after accumulator (barg)	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20
Storage diameter (m)	3,60	3,60	3,60	3,60	3,60	3,60	3,60	3,60	3,60
Shaft	13%	13%	13%	13%	13%	13%	13%	13%	13%
Brine flow (t/h)	150 t/h	150 t/h	150 t/h	150 t/h	138 t/h	121 t/h	101 t/h	71 t/h	50 t/h
Brine flow (m3/h)	165,86	165,86	165,86	165,86	152,59	133,79	111,68	78,51	55,29
Total storage lenght (m)	7,98	13,05	15,00	17,84	19,00	19,00	19,00	19,00	19,00
L/D	1,69	3,10	3,83	4,43	4,75	4,75	4,75	4,75	4,75
ferrule lenght	6,084	11,160	13,788	15,948	17,105	17,105	17,105	17,105	17,105
Top lenght	1,895	1,895	1,895	1,895	1,895	1,895	1,895	1,895	1,895
Water level	2,270	2,270	2,270	2,270	2,270	2,270	2,270	2,270	2,270
Initial water volume (m3)	50	84	102	116	124	124	124	124	124
final water volume (m3)	55	89	107	121	129	129	128	128	127
Total volume (m3)	74	126	153	175	186	186	186	186	186
Filling (%)	66,9%	66,7%	66,6%	66,6%	66,6%	66,6%	66,6%	66,6%	66,6%
HP separator pressure (bara)	7,40	7,40	7,40	7,40	7,40	7,40	7,40	7,40	7,40
MP separator pressure (bara)	3,80	3,80	3,80	3,80	3,80	3,80	3,80	3,80	3,80
LP separator pressure (bara)	1,23	1,23	1,23	1,23	1,23	1,23	1,23	1,23	1,23
End charge pressure (bara)	6,00	5,50	5,30	5,15	5,00	4,75	4,50	4,00	3,50
New separator pressure (bara)	**6,50**	**6,00**	**5,80**	**5,65**	**5,50**	**5,25**	**5,00**	**4,50**	**4,00**
End discharge pressure (bara)	1,43	1,43	1,43	1,43	1,43	1,43	1,43	1,43	1,43
Storage capacity (kg)	5372	8213	9562	10610	10991	10448	9886	8697	7406
leak flowrate (%)	10%	10%	10%	10%	10%	10%	10%	10%	10%
Steam from separator (kg)	5378,4	8591,4	9930,6	10956,6	11043	11124	10532,7	9252,9	7929,9
Separator vapor fraction (%)	1,2%	1,9%	2,2%	2,4%	2,7%	3,1%	3,5%	4,3%	5,3%
Storage capacity (MWh)	3,5	5,3	6,1	6,8	7,1	6,7	6,3	5,5	4,7
Capacity margin without NCG consideration (%)	-31%	6%	23%	36%	41%	34%	26%	11%	-6%

1. Storage budget price	186 200 €	291 000 €	345 300 €	389 800 €	413 700 €	413 700 €	413 700 €	413 700 €	413 700 €
2. Piping & Valves & pumps & instrumentations	190 416 €	190 416 €	190 416 €	190 416 €	190 416 €	190 416 €	190 416 €	190 416 €	190 416 €
3. Separator	180 110 €	180 110 €	180 110 €	180 110 €	167 960 €	150 748 €	130 498 €	100 124 €	78 862 €
4. Civil works + Piping support	141 938 €	177 785 €	191 522 €	211 598 €	218 831 €	217 531 €	216 046 €	213 909 €	212 478 €
5. Insulation pipes & vessels	143 991 €	159 141 €	164 946 €	173 431 €	176 885 €	176 885 €	176 885 €	176 885 €	176 885 €
6. Construction site base & lifting	45 000 €	45 000 €	45 000 €	45 000 €	45 000 €	45 000 €	45 000 €	45 000 €	45 000 €
7. EAI	30 000 €	30 000 €	30 000 €	30 000 €	30 000 €	30 000 €	30 000 €	30 000 €	30 000 €
TOTAL	**920 000 €**	**1 080 000 €**	**1 150 000 €**	**1 230 000 €**	**1 250 000 €**	**1 230 000 €**	**1 210 000 €**	**1 180 000 €**	**1 150 000 €**
k€/MWh	265 €	204 €	187 €	181 €	177 €	184 €	191 €	213 €	245 €

When the new IP separator pressure increases, the stored energy shows a maximum, because it is limited at low pressure by the maximal length / volume of the accumulator, and at high pressure by the maximal steam flowrate. The maximal is at 5.5 bar (Figure 30). The minimal cost per kWh is also at 5.5 bar. In order to have a safety margin, a pressure of 5.25 bar seems realistic; the accumulator volume is then 186 m^3. (Figure 31).

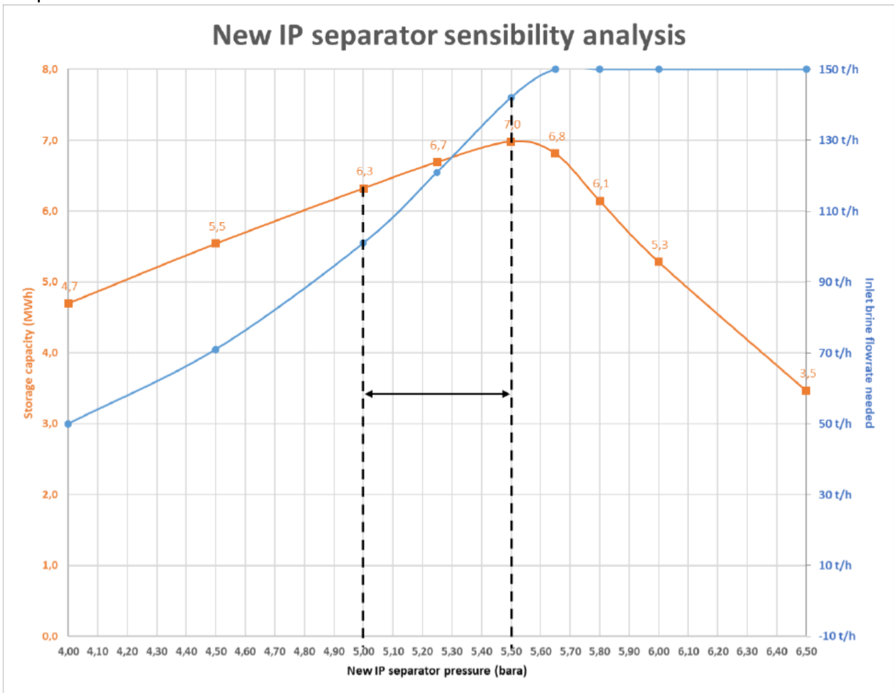


Figure 30. Evolution of stored energy and brine flowrate for various new IP separator pressures

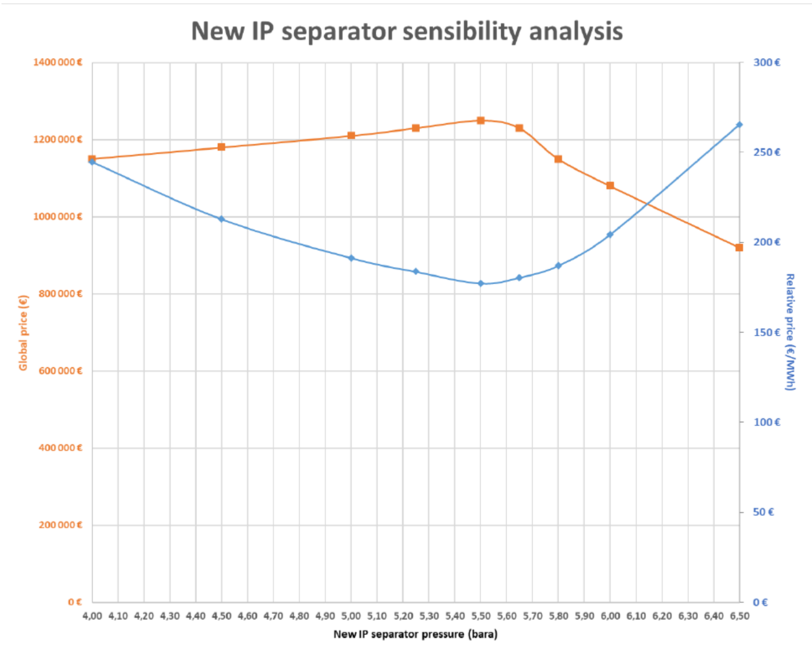


Figure 31. Evolution of global and relative costs for various new IP separator pressures

4.2 Predesign of the PCM module

As for the Kizildere 1 site, the target capacity of the PCM module on the Kızıldere 2 site is 2 MWh, for 3 hours of charging and discharging phases. The proposed technology is also a shell and tubes heat-exchanger with a single pass on the tubes side to ease cleaning, and the tubes will be finned on PCM side in order to enhance its conductivity (Figure 32).

The PCM module will consist of:

– The brine circuit including 2 collectors, 2 distribution plates and the finned tubes,

- The shell filled with Phase Change Material, and having at the top a gas sky to accommodate the volume change consecutive to the phase change of the PCM.

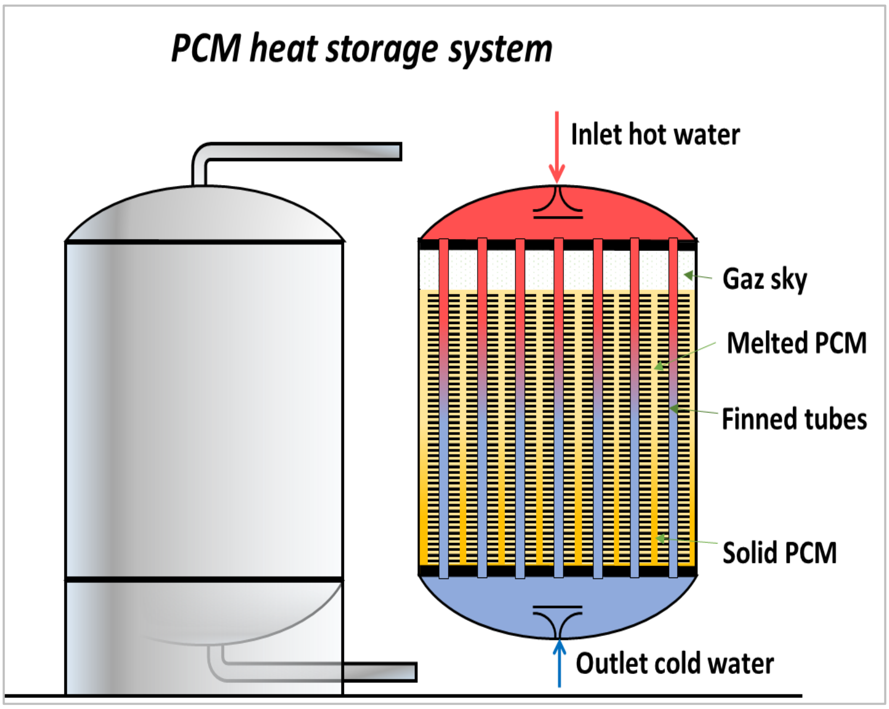


Figure 32. PCM heat storage working principle

Thermally, the PCM storage functions as follows:

- During the charge, the "heat transfer hot fluid" (whose temperature is higher than the PCM melting temperature) enters by the top collector and flows down the module inside the finned tubes, transfers its heat to the PCM, and goes out colder by the bottom collector. During this phase, the solid PCM melts and becomes liquid.
- During the discharge, the "heat transfer cold fluid" enters by the bottom collector and flows up the module inside the finned tubes, recovers the PCM heat, and goes out hotter by the top collector. The temperature of the heat transfer fluid at the output during the discharge is close to the melting temperature of the PCM. During this phase, the PCM changes its state from liquid to solid.

From the identified PCMs, adipic acid and HITEC are selected as most promising PCMs. The selection was made in Task 2.1, based on the relevant material properties for a PCM module, namely melting temperature, melting enthalpy, cycle stability and super-cooling (Deliverable 2.1), the main properties are summarized in Table 6:

Table 6. Selected PCM main properties

	Tmelt [°C]	ΔH melt [kJ/kg]	Density [kg/m³]
Adipic acid	150	268	1360
HITEC	140	110	2006

Change in PCM volume during the phase change is an important design parameter. The bulk density of the PCM determines the volume of PCM that can be loaded into the PCM module and the melt density determines the volume change during phase change. Significant volume changes of the PCM could lead to drastic changes in stresses in the PCM module, which is undesirable. To support CEA with the design data, TWI carried out experiments with the final selected PCM material (i.e. HITEC salt) to ascertain the bulk and melt density. Bulk density measurements were extended for the bulk solid (ambient temperature) and melt density measurements were performed by measuring the volume change in the solid before and after melting at 165 °C. The bulk density measurements were performed at ambient temperature as per ASTM standard D7481-18 using i) graduated cylinder method and ii) volumeter method. Figure 33 shows the photograph of the volumeter.

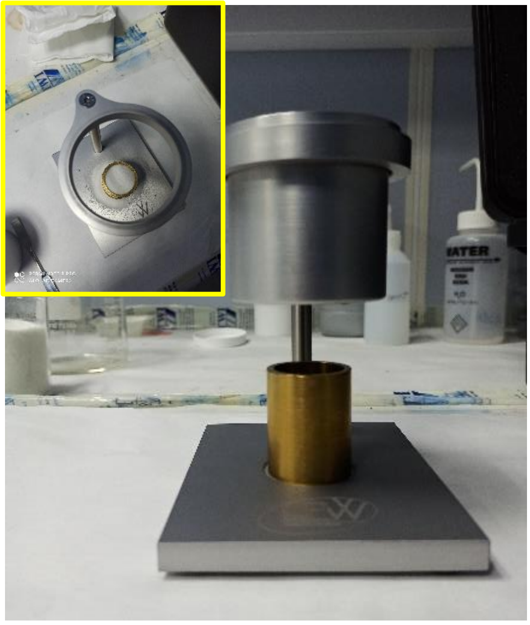


Figure 33. Photograph showing the volumeter that has been employed by TWI to perform the bulk density measurements of HITEC salt

Method 1: Graduated Cylinder Method

100 g of the HITEC salt, previous ground (using mortar and pestle) is weighed (designated as ‘m’) and is passed through a stainless steel (SS) mesh (size ~1.9 mm) into a dry graduated cylinder of 100/250 mL without compacting. The powder is levelled without compacting and the apparent volume to the nearest graduated cylinder reading (‘V’ in mL) is noted. Bulk density is calculated by using the formula (g/cm^3) = m/V

Since the powder density resulted in too low apparent tapped volume (~90 ml), experiment was performed using a 100 ml graduated measuring cylinder (In principle, the untapped apparent volume should occupy at least 60 % of the total volume of the cylinder i.e., between 150 mL and 250 mL)

Method 2: Measurement in a volumeter

The apparatus consists of a top funnel that collects the powder and allows it to pour into a cylindrical cup mounted directly below it. Photograph of the apparatus is shown in Figure 33. Initially, weight of the empty brass cylinder (w1; volume: 25 cm^3) is noted down. Ground HITEC salt is passed to flow through the apparatus into the sample receiving cylindrical cup until it overflows, using 25 cm^3 of powder with the cylindrical cup. The excess HITEC salt from the top of the cup is carefully scraped by smoothly moving the edge of the blade of spatula. The bulk density is calculated by calculating the difference between the weights w1 and w2 and dividing by the volume of the brass cylinder (V) [V=25 cm^3].

The bulk density values (measured at ambient conditions) obtained from both the methods were in the range 1050 kg/m^3 to 1070 kg/m^3.

Density measurements for the HITEC salt at 165 ° C were also performed using the volume displacement method. The density of the melt at 165 ° C was 1950 kg/m^3 and the solid (re-solidified melt) is 1990 kg/m^3. The values are represented in Table 7. As can be seen from Table 7, the density of the melt at 165 °C seems to be different from the ones presented in Table 6.

Table 7. Table showing the bulk density of solid and melt

	Bulk density of solid at ambient temperature		Density of melt at 165° C	Density of the solid (re-solidified melt)	Reference
Method	Mesh sieve	Volumeter	Volume displacement	Volume displacement	ASTM D7481-18 and as suggested by consortium
Value, kg/m³	1080	1055	1990	1950	

This could be attributed to the influence of temperature on the density values, which show a decreasing trend with increase in temperature (2050 kg/m³ at 140°C vs 1950 kg/m³ at 165°C). These results signify that the density change of the melt at 165 °C and above might not affect the design constraints/parameters of the PCM module.

The preselected tubes are commercial finned tubes with aluminium circular fins (Figure 34).

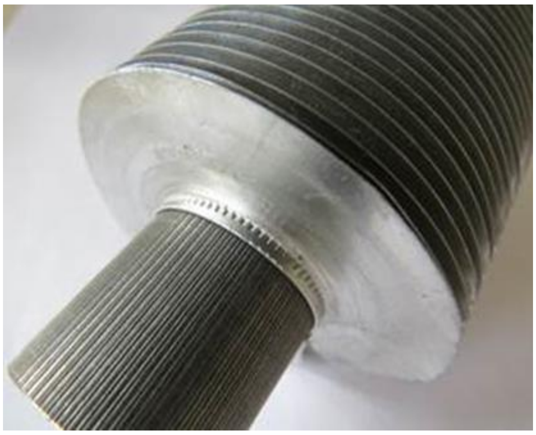


Figure 34. Tubes with circular aluminium fins

The main geometric properties of these tubes are (Figure 35):

- Internal diameter of the tube: 20 mm
- External diameter of the tube: 25.4 mm
- External diameter of the fins : 57.4 mm
- Thickness of the fins: 0.4 mm
- Space between fins: 2.54 mm
- Gap between fins external diameter: 5 mm
- Hydraulic inserts diameter: 13.5 mm

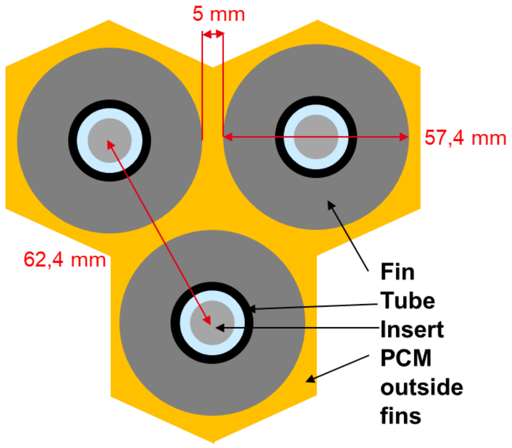


Figure 35. Geometry of the triangular pitch of the tubes inside the module

As identified in M.MARTINELLI's thesis [1], the flow regime in the tubes of a PCM storage with liquid water as heat transfer fluid, is naturally in the transition zones between the natural convection flow and the forced convection flow. Those unsteady and hardly predictable zones should be avoided (Figure 36). In order to modify the flow regime, and avoid the transition zones, one of the solutions is to add hydraulic inserts in the tubes to reduce its hydraulic diameter and consequently decrease the Grashoff number. The insert addition creates an annular flow space (Figure 37).

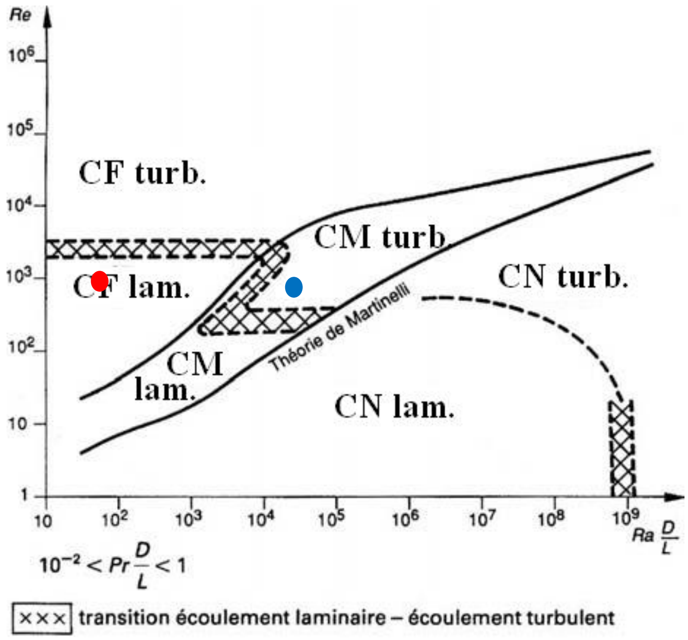


Figure 36. Regimes of natural, forced and mixed convection for flow through vertical tubes. Blue point = flow regime with tubes without intern inserts, Red point = flow regime with intern annular intern inserts.

Figure 37. Carbon steel tubes with circular helical aluminium fins and cylindrical insert used as cross-sectional area reducer

4.2.1 Predesign with Adipic acid as PCM

CEA developed a PCM storage model with the DYMOLA (Dynamic Modeling Laboratory) Software, a commercial modelling and simulation environment based on the Modelica modelling language.

The first design and calculations for the module were done with the Adipic acid as PCM.

In order to simulate all the heat transfer phenomena in the PCM, and between the tube and the fluid, we use a 1D radial model in the fluid and 2D model in the PCM.

The finned tubes are represented in this model, taking into account the fluid flow, the tube, the PCM between the fins and the free PCM in the module. Mass flowrate and temperature boundary conditions are imposed at the input, and pressure boundary conditions are imposed at the output. Both, top and bottom collectors, are represented as volumes 0D.

The module is axially meshed (1D), the module is axially meshed (1D), and the PCM region is moreover radially meshed (2D). This region is divided into three zones that have a different thermal conductivity:

- First zone: wall of the finned tubes (steel 304: ρ = 8010 kg/m3, λ = 49.6 W/m/K, Cp = 450 J/kg/K)
- Second zone: Aluminium fins + PCM. This zone is considered as a homogeny mix. For this mix, we calculate an equivalent density $\rho = \frac{m_{Fin}+m_{PCM}}{V_{Fin}+V_{PCM}}$, an equivalent heat capacity $Cp = \frac{Cp_{fin} * m_{fin} + Cp_{PCM} * m_{PCM}}{m_{fin}+m_{PCM}}$, taking for the fins the Aluminum properties (ρ = 2698 kg/m^3, Cp = 900 J/kg/K), and for the PCM the properties of Adipic acid.
- Third zone: The free PCM outside of the fins. For this zone, the properties of the wall are those of the PCM, the Adipic acid.

Natural convection in the PCM and its density change during phase change are not taken into account. The model is purely conductive on the PCM side, which produces some uncertainties during the solidification and the fusion phases. The fluid distribution in the tubes is supposed perfect, and the heat losses are neglected.

The geometry of the module for this design with the Adipic acid as PCM is summarized in Table 8. The module useful height is the solid PCM height in the shell. The final height is equal to the addition of the useful height, the top and bottom collectors and the gas sky height.

Figure 38 represents the energy evolution in the storage during several cycles of charge and discharge. This energy reaches the target value of 2.2 MWh at the end of three hours of charge.

The water inlet and outlet temperatures of storage during one charge are represented in Figure 39. The incoming hot fluid gives its heat to the PCM, which absorbs the heat and changes phase from solid to liquid state. During the charge, the heat transfer fluid initially comes out very cold as it also recovers the cold stored in the PCM and the metal structures during the previous discharge, then it shows a plateau around 150°C symptomatic of the progressive melting of the PCM, and finally gradually rises towards the inlet temperature. The charge stops before the end of this final rise during which the stored power tends towards zero (Figure 40).

Table 8. Geometry and operation characteristics of the PCM module with the HITEC salt as PCM

		Case Adipic acid
Numbre of tubes		931
Module useful height	**[m]**	6
Module internal diameter	**[m]**	2,1
Module useful volume	**[m3]**	21
Mass PCM	**[tons]**	20
Inserts diameter	**[mm]**	13,5
Fiocco / distance between 2 fins	**[mm]**	5
Temperature charge	**[°C]**	**165**
Temperature discharge	**[°C]**	107
Charging flowrate	**[kg/s]**	9,5
	[t/h]	34
Duration of charge	**[h]**	**3**
Discharging flowrate	**[kg/s]**	4
	[t/h]	14,4
Duration of discharge	**[h]**	**3**
Capacity	**[MWh]**	**2,2**

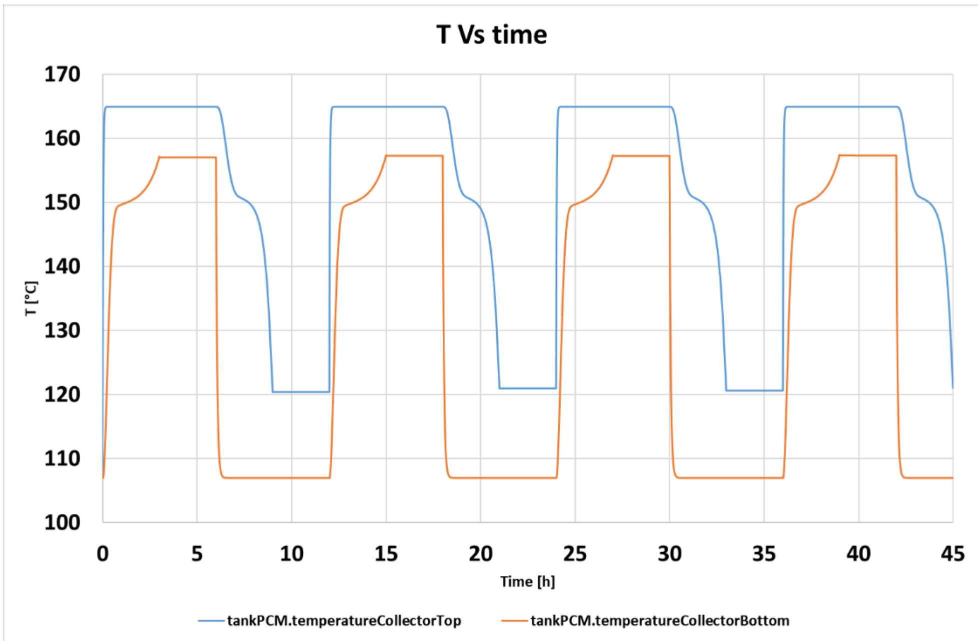


Figure 38. Top and bottom temperatures evolution during several cycles of charge and discharge

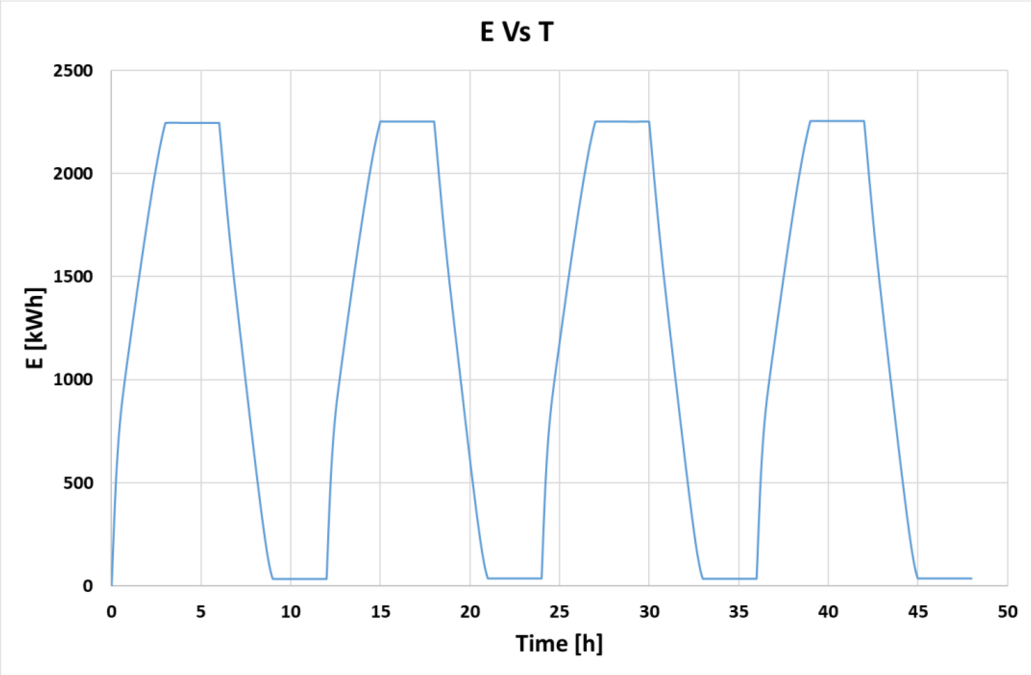


Figure 39. Stored energy evolution during several cycles of charge and discharge

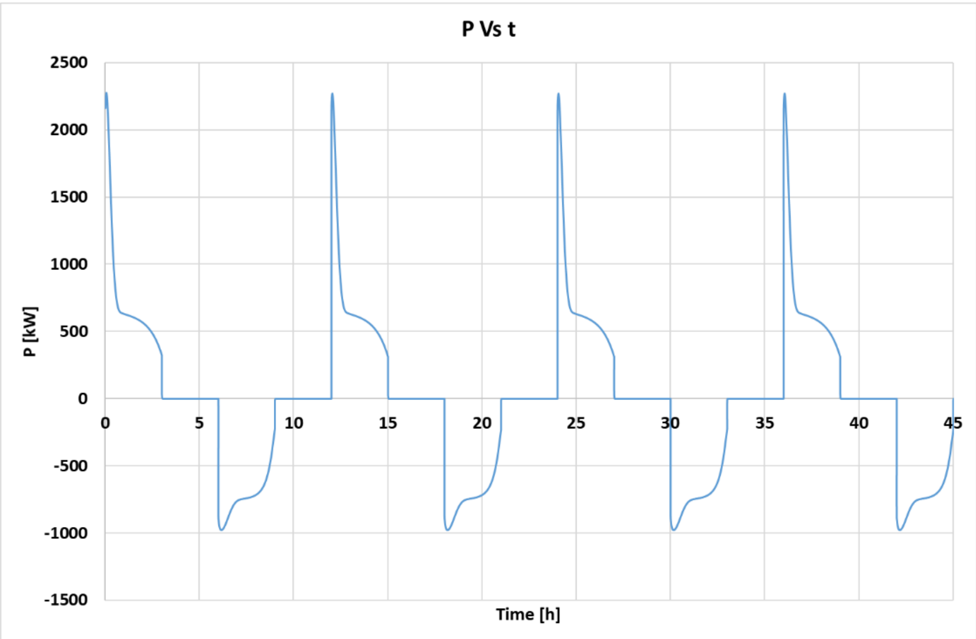


Figure 40. Exchanged power evolution during several cycles of charge and discharge

In Task 2.1, an ageing test was performed for adipic acid and showed a reduction of the melting enthalpy of up to 10% after 1000 cycles. In addition, corrosion tests showed that it is not compatible with the carbon steel and aluminium. It has also a high vapour pressure, which requires a module with a closed pressurized sky.

At the end of this activity of PCMs characterisation in Task 2.1, the HITEC salt was preferred to the adipic acid because it is more stable and compatible with the alloys of the heat exchanger (December 6th 2022). The pre-design of the PCM module had to be done with this new PCM.

4.2.2 Predesign with the HITEC salt as PCM

The same geometry and same DYMOLA model is used for the simulations with the HITEC salt as PCM (instead of the adipic acid). This study was done with hydraulic inserts inside the tubes, after the high-pressure (HP) separator: 165°C, 7.85 bars.

The geometry of the module with HITEC salt is summarized in Table 9. The module useful height is the solid PCM height in the shell. The total height is equal to the addition of the useful height, the top and bottom collectors and the gas sky height. Due to the lower density of the Adipic acid, the useful volume of the module with the HITEC salt is higher than its volume with this acid. In addition, a larger quantity of HITEC salt is needed to reach the target energy of 2 MWh, due to the higher energy density of the HITEC salt compared to the Adipic Acid.

Figure 41 represents the energy evolution in the storage during several cycles of charge and discharge. This energy reaches the target value of 2.15 MWh at the end of three hours of charge.

The water inlet and outlet temperatures of storage during one charge are represented in Figure 42. During the charge, the heat transfer fluid initially flows out very cold as it also recovers the cold stored in the PCM and the metal structures during the previous discharge, then it shows a plateau around 140°C symptomatic of the progressive melting of the PCM, and finally gradually rises towards the inlet temperature. The charge stops before the end of this final rise during which the stored power tends towards zero (Figure 43).

Table 9. Geometry and operation characteristics of the PCM module with the HITEC salt as PCM

		Case HITEC salt
Numbre of tubes		1045
Module useful height	**[m]**	6,5
Module internal diameter	**[m]**	2,2
Module useful volume	**[m3]**	25
Mass PCM	**[tons]**	38,4
Inserts diameter	**[mm]**	13,5
Fiocco / distance between 2 fins	**[mm]**	5
Temperature charge	**[°C]**	**165**
Temperature discharge	**[°C]**	107
Charging flowrate	**[kg/s]**	5,5
	[t/h]	20
Duration of charge	**[h]**	**3**
Discharging flowrate	**[kg/s]**	4,5
	[t/h]	16,2
Duration of discharge	**[h]**	**3**
Capacity	**[MWh]**	**2,15**

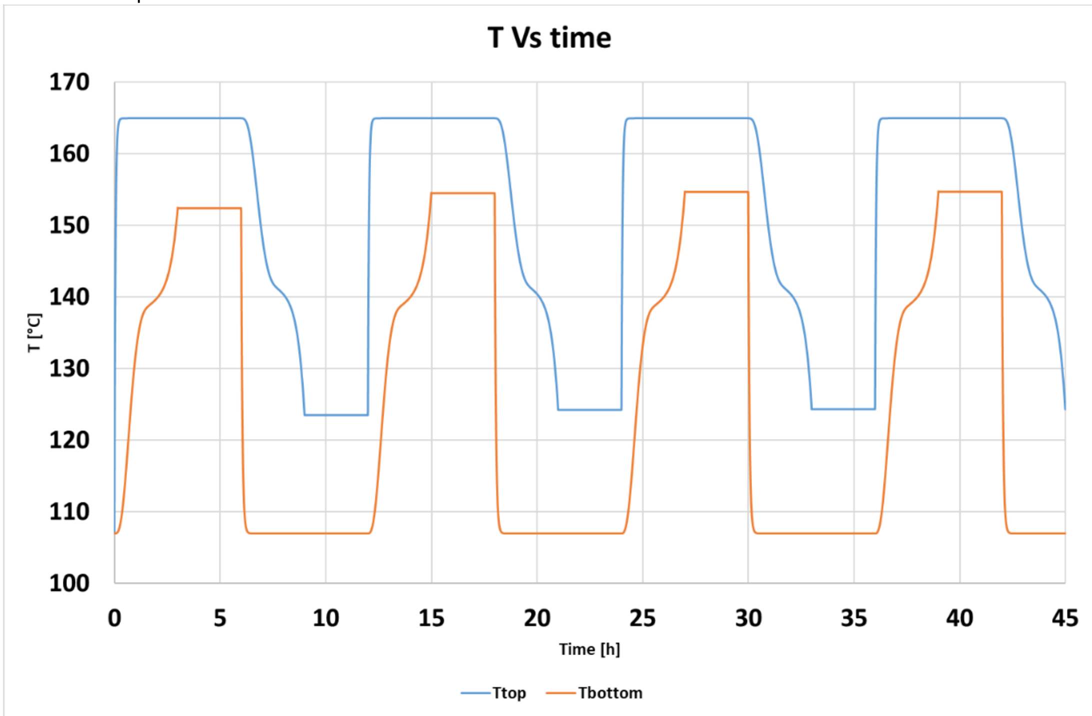


Figure 41. Top and bottom temperatures evolution during several cycles of charge and discharge

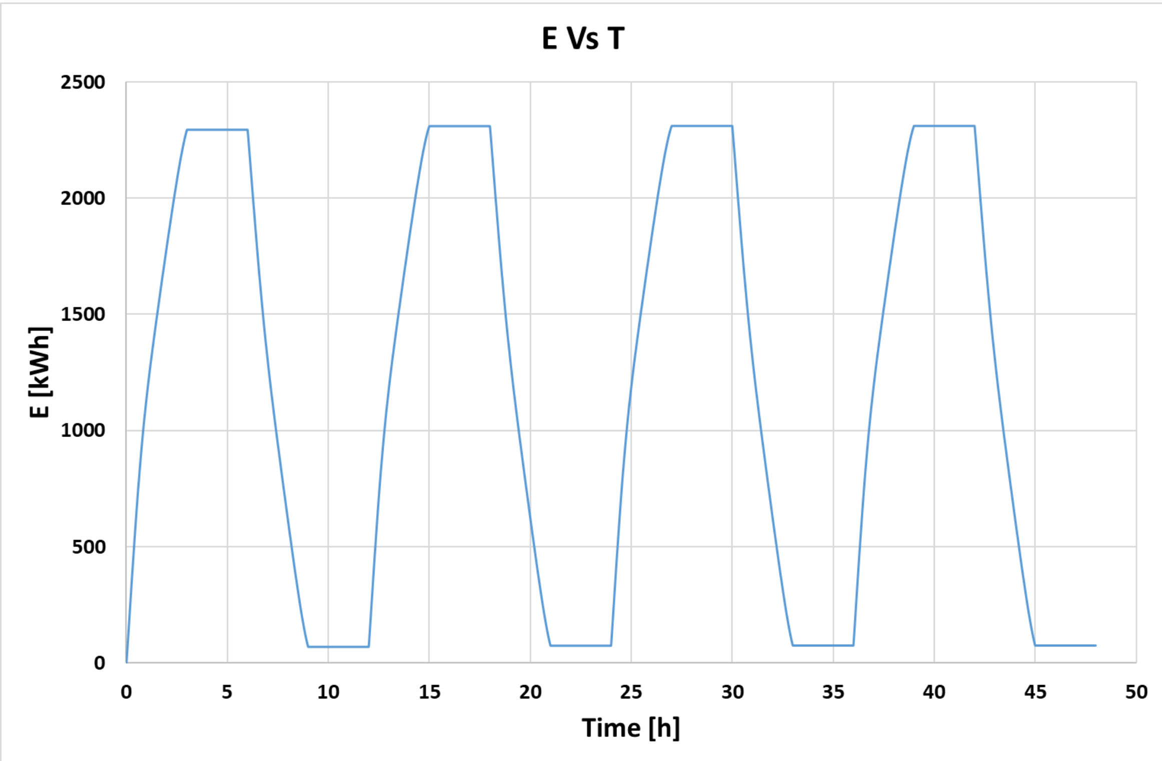


Figure 42. Stored energy evolution during several cycles of charge and discharge

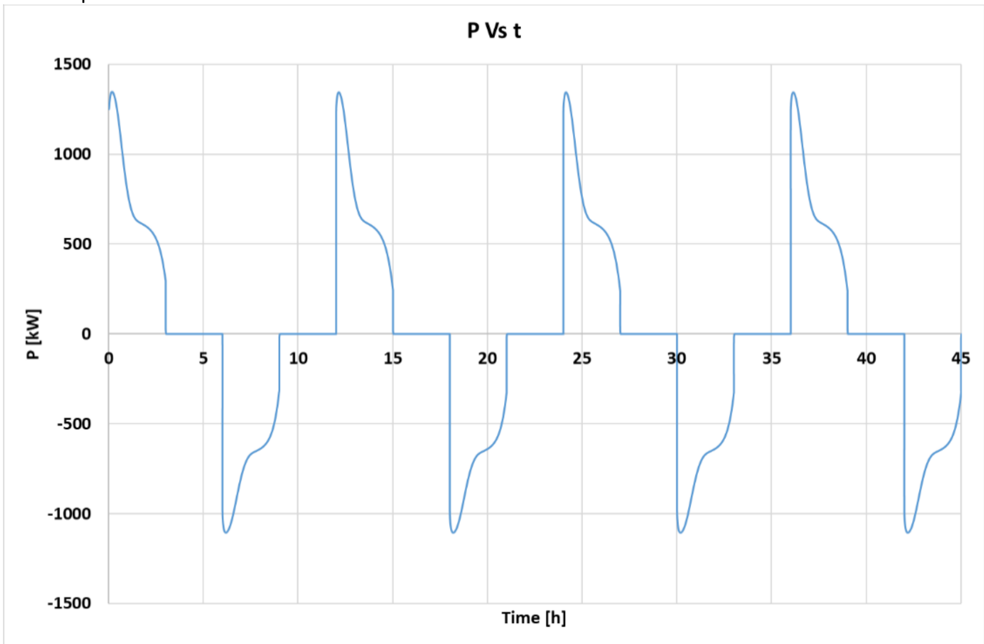


Figure 43. Exchanged power evolution during several cycles of charge and discharge

The specificity of the Kızıldere 2 site is to have a high brine temperature (mixture of water, mineral salts and dissolved gases) of 165°C and to use this brine directly in the process, without intermediate brine/water exchanger. The major issue is therefore to design a storage system adapted to the particular conditions of the brine taken several kilometres underground, i.e. a high rate of incondensable gases (mainly CO_2) and highly mineralized water with a high risk of deposition as soon as the temperature drops. The brine minerals are mainly made up of silicate compounds whose solubility decreases with temperature. For this reason, CEA proposed a simple pass module, in order to ease cleaning. However, the presence of the hydraulic inserts in the tubes may increase the effect of the scaling. Therefore, these inserts were not approved by ZORLU due to the scaling risk on January 18 2021 and a new design was proposed to avoid the hydraulic inserts inside the tubes.

4.2.3 Second predesign to avoid the hydraulic inserts

A solution, that allows avoiding the hydraulic inserts, is to increase the flowrate by tube, by increasing the PCM amount around each tube and enhancing the heat exchange in the PCM by adding aluminium profiles in the PCM zone (Figure 44).

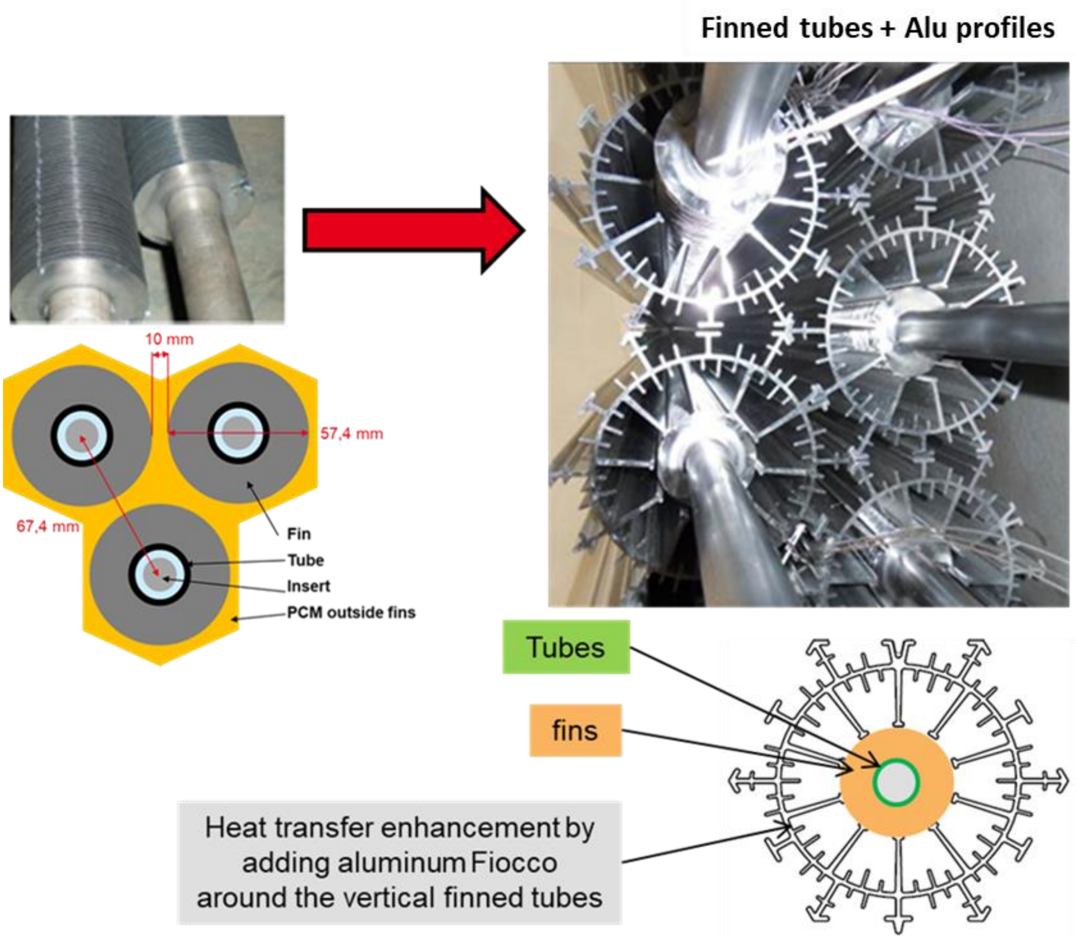


Figure 44. Scheme explaining the two designs of the PCM module: With and without hydraulic inserts

This new design allows a decrease of the tubes number, which increases the flowrate by tube. It results in an increase of the Re number in each tube and allows to escape the transition zones (Figure 45).

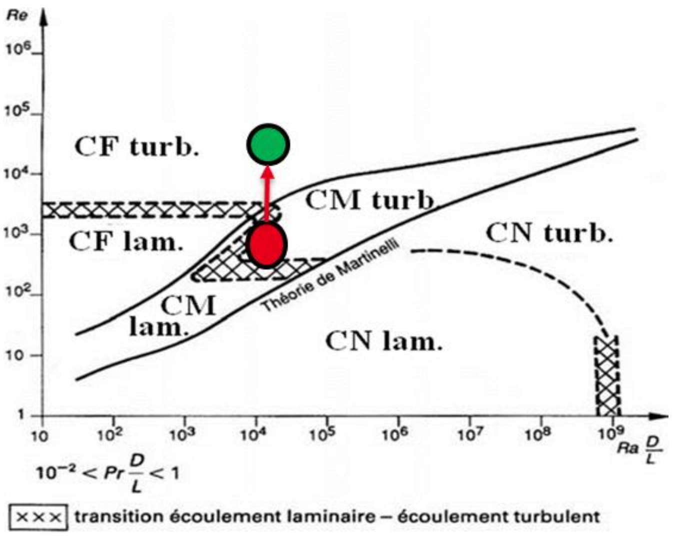


Figure 45. Regimes of natural, forced and mixed convection for flow through vertical tubes. Green circle with aluminium profiles on the PCM side, Red circle without aluminium profiles

With the same geometry of the finned tubes, different cases of design were tested by modifying the distance between the finned tubes (Table 10).

Table 10. Predesign cases with various distance between fins external diameters

	Case F5-1	Case F5-2	Case F5-3	Case F5-4	Case F5-5
Number of tubes	**175**	**241**	**301**	**367**	**517**
Inserts diameter [mm]	**0**	**0**	**0**	**0**	**0**
Distance between 2 fins [mm]	**94**	**70**	**60**	**50**	**34,5**

The design conditions are otherwise similar to the previous design with hydraulic inserts:

- After the high-pressure (HP) separator: 165°C, 7.85 bars.
- Maximum brine flowrate : is 50 t/h.
- PCM: HITEC salt.

The results of the different cases of study are summarized in Table 11. The addition of the aluminium profiles is not sufficient to avoid the transition zone. The flowrate has to be increased to a minimal value that allows escaping from the transition zone, sometimes up 50t/h, the maximum flowrate after the HP separator, which leads to a reduction of the charging and discharging times, the duration of 3 hours cannot be respected anymore, which was accepted by Zorlu. Still the increase of flowrate is an issue on Kizildere 2 behind the HP separator, as was discovered during the engineer studies led by Naldeo in WP7. The flowrate may be higher than after the HP separator, but the charging temperature is lower (153°C), which modifies the PCM module design. Table 11 shows a comparison of the calculations after the HP separator (Tmax = 165°C) and the new IP separator (Tmax = 153°C), with the same geometry (case F5-2). The charging flowrate is higher after the new IP separator, because the difference of temperature is lower. In addition, the module is 5% bigger after the new IP separator because there is less sensible heat stored in the module. Two suitable geometries are proposed in Table 11 after the new IP separator, the main differences are the module height and the number of tubes.

Table 11. Comparison of the calculations after the HP separator (Tmax = 165°C) and the new IP separator (Tmax = 153°C)

		Cas F 5 - 2 IP sep	Cas F 5 - 2 IP sep	Cas F 5 - 2 HP sep	Ref case
Color					
Numbre of tubes		241	301	241	1045
Module useful height	**[m]**	7	6	6,5	6,5
Module internal diameter	**[m]**	2,19	2,44	2,19	2,2
Module useful volume	**[m3]**	26	28	24,5	25
Mass PCM	**[tons]**	40	42,1	36,6	38,4
Inserts diameter	**[mm]**	0	0	0	13,5
Fiocco (distance between 2 fins)	**[mm]**	70	70	70	5
Temperature charge	**[°C]**	**153**	**153**	**165**	**165**
Temperature discharge	**[°C]**	107	107	107	107
Charging flowrate	**[kg/s]**	20	18	10	5,5
	[t/h]	72	65	36	20
Duration of charge	**[h]**	**3**	**3**	**2,5**	**3**
Discharging flowrate	**[kg/s]**	12,4	12,4	10	4,5
	[t/h]	45	45	36	16,2
Duration of discharge	**[h]**	**2,2**	**2,2**	**2,5**	**3**
Capacity	**[MWh]**	**2**	**2,1**	**2,1**	**2,15**

In February 2022, the GeoSmart partners decided to install the module after the HP separator, because the 2 storage modules can be more independent.

The geometry of the module with the new design case F5-2, and the HITEC salt as PCM is summarized in Table 12. The module useful height is the PCM height in the shell. The final height is equal to the addition of the useful height, the top and bottom collectors and the gas sky height.

Table 12. Geometry and operation characteristics of the PCM module with the new design case F5-2, and the HITEC salt as PCM

		Cas F 5 - 2 HP sep
Numbre of tubes		241
Module useful height	**[m]**	6,5
Module total height	**[m]**	10 to 11
Module internal diameter	**[m]**	2,19
Module useful volume	**[m3]**	24,5
Mass PCM	**[tons]**	36,6
Inserts diameter	**[mm]**	0
Fiocco (distance between 2 fins)	**[mm]**	70
Temperature charge	**[°C]**	**165**
Temperature discharge	**[°C]**	107
Charging flowrate	**[kg/s]**	10
	[t/h]	36
Duration of charge	**[h]**	**2,5**
Discharging flowrate	**[kg/s]**	10
	[t/h]	36
Duration of discharge	**[h]**	**2,5**
Capacity	**[MWh]**	**2,1**

4.2.4 PCM module cleaning procedure

For the cleaning of the PCM module, Zorlu proposed seven different procedures (Table 13). GeoSmart consortium worked together for reducing the cost and introducing the most efficient way to reduce the scaling risk in the PCM module. Among the mature solutions, the cheapest procedure is “option 5” that includes a rinsing step with clear water, which will have an energetic cost on the energy stored in the module and was therefore investigated by CEA.

CEA evaluated the impact of the cleaning procedure (option 5) on the PCM storage and the steam accumulator capacity. Three different studies were done for three different “rinsing water” sources that have different levels of temperature:

- Cold water at 25°C (cooling tower)
- Water from the outlet of the secondary circuit of the WP4 heat exchanger, at 55°C
- Water from the steam accumulator (SA) at 149°C (charging temperature) / 109°C (discharging temperature)

Table 13. Cleaning procedures of the PCM module proposed by Zorlu

Cleaning Options	Cas F 5-1 41 tph Charge 41 tph Discharge 10 m3 Rinsing Duration of Charge and Discharge 3h	Cas F 5-2 36 tph charge 36 tph discharge 10 m3 Rinsing Duration of Charge and Discharge 2.5 h	Cas F 5-3 45 tph charge 45 tph discharge 10 m3 Rinsing Duration of Charge and Discharge 2.2 h	Cas F 5-4 50.4 tph charge 50.4 tph discharge 10 m3 Rinsing Duration of Charge and Discharge 2 h	Cas F 5-5 50.4 tph charge 50.4 tph discharge 10 m3 Rinsing Duration of Charge and Discharge 1.8 h	Adventages	Disadventages
Option 1 - Online Dosing	$ 169,020.00	$ 126,000.00	$ 134,100.00	$ 128,592.00	$ 123,148.80	*not corrosive *online and shock dosage application to brine	*may need offline cleaning * cost
Option 2- Shock Dosing	$ 107,120.00	$ 97,520.00	$ 114,800.00	$ 125,168.00	$ 125,168.00	*not corrosive *medium price	*shock dosage for 20 minutes *man need offline celaning *cost
Option 3 - Offline Cleaning	$ 182,800.00	$ 182,800.00	$ 182,800.00	$ 182,800.00	$ 182,800.00	*effective on both silica and calcium carbonate	*acid solution is corrosive to carbon steal cleaning duration is not known, it will determinated by chemical analysis *cost
Option 4 - Online Dosing & Offline Cleaning	$ 92,506.26	$ 92,196.81	$ 92,221.68	$ 92,157.02	$ 92,101.32	* online dosing for karbonates and offline alkaline cleaning for silicate *not corrossive	*cost *may need mechanical cleaning
Option 5 - Rinsing and Cleaning	$ 31010.4 +	$ 31010.4 +	$ 31010.4 +	$ 31010.4 +	$ 31010.4 +	*lower the cleaning price by diluting brine	*water supply is not determinated (cooling effect for cooling tower, and extra steam requirement for SA.) * corrosion tendency should be discussed * medium cost
Option 6 - Energized Oxygen	$ 30000+	$ 30000+	$ 30000 +	$ 30000 +	$ 30000+	* not corrosive *scale preventation observed in demo plant application	*not completely proven, a new technique for geothermal fluid treatment *medium cost
Option 7 - Coating	?	?	?	?	?	* not need chemical cleaning when it used with rinsing	* deposition protection? *cost *aging

Chemicals, pumps , storage tanks and nozzles all inculuded.
Working Period 180 days

4.2.4.1 Cleaning procedure option 5: cold water at 25°C

The rinsing volume is minimum twice the volume of the PCM module on waterside. It means that 6 m³ of process cold water will flow through the PCM storage after each charge and discharge (Figure 46). We consider a duration of 15 minutes for each cleaning after each charge and discharge, which results in a cleaning flowrate of 24 t/h.

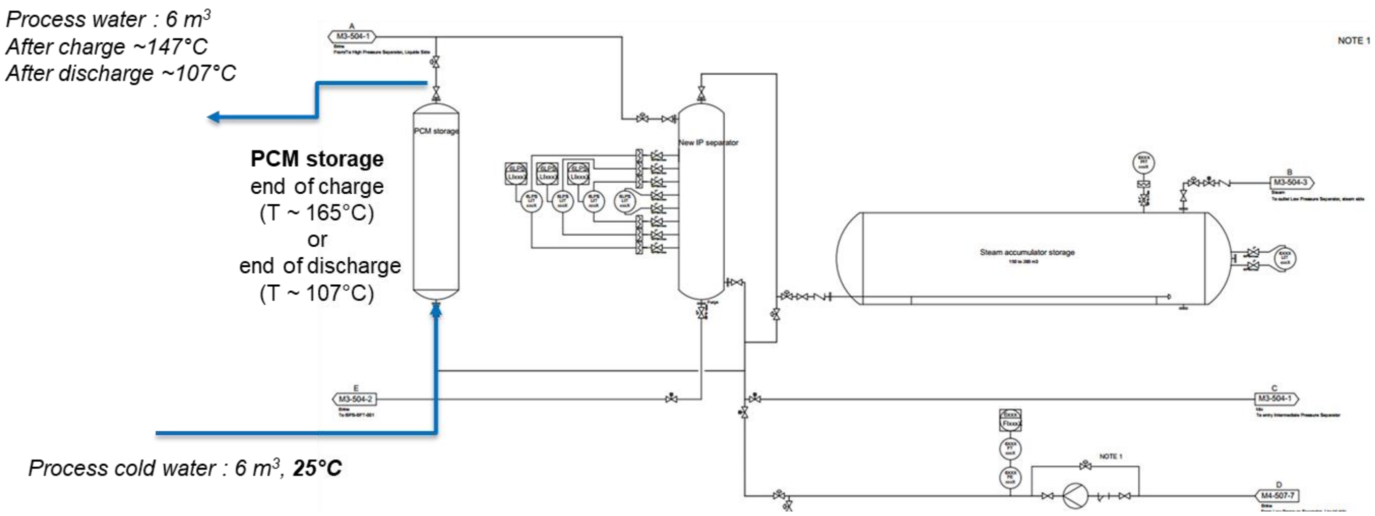


Figure 46. Scheme of the rising procedure of the PCM module with cold water at 25°C

As shown in Figure 47, the lost energy is 0.81 MWh after the charge and 0.4 MWh after the discharge. The energy needed to charge the PCM module is 2.54 MWh (2.14 MWh (Storage capacity) + 0.4 (cleaning)) but the net recovered energy at the discharge is 1.32 MWh only (2.14 MWh (capacity) -0.81 MWh (cleaning)), representing 52% % of the charged energy.

The temperature of the bottom and top collectors drop drastically, with 25°C at the bottom and respectively 116°C (charge) and 60°C (discharge) at the top (Figure 48). The rapid quench of domed ends, distribution plates and tubes may induce mechanical stress and failure that should avoided by all means.

The cleaning water, after the charge, could be used to produce steam for the LP separator (107°C), this energy is evaluated around 0.06 MWh.

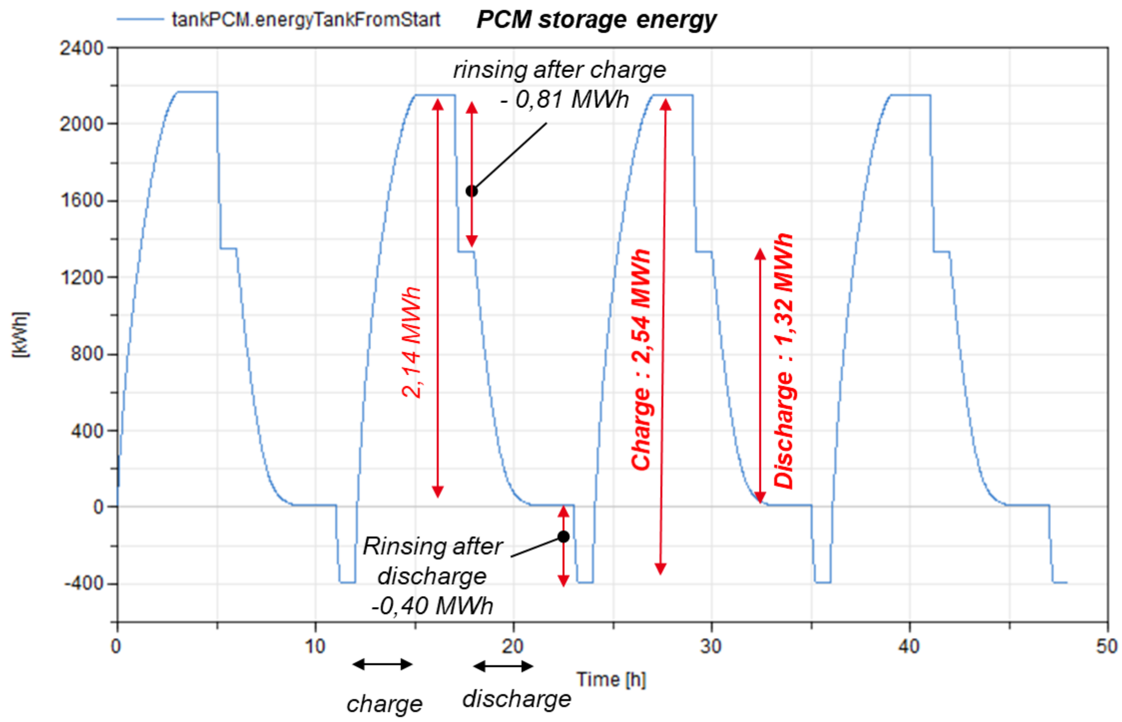


Figure 47. Evaluation of the energy losses in the PCM module - Rinsing after each charge and discharge with 6 m³ of cold water at 25°C

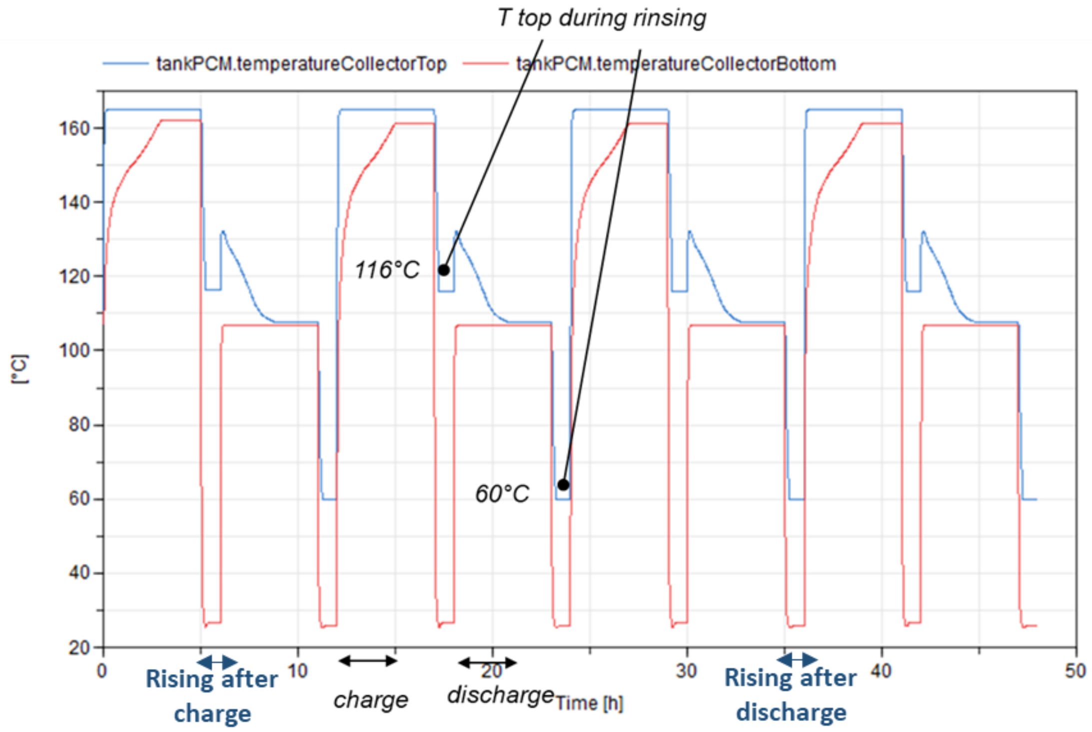


Figure 48. Variations of temperatures in the PCM module - Rinsing after each charge and discharge with 6 m³ of cold water at 25°C

4.2.4.2 Cleaning procedure option 5: water from the WP4 heat exchanger at 55°C

In this case, 6 m³ of water at 55°C from the outlet of the secondary circuit of the WP4 heat-exchanger is used to rinse the PCM storage after each charge and discharge (Figure 49). We consider a duration of 15 minutes for each rinsing after each charge and discharge, which results in a rinsing flowrate of 24 t/h.

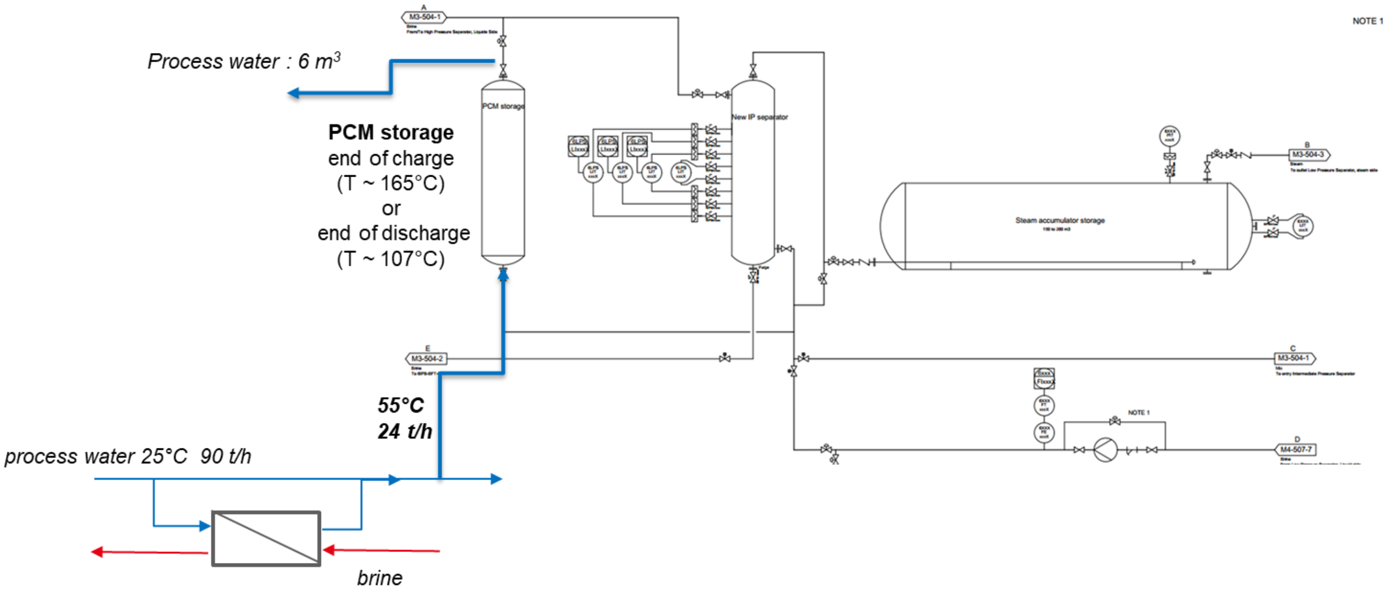


Figure 49. Scheme of the rising procedure of the PCM module with water from the WP4 HX at 55°C

As shown in Figure 50, the lost energy is 0.65 MWh after the charge, and 0.28 MWh after the discharge. Therefore, the energy needed to charge the PCM module is 2.42 MWh and the net recovered energy is 1.49 MWh and represents 62% of the total. A higher rinsing temperature of 55°C lowers the energy losses but they remain high compared to the total capacity of the PCM module.

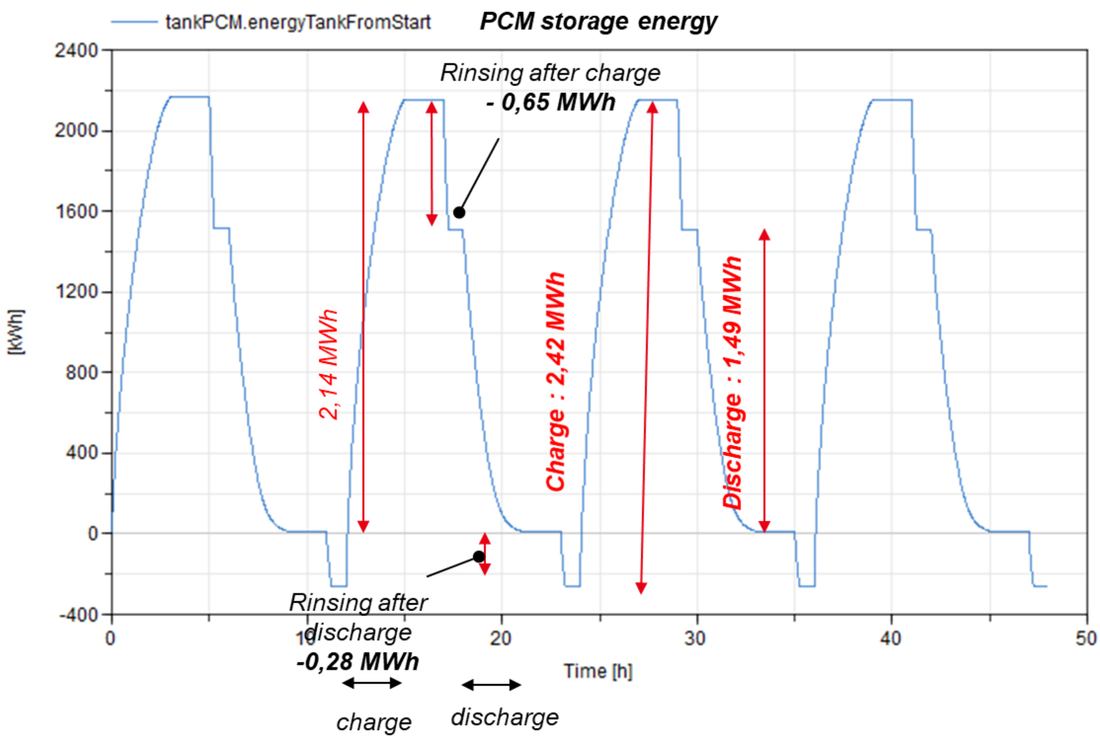


Figure 50. Evaluation of the energy losses in the PCM module - Rinsing after each charge and discharge with 6 m³ of water at 55°C from the WP4 HX

4.2.4.3 Cleaning procedure option 5: water from the SA at 149°C / 109°C

For this case, we rinse the PCM module with water from the steam accumulator. During the charge of the steam accumulator, 6 m³ are emptied from the SA to rinse the PCM storage and go to the LP separator (Figure 51). In addition, the SA is refilled with 6 m³ of cold water before the end of the charge. This results in an increase of the charge period of the SA to reach its maximal capacity.

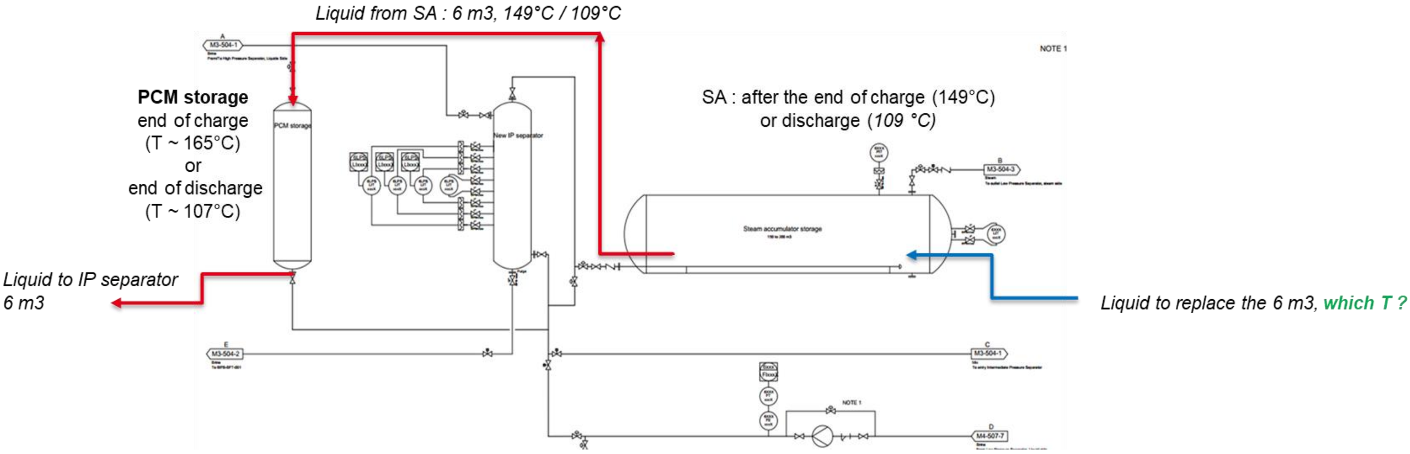


Figure 51. Scheme of the rising procedure of the PCM module with water from SA

For the calculations, the conditions for the SA are:

- Liquid volume : 125 m³
- End of charge : 4,7 bara & 149°C
- End of discharge : 1,4 bara &109°C
- Non condensable gas taken into account with sweep flowrate to reduce their effect

As shown in Figure 52, the lost energy is 0.09 MWh after the charge, and null after the discharge. Therefore, the energy needed to charge the PCM module is 2.14 MWh and the useful recovered energy at the discharge is 2.05 MWh, representing 96% of the total. This procedure is optimal for the PCM module but has an impact on the stored energy of the Steam accumulator.

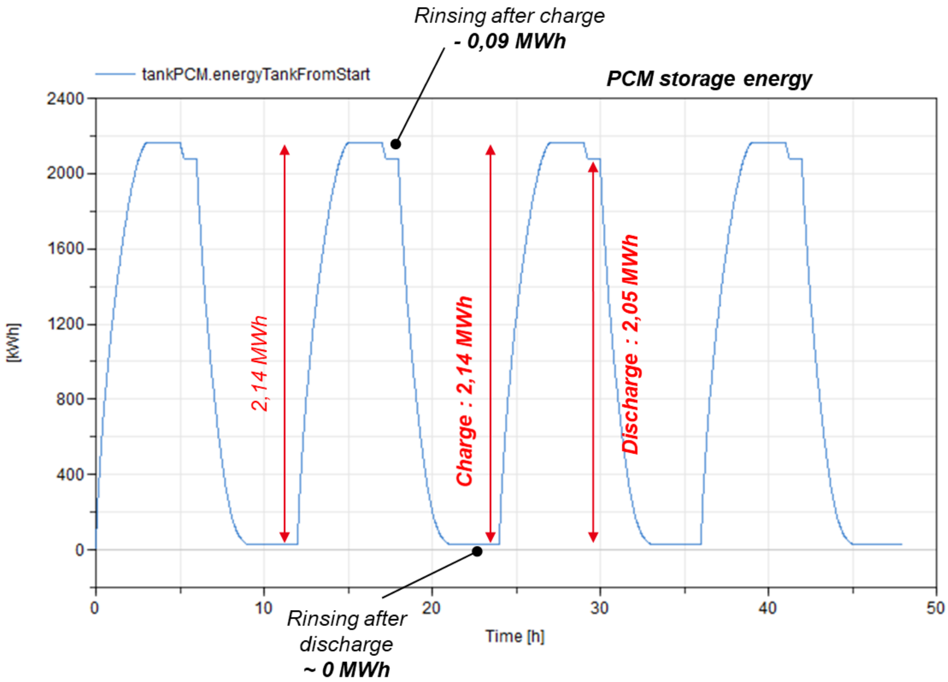


Figure 52. Evaluation of the energy losses in the PCM module - Rinsing after each charge and discharge with 6 m³ of water at 107 to 149°C from the SA

The strategy that could be implemented for the rinsing procedure via the SA (Figure 53):

- [1] Rinsing after the previous discharge : 15 min
- [2] Refill after the rinsing with water at 25°C: 15 min
- [3] Rinsing before the end of the charge : 15 min, 2h30 after the beginning of the charge
- [4] Refill before the end of the charge with water at 25°C : 15min, 2h45 after the beginning of the charge

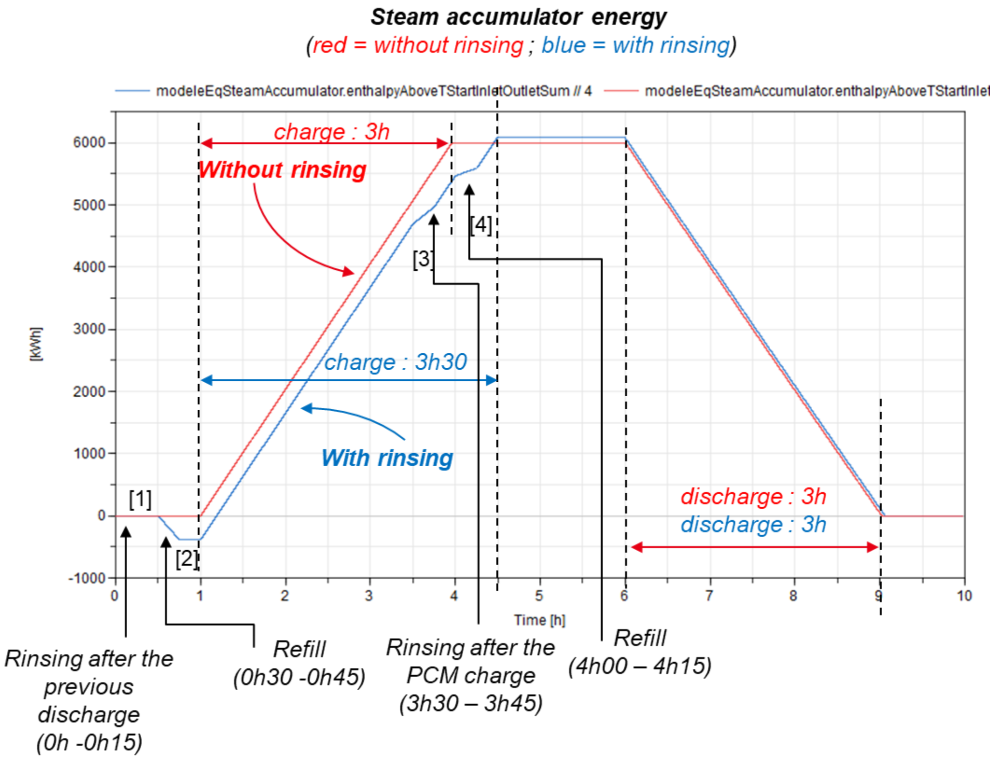


Figure 53. Evaluation of the energy losses in the SA with the chosen strategy of the rising of the PCM module (option 5: rising of the PCM module with water from the SA)

For the reference case, the SA is charged at a power of 2 MW during 3 hours, the charged energy is 6 MWh. If the rinsing procedure is applied, and the charging power maintained, the charging time must be longer to compensate the energy removed from the SA (respectively 0.62 MWh and 0.38 MWh after the charge and discharge) and with last 3h30, the total charging energy will be 7MWh, whereas the discharged energy will remain 6MWh.

This solution allows a very high restitution of the stored energy of the PCM module, but decreases the stored energy in the SA by 1MWh and is, in the end, quite close to the first solution (rinsing at 25°C) (Table 14). Still the solution using the SA is less dangerous for the PCM module and will allow avoiding thermal stress on the module heat-exchanger.

4.2.4.4 Synthesis of cleaning impact

Table 14 summarizes the evaluation of the impact of the cleaning procedure (option 5) on the PCM storage and the steam accumulator capacity, for four rinsing temperatures (the case 85°C is not detailed).

Table 14. Synthesis of the cleaning procedure (option 5) impact on the PCM storage and SA capacities

rincing water		PCM storage energy lost [MWh]			SA energy lost [MWh]			Total energy lost [MWh]				
		after charge	after discharge	each cycle charge & discharge	after charge	after discharge	each cycle charge & discharge	after charge		after discharge		each cycle charge & discharge
cold water	25°C	-0,81	-0,40	-1,21				-0,81	67%	-0,40	33%	-1,21
water after WP4 HX	55°C	-0,65	-0,28	-0,93		*unused*		-0,65	70%	-0,28	30%	-0,93
water after WP4 HX, before junction with the by-pass	HYP : 85°C	-0,47	-0,13	-0,60				-0,47	78%	-0,13	22%	-0,60
water from the SA with water to refill at 55°C	109°C - 149°C (refill with 55°C)	-0,09	0,00	-0,09	-0,62	-0,38	-1,00	-0,71	65%	-0,38	35%	-1,09

In conclusion, the energy lost in the PCM storage is directly related to the difference between the module and rinsing water temperatures and is therefore higher after the charge than after the discharge. The ideal situation is to have the same water temperature as the module itself, which is nearly achieved by using the water from the steam accumulator, this solution will be implemented on Zorlu's site. Using water at high temperature has also the great advantage to minimize the thermal stress on the PCM module heat-exchanger. Still, considering the two modules, there is no net energy advantage if the SA is refilled with water at 25°C. An idea could be to refill the SA with hotter water coming from the outlet of the WP4 heat-exchanger when possible. The final procedure and implementation will be detailed in WP7. In addition, the frequencies of cleaning and the rinsing volumes will have to be optimized experimentally on Zorlu's site after the PCM module commissioning.

4.3 Conclusion

Kizildere 2 is a 3-stage flash plant combined with a bottoming binary (ORC) cycle that facilitates the installation of storage modules because there are several levels of pressure and temperature.

The consortium proposed the addition of a new separator after the HP separator to store steam with a lower content of CO_2, because it has a great impact on the dimensioning of the steam accumulator. The pressure of this new separator was optimized in order to receive a steam accumulator of 5 MWh with a charge and discharge duration of 3 hours. The module was pre-designed with preliminary values of the pressure drops before and after the steam accumulator, but these values have an impact on the SEA performance. Therefore, these pressure drops will have to be calculated more precisely in WP7 on the real site geometry and the final design of the SA (WP7) could have to be adapted to these new conditions. As for Kizildere 1, CEA highlighted the impact of non-condensable gases on the design of the steam accumulator and proposed several strategies of mitigation of this effect, at least one of them will be implemented.

The PCM module pre-design was much longer than expected for several reasons. The first PCM that was selected, adipic acid, was very promising but revealed to be too corrosive in the end. A new series of tests were performed at Fraunhofer and TWI on the second choice, HITEC salt. This salt has a lower melting temperature and a lower melting enthalpy, and it was compatible with standard carbon steel and with aluminium, and very stable. Thus, it was selected in the end.

In the meantime, CEA performed a first pre-design of the PCM module with adipic acid, followed by a second one with HITEC salt. These first 2 designs included hydraulic inserts inside the tubes to enhance the convective transfer on water side. In January 2022, Zorlu has proposed to remove these inserts due to the increasing scaling risk and cleaning difficulties with reduced diameter in the tubes. A second design of the PCM module was then calculated, with fewer tubes and the addition of aluminium profiles in the PCM. A variant was also calculated in the case the PCM module is installed behind the new IP separator instead of after the HP separator because there was high singular pressure drop after the HP separator. In the end, the decision was taken to build the PCM module with aluminium profiles and for it to be installed after the HP separator and in parallel to the new IP separator.

Zorlu proposed several procedures for the cleaning of the PCM module in order to avoid scaling during the stand-by periods between charges and discharges. The cheapest and more mature one included a step of rinsing with clean water. CEA studied the energetic impact of this rinsing step, which was high if the water was cold, and proposed to use the water from the steam accumulator. This solution will be implemented in WP7.

5. INSHEIM SITE

Insheim site entered the project in 2021 after the suspension, to replace the Balmatt site. The owner of the power plant was Pfalzwerke GeoFuture GmbH (PG GmbH) until 31st December 2021 and the ownership was transferred to the Vulcan Energie Ressourcen GmbH on the 1st January 2022, so that the plant is now operated by Natürlich Insheim GmbH (VNI), which is part of the Vulcan group.

The site is located at Insheim in Southern Palatinate, Germany. The brine feeds directly an ORC, which produces electricity with an installed nominal electrical capacity of 4.8 MWe. The geothermal power plant has been operated for almost 10 years with a high return of experience and thus may serve as an exemplary site for the Upper Rhine Graben (URG).

5.1 TES objectives

The VNI-Team in cooperation with CEA and Naldeo is working on the design of the TES system at the Insheim site to demonstrate the benefit of such a system in a typical URG geothermal power plant. VNI had regular online meetings with partners, CEA and NALDEO, organized by TWI, sharing data and information about the concept to integrate TES on the Insheim site. One onsite meeting has been hosted by VNI in April 2022 where WP2 partners have seen the surface facilities of the Insheim Geothermal Power plant. It was the opportunity also to talk about where the innovation could take place.

An opportunity study of TES on Insheim geothermal installation has been initiated, with frequent updates of VNI's expected process architecture.

With the first architecture presented (Figure 54), the first interests in thermal storage were either:

- The optimization of electricity production through the ORC (scenario 1)
- The heat supply of greenhouses (scenario 2)

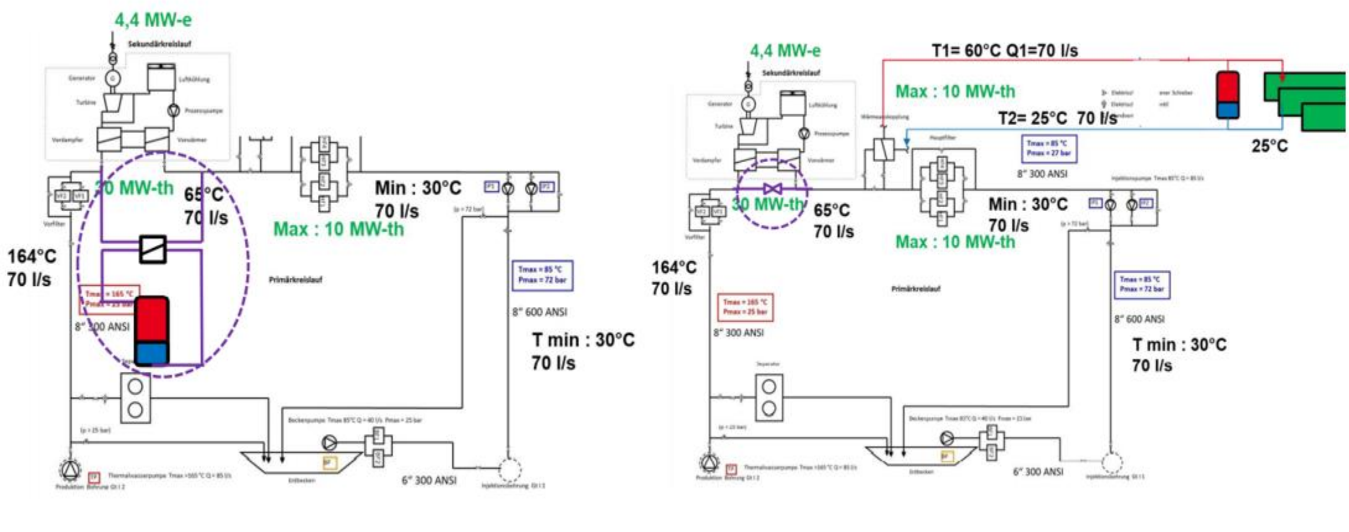


Figure 54. T architecture proposed (scenario 1 on the left, scenario 2 on the right)

The commercial strategy at VNI has evolved, and the architecture evolved in parallel and changed several times due to changing collaborations. Within the third new strategy, the heat from the geothermal well will be used to supply a district heating (DH) network and the excess energy will be used to produce electricity via an ORC.

CEA and Naldeo proposed two configurations for positioning and using the TES each with its advantages and its drawbacks (Figure 55).

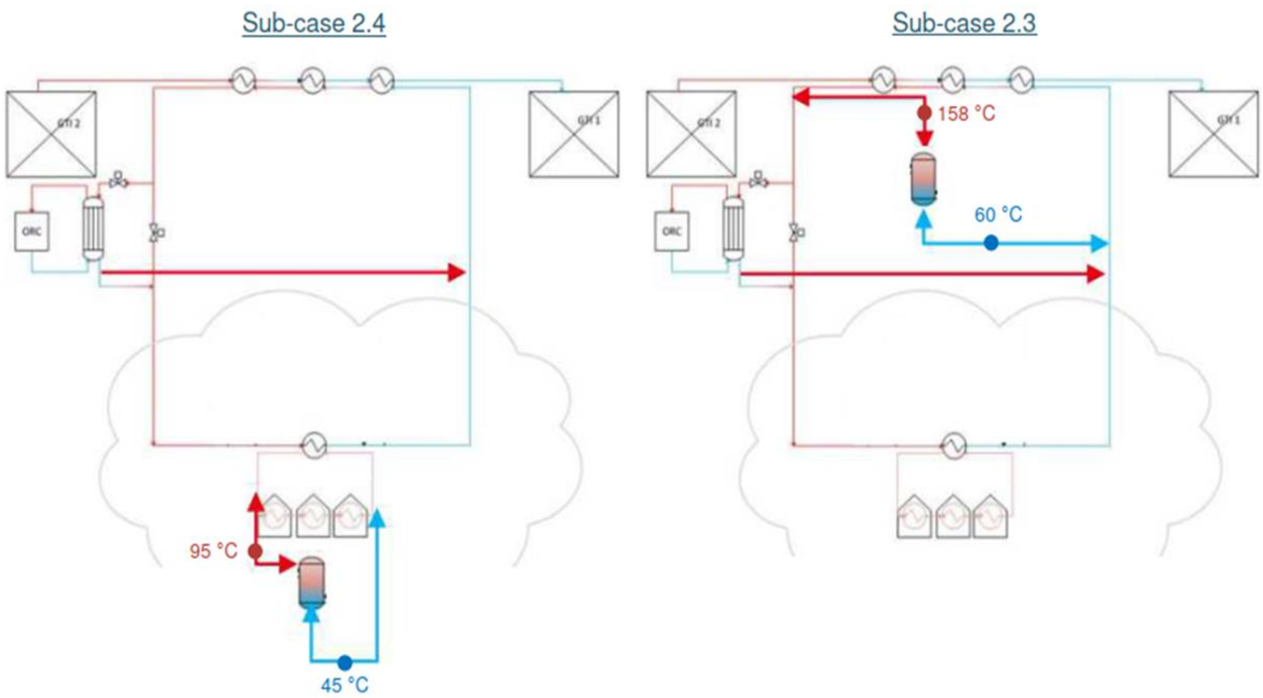


Figure 55. Last two configurations for the positioning of the TES system

In subcase 2.4, the storage is atmospheric (between 45°C and 95°C) and close to the district heating, whereas in subcase 2.3 it is on site and pressurized (between 60°C and 158°C). In the subcase 2.4, the TES can only be used to supply the district heating needs, whereas in the subcase 2.3, the TES can be used both for the district heating needs and for the ORC. According to a cost estimate by Naldeo, the pressurized storages are more expensive than atmospheric ones, about twice as expensive for the same capacity, but the calculations do not include the civil works, piping, instrumentation and the implementation of the TES system (Table 15). If these elements were taken into account, the difference would be less.

These cost estimations are done assuming the following hypotheses:

- 1 mm/s of flow velocity in the module to maintain a stable thermocline temperature front
- 3 hours charging / 3 hours discharging
- Maximal diameter: 3.8 m, to ease transport
- Maximal total height: 20 m, to ease transport

Table 15. Cost analysis of atmospheric (cases 1 to 3) and pressurised thermoclines (cases 4 to 6) for 5, 10 and 15 MWh capacity (without civil works and piping costs).

Cas N°	-	n°1	n°2	n°3	n°4	n°5	n°6
Objective Capacity	MWh_{th}	5	10	15	5	10	15
Storage PS	barg	0,5	0,5	0,5	10,0	10,0	10,0
Storage TS	°C	100	100	100	200	200	200
T°C cut-off decharge	°C	95,0	95,0	95,0	158,0	158,0	158,0
T°C cut-off discharge	°C	45,0	45,0	45,0	60,0	60,0	60,0
STORAGE ENERGY DESIGN							
Power	MW_{th}	1,7	3,3	5,0	1,7	3,3	5,0
Pnom	MW/sto	1,7	1,7	1,7	1,7	3,3	2,5
Q nom/sto	m3/sto	29,6	29,6	29,6	15,6	31,1	23,4
Average Power	MWh/sto	1,67	1,67	1,67	1,67	3,33	2,50
Nominal Storage flowrate	mm/s/ Sto	1,00	1,00	1,00	1,00	1,00	1,00
Average Storage flowrate	mm/s	1,00	1,00	1,00	1,00	1,00	1,00
Usefull volume	%	94,6%	94,6%	94,6%	95,6%	94,6%	95,1%
Maximum flowrate in one TES	m3/h	59,3	118,5	177,8	31,1	62,3	93,4
Maximum power for one TES	MW	3,3	6,7	10,0	3,3	6,7	10,0
Number of storages	-	1	2	3	1	1	2
Øcuve	m	3,25	3,25	3,25	2,35	3,33	2,88
Htotal	**m**	**15,6**	**15,6**	**15,6**	**15,3**	**15,8**	**15,6**
Thickness of storage	**mm**	**4,0**	**4,0**	**4,0**	**13,0**	**18,0**	**16,0**
Mass	**tons**	**5,7**	**11,4**	**17,1**	**11,7**	**22,6**	**34,8**
Energy density	**kWh/m3**	**43,4**	**43,4**	**43,4**	**83,4**	**81,5**	**82,4**
STORAGE BUDGET PRICE		79 800 €	159 600 €	239 400 €	175 500 €	339 000 €	522 000 €

VNI studied the advantages and disadvantages of both configurations, and preferred the sub case 2.3 with a pressurised storage, due to operation, control, budget and planning reasons. The analysis of the energy density regarding storage capacity shows that for the previous hypotheses (in particular a charging/discharging time of 3 hours), the optimum storage is the 10 MWh_{th} one (Figure 56). This is explained by the fact that fulfilling 15 MWh_{th} storage capacity implies the adding of another storage volume and some additional cost.

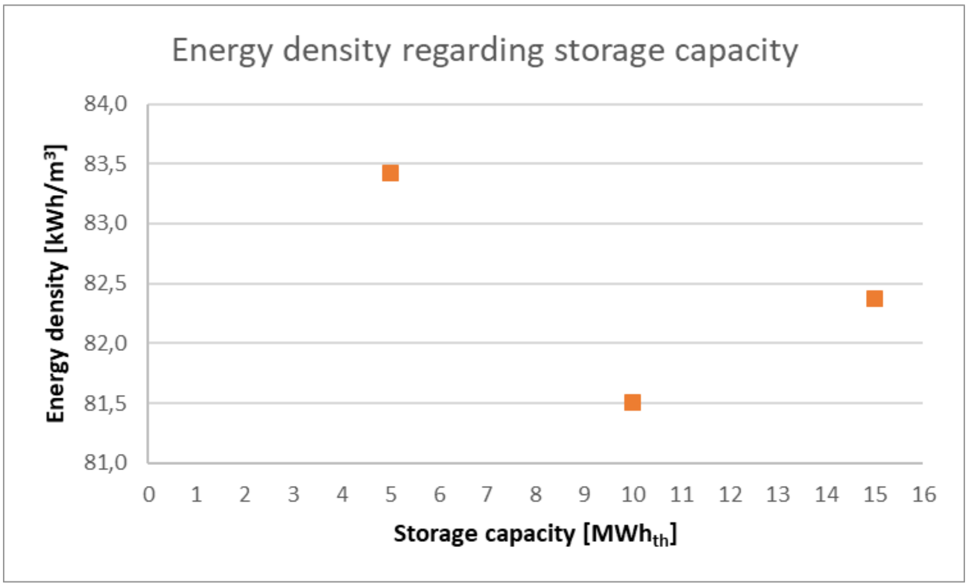


Figure 56: Energy density regarding storage capacity

Figure 57 presents the latest PFD of the Insheim site with the implementation of the storage system. The orange circuit represents the brine open circuit between the production well and the injection well. Heat is exchanged between the brine circuit and the industrial water closed loop (blue circuit) thanks to a heat exchanger with a total nominal power of 28 MW. This secondary water circuit delivers heat to the ORC (green circuit of isopentane), and to the district heating network (brown circuit). The TES is implemented on the secondary water cycle.

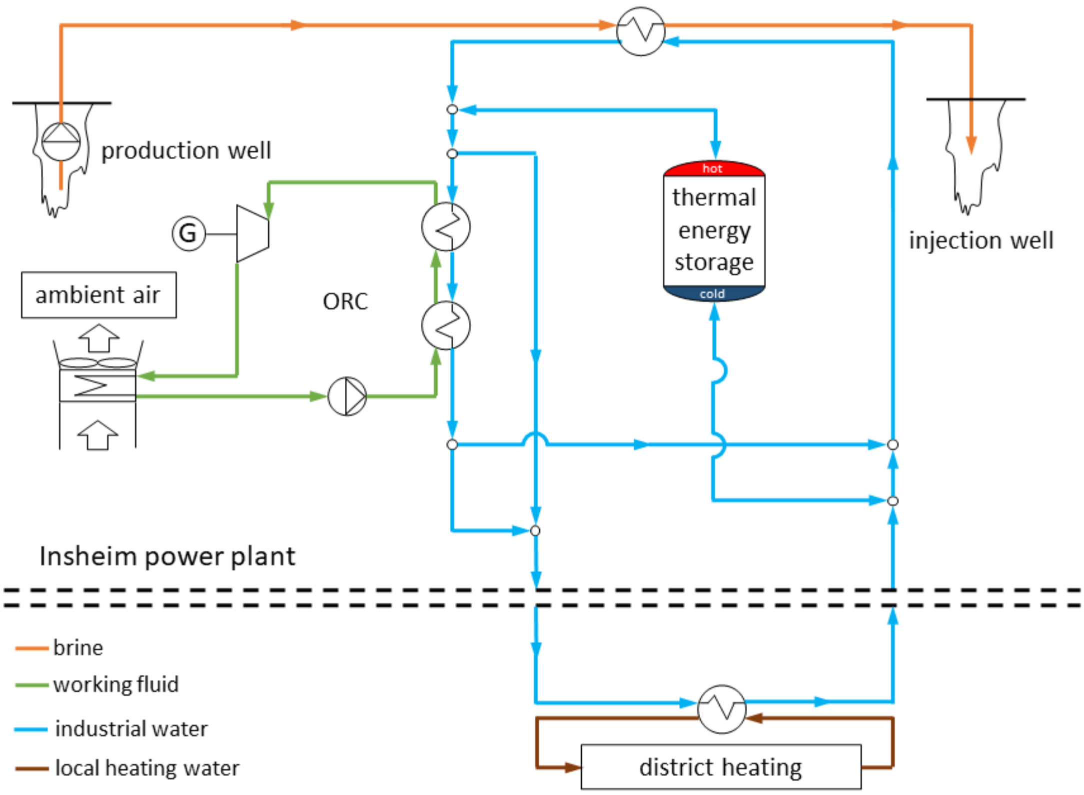


Figure 57. Simplified PFD of the Insheim site with the implementation of the TES system

VNI has little information on typical needs of district heating over one year. We make the hypothesis that the evolution of needs of the district heating, hour by hour, is similar to the Balmatt district heating, taking into account a reduction factor (Figure 58).

CEA and Naldeo proposed several possible objectives for the TES. Some of the objectives depend on the district heating needs. For example, if the power DH need is higher than the geothermal capacity (24 MW), the TES can be used to supply the DH need. Otherwise, if the power DH need is intermediate, between 17 MW and 24 MW, the TES can also be used to reduce the ORC downtime that occurs when the ORC power is below 30% of its nominal value. For low thermal energy needs, these two objectives are not relevant.

The maximum power of 8 MW corresponds to the first row of the Table 16, which corresponds to a low need of the district heating.

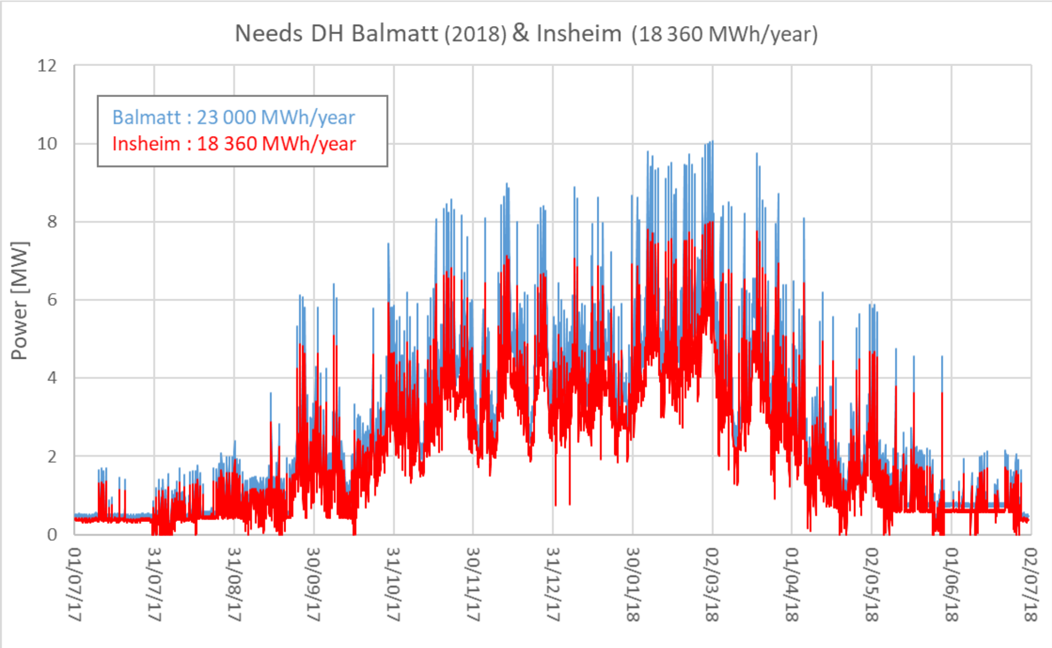


Figure 58. District heating needs (in red with a maximal value of 8 MW), extrapolation from Balmatt district Heating needs (in blue).

Table 16. Possible objectives of the TES on Insheim site

Needs (DH)		Possible objectives for the TES				
		reduce the variation of thermal power for ORC	reduce the ORC downtime	fulfill the needs	more power for the ORC when the outside T is low	redundancy when shutdowns
quite low	< 17 MW	X	-	-	x	x
intermediate	17 MW < … < 24 MW	X	X	-	x	x
high	> 24 MW	X	X	X	x	x

Therefore, for the Insheim site, the possible objectives of the TES are:

- Reduce the variation of thermal power for the ORC
- More power for the ORC when the outside temperature is low
- Redundancy during well shutdowns

5.1.1 TES objective: reduction of the ORC power variation

Without storage, the variation of DH need immediately results in a similar power variation for the ORC. Figure 59 shows the distribution of power variation from hour to hour for the DH needs. Therefore, the TES can be used to reduce the variation of thermal power supplied for the ORC.

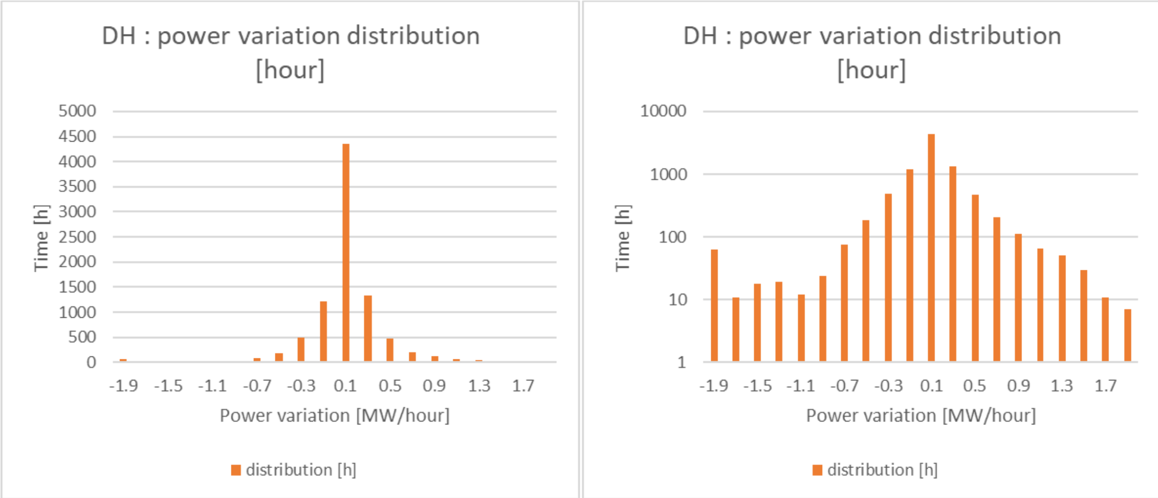


Figure 59. District heating power variation distribution (log scale on the right)

A CEA in-house software, PERSEE, was used to estimate the impact of the TES on the ORC power variation. This software determines the power output of the system for a whole year assuming real production (geothermal energy), DH needs (Figure 60), and ORC efficiency depending on the outside temperature using a MILP method. In this global approach, the TES is defined by a capacity and a maximal power of charge and discharge. PERSEE finds on an hourly basis the solution that maximizes the ORC production once the DH need is covered and that minimizes the ORC power variation.

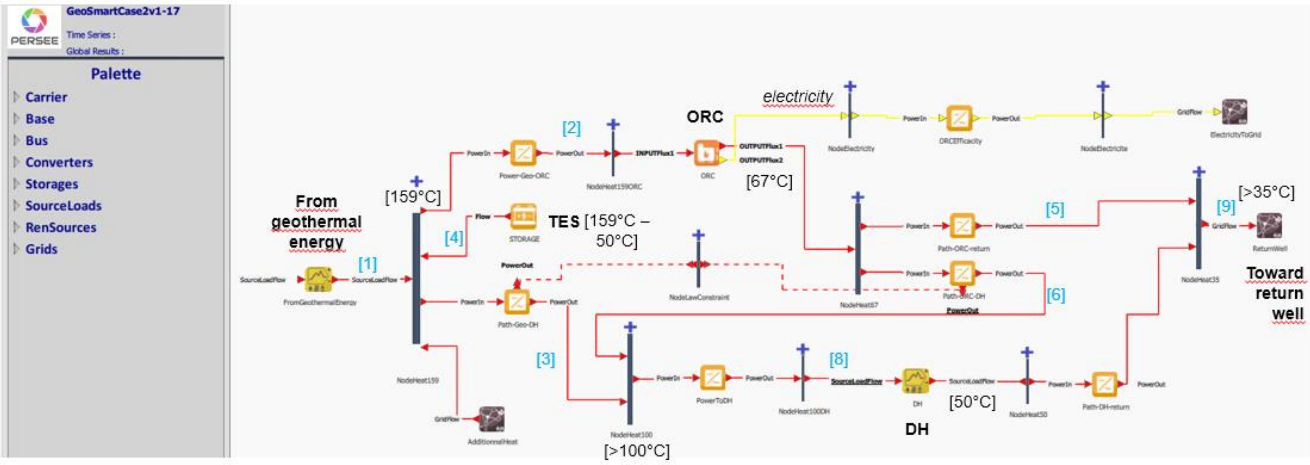


Figure 60. PERSEE representation, in a power point of view, of the Insheim geothermal site with TES district heating.

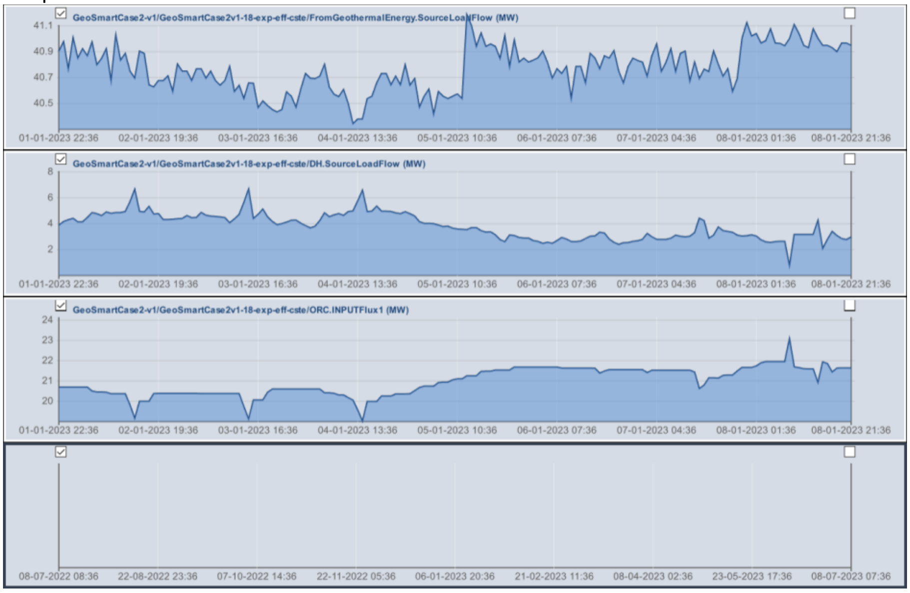


Figure 61. Example of geothermal power (top), DH need (middle top) and ORC power (middle bottom) for a week in winter without TES (bottom).

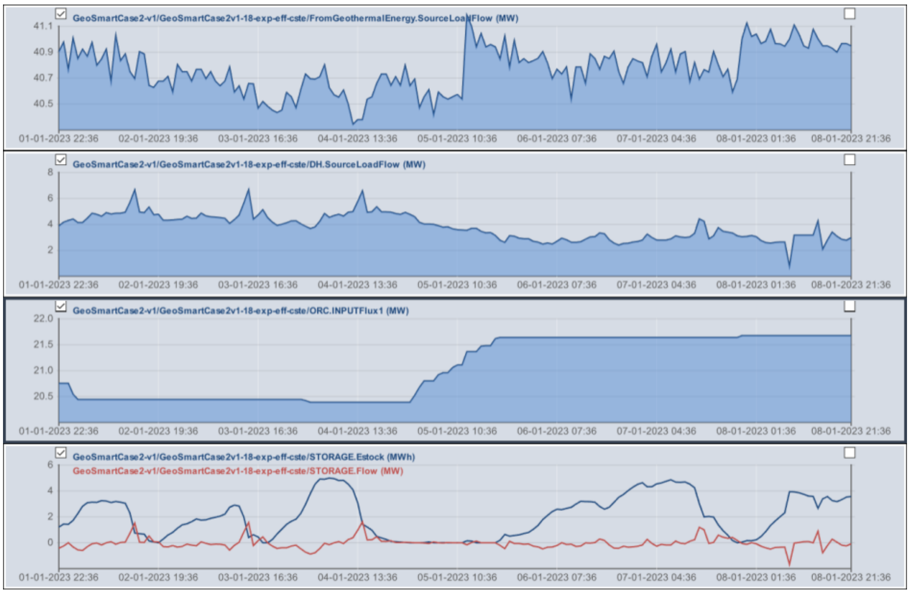


Figure 62. Example of geothermal power (top), DH need (middle) and ORC power (middle bottom) for a week in winter with a 5 MWh TES (bottom: TES energy in blue and TES power in red).

Without TES, the ORC power variations are the direct consequences of the DH need variation (Figure 61). With TES (for example 5 MWh in Figure 62), the variations of ORC power are well limited.

Considering the variations of ORC power higher than 0.2 MW from one hour to another, for example, the number of variation hours is around 700 hours, and it decreases to 155 hours with a TES of 5 MWh and less than 100 for a TES of 10 MWh (Figure 63). Consequently, the TES can be used to reduce the ORC output power variations.

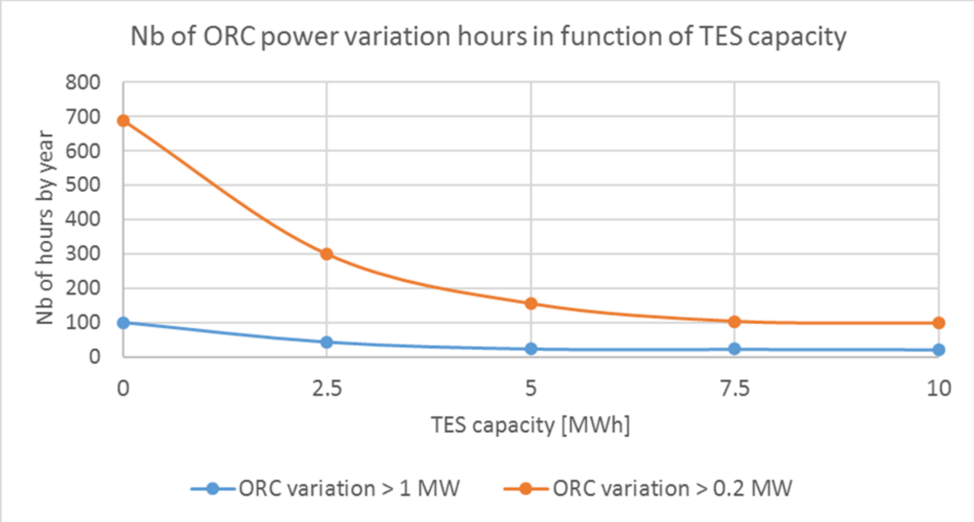


Figure 63. ORC power variations versus the TES capacity

Consequently, the TES can well reduce the ORC power variations.

5.1.2 TES objective: increase the ORC production

In addition, the TES can be used to increase the ORC electricity production by supplying heat to the ORC when its efficiency is higher, (i.e. when the outside temperature is low). The same software (PERSEE) was used to evaluate the interest of using the TES to increase the ORC production.

The electricity production of the ORC increases by increasing the TES capacity: it increases by 25 MWh with a TES capacity of 10 MWh for example (Figure 64). However, the interest remains negligible compared to the yearly production (20 000 MWh).

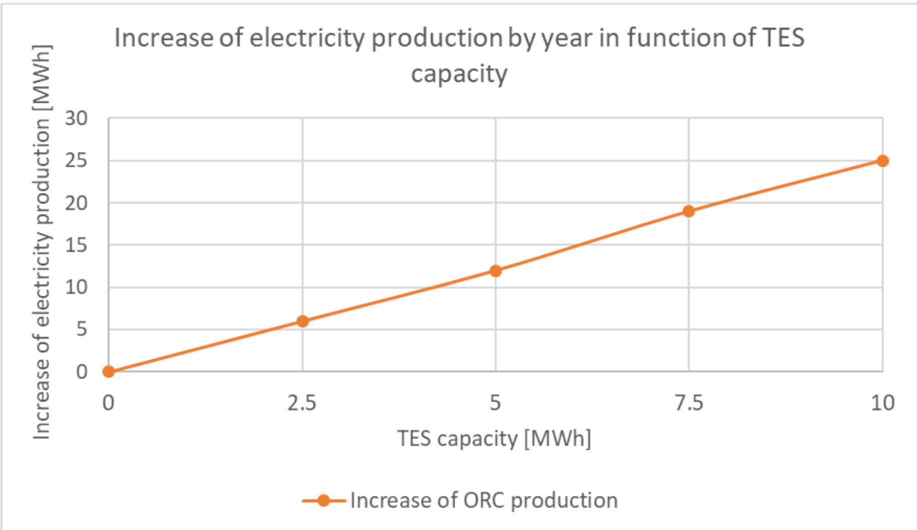


Figure 64. Increase of the ORC's electricity production per year versus the TES capacity

5.1.3 TES objective: redundancy during geothermal plant shutdowns

In case of a failure of the geothermal fluid pump, the heat supply for the district heating network may not be covered. Thus, it is important to consider the objective of redundancy for the supply of the district heating system. It seems reasonable to assume that a high demand (> 6 MWth) may not coincide with a failure of the geothermal fluid pump. Thus, it is suggested that covering a peak heat demand of 6000 kWth can be assumed, which needs to be covered with the thermal energy storage. The heat demand can be provided for about 100 minutes if a storage size of 10 MWh is assumed. In order to supply the heat demand at 100°C, the stored industrial water (160 °C, 44 m^3/h) will be mixed with water from the back flow (45 °C in winter as a conservative estimate, 50 m^3/h), the total flow rate being 94 m^3/h. In this context, it is important to consider the maximum speed of discharge because the discharging time (< 2 hours) is shorter than the design one (3 hours) of Table 16. For 44 m^3/h, the velocity is 1.5 mm/s, below the safe limit of 2 mm/s. The ORC will not be operated in such a scenario to allow the maximum heat supply for the district heating system.

It is important that the TES may not cover the heat supply during the maintenance, where the plant is shut down. This maintenance will always be planned and therefore, alternative heat supply can be provided during that time in advance. However, the TES may still be used during unexpected plant shutdowns, which will be tested during operation.

A large TES will most likely increase the economic efficiency during day-night-operation and for smoothing electricity production to a small extent, which is shown in Figure 65. Since the cost for the installation of a larger storage will increase, a storage capacity of 10 MWh is preferred by VNI.

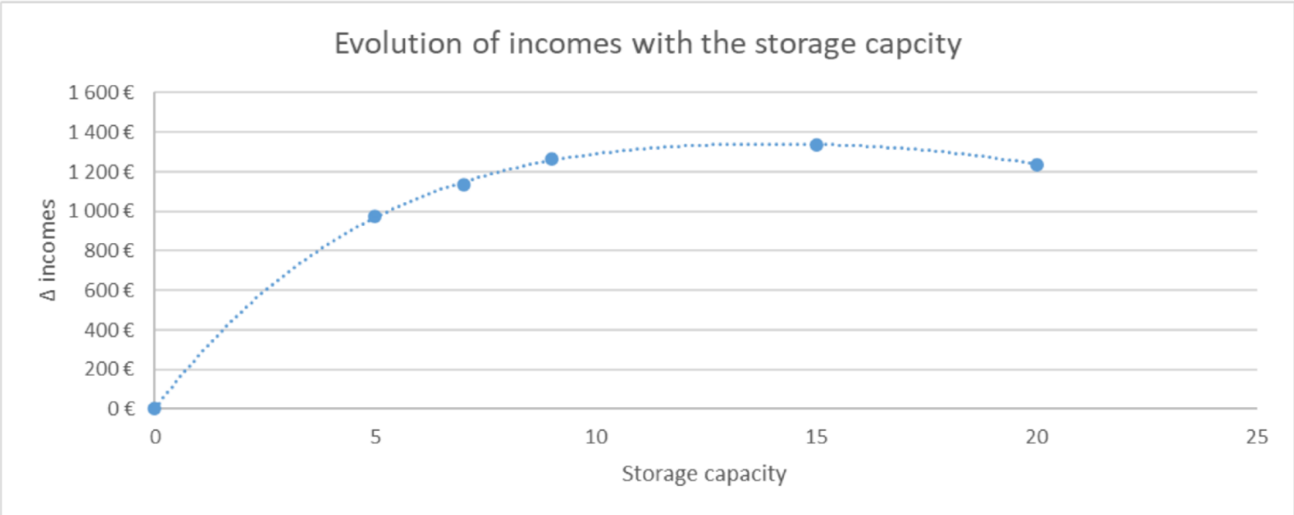


Figure 65. Evolution of the income with increasing storage size/capacity in MWh (from NALDEO).

5.2 Conclusion

Insheim site entered the project in 2021 after the suspension, to replace the Balmatt site. The site is located at Insheim in Southern Palatinate, Germany. The brine feeds directly an ORC with an installed nominal electrical capacity of 4.8 MWe. The commercial strategy at VNI has evolved recently. The heat from the geothermal well will be used to supply the district heating network and the excess energy will be used to produce electricity via an ORC. For this new commercial strategy, the project partners proposed two main solutions for the storage unit, either an atmospheric thermocline storage close to the district heating network or a pressurised thermocline storage on the geothermal plant site. They proposed the related PFD of the TES connected to the Insheim circuits.

Naldeo evaluated the cost of the 2 solutions for an energy range of 5 to 15 MWh and showed that the optimum was close to 10 MWh for the pressurised version.

VNI selected in the end the pressurised technology according to various criteria, in particular a criteria of delay (easier to install the storage on their site) and a criteria of flexibility between heat supply and electricity production.

The partners have identified 3 main objectives for the TES:

– Reduce the variations of thermal power for the ORC due to the district heating variable demands

- Produce more power for the ORC when the outside temperature is low
- Assure a safe redundancy for the district heating during geothermal well shutdowns

CEA has evaluated the impact of the TES for an energy range of 2.5 to 10 MWh. A 10 MWh TES will reduce drastically the variations of thermal power going to the ORC, will have a very small effect on the ORC production and will compensate shutdowns. Therefore, the objectives n°1 and n°3 will be tested in priority on the Insheim site.

The final pre-design of the TES for Insheim site is:

- Pressurised water thermocline
- Design pressure: 10 barg
- Nominal charging temperature: 160°C
- Nominal discharging temperature: 45°C
- Energy content: 10 MWh
- Charging / discharging time: 2 to 4 hours
- Diameter: 3,33 m
- Total Height: 15,8 m

6. STATE OF CHARGE (SOC) DETERMINATION METHODOLOGY

This paragraph aims to briefly explain a methodology to determine the SoC of the storage modules on Kızıldere 2 and Insheim sites. This is a key issue for optimal management of TES systems.

The SoC cannot be measured directly, but it can be estimated from variables measurements. One of the methodologies is to instrument the TES system with temperature sensors, at the inlet, the outlet, and at different levels (axially and radially) inside the module.

From the temperature sensors information, the energy of the TES systems can be calculated, which allows the determination of the SoC.

The results of the experimental work at the demonstration sites will be analysed, in order to determine the optimal number and position of the temperature sensors that allow determining accurately the SoC.

This methodology will be investigated in the WP6 and WP7, experimentally after the commissioning of the storage modules.

7. CONCLUSIONS

WP2 aims at doing the pre-design of the heat storage demonstrators that will be detailed designed, manufactured, installed and tested in respectively WP6 (Balmatt site at the beginning of the project, Insheim site after) and WP7 (Kizildere 1 site at the beginning of the project, Kizildere 2 site later). WP2 includes several Tasks such as the screening of suitable storage materials and alloys (Task 2.1), the development of design models (Task 2.3), the manufacture and test of the storage modules at small scale (Task 2.4) and the study of the pre-installation on site (Task 2.5 and 2.6). Task 2.2 called “Design of thermal energy storage system” is the main task and is detailed in this deliverable D2.2. The objective is to select the best technology for the geothermal sites, to find the best way to install it on site and determine by the same way the operating conditions and limitations, and to size it in order to achieve specific energetic and economic objectives. The three technologies that are envisaged are a pressurised thermocline, a steam accumulator or a Phase Change Material module. The objectives are to implement one demonstrator on the first site (Balmatt and Insheim) and two demonstrators on the second site (Kizildere 1 and Kizildere 2).

This Task has suffered several delays and extra non-scheduled activities, mainly because of the transfer of the demonstration activities on other sites. The pre-design started before the project suspension for the Balmatt and Kizildere 1 sites and ended after the suspension for the Insheim and Kizildere 2 sites.

The following WP objectives that have been met are:

For Balmatt site (Belgium, owner VITO):

- Implementation of the storage system on the Balmatt site
- Predesign of the pressurized thermocline storage system
- Sensitivity analysis concerning the extension of the District Heating demand and the addition of an ORC
- Interest of the storage system in case of a restart at lower flowrate and power

These studies were conducted during the first period of the project, until the decision of not restarting the Balmatt site and transferring the activity to Insheim site in Germany after the project suspension.

For the Kizildere 1 site (Turkey, owner Zorlu):

- Implementation of the heat storage modules on Kizildere 1 site including some modifications of the site
- Predesign of the steam accumulator
- Strategies to mitigate the effect of CO_2 on the steam accumulator
- Predesign of the PCM module

These studies were conducted during the first period of the project, until the decision of transferring the activity from Kizildere 1 to Kizildere 2 (same owner Zorlu) after the project suspension.

For the Kizildere 2 site (Turkey, owner Zorlu):

- Implementation of the heat storage modules on Kizildere 2 site including some modifications of the site (new IP separator)
- Predesign of the steam accumulator
- Strategies to mitigate the effect of CO_2 on the steam accumulator
- Predesign of the PCM module with 2 PCM (adipic acid and HITEC salt) with hydraulic inserts
- Predesign of the PCM module (HITEC salt) without hydraulic inserts but addition of aluminium profiles
- Choice of the PCM module installation on the site, after the HP separator is preferred to after the new IP separator
- Procedures to clean the PCM module and selection of the 5th one (more mature and less expensive)
- Energetic impact of the rinsing step of this cleaning procedure evaluated and mitigated by rinsing with hot water from the steam accumulator

These studies were conducted after the suspension that lasted from June 2020 to February 2021 and were achieved end of January 2022.

For the Insheim site (Germany, owner VNI):

- Objectives for the TES for the new Insheim site configuration connected to the DH network
- Implementation of the storage system on the Insheim site
- Predesign of the pressurized thermocline storage system

These studies were conducted after the suspension that lasted from June 2020 to February 2021 and were achieved end of July 2022.

A SoC determination methodology was proposed in Task 2.2, and will be investigated in WP6 and WP7.

REFERENCES

[1] M.Martinelli, « Stockage d'énergie thermique par changement de phase – Application aux réseaux de chaleur ». Decembre 5 2016.