STORY

added value of STORage in distribution sYstems

Deliverable 5.8
Report Chapter on Private Multi-energy Grid in Belgium

Revision 1.2
Preparation date .. 2020-07-07 (M62)
Due date 2020-04-30 (M60)
Lead contractor .... BEN
Dissemination level PU

Authors:
Al Koussa Jad ...... VITO
Jan Diriken .... VITO
Ana Gonçalves Soares. VITO
Carlo Manna .... VITO
Jef Verbeeck .... VITO
Johan Van Bael ... VITO

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646426

Project STORY - H2020-LCE-2014-3

Table of contents

Disclaimer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646426

1 Publishable executive summary

The European project STORY demonstrates and evaluates innovative approaches for energy storage systems in the residential and industrial sectors. The overall objective of STORY is to show the benefit storage can bring for a flexible, secure and sustainable energy system. The project specifically focuses on the added value of energy storage in distribution systems.

Being a cheap alternative to electrical storage, thermal energy storage provides an important tool to decouple heat production and demand and thus enhance the flexibility of an energy system. This is particularly valid when a Combined Heat and Power (CHP) unit is present in the energy system. Without thermal storage, the operation of a CHP is usually driven by the heat demand and the produced electricity can be considered as a by-product. The inclusion of thermal energy storage is crucial to unlock the flexibility of the system and allow for smart control to achieve certain goals. As an example, the electricity consumption can be increased during periods when electricity prices are high to gain an economic benefit.

At the private multi-energy grid in Belgium, a wood joinery has decided to use a combination of a waste wood boiler, an ORC (Organic Ranking Cycle, CHP unit) and two storage vessels to maximize the self-sufficiency in heat and electrical energy using the locally available waste wood.

Monitoring and methods developed has shown that accurate knowledge of the State-Of-Charge (SOC) of the storage vessels during operation allows the control system to better optimize the control actions. This control can be optimized to for instance reduce operational cost and /or increase self-sufficiency: by knowing the SOC of the storage vessels, the control can know how much heat to produce at night and stored in the vessels to be used the next day. Also, by continuously monitoring the SOC, the control can forecast when the vessels should be loaded, or electrical production prioritized to avoid loss of comfort to the users.

The major lesson learned in this demonstrator is that when a combination of technologies is considered, good knowledge of the different systems and their limits is crucial. This can be done by for example having a "technology integrator/aggregator" that can integrate the different components together and setup clear responsibilities regarding any issues that may arise during operation. Also, it is important to develop a control system that considers the limits of the different components to guarantee the safety of operation and to avoid costly technical problems and long downtimes.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646426

Project STORY - H2020-LCE-2014-3

2 Private multi-energy grid

2.1.1 Introduction

In this chapter the different technologies installed at the multi-energy grid and the full system design are presented and the results of the monitoring are shown. Moreover, some further info is given regarding the state of charge determination methodology and its usefulness and accuracy. Lessons learned are conclusions are also given at the end.

2.1.2 Objectives

The objective of the multi-energy grid is to show the added value of thermal energy storage on the flexibility of a Combine Heat and Power installation such as an Organic Rankine Cycle (ORC).
The demonstration further shows the integration of different types of technologies and the interoperability between the thermal and the electrical grid. More specifically, the multi-energy grid demonstrator aims at:

- Efficiency enhancement and active control of ORC through use of thermal storage.
- Quality of estimating state of charge of the thermal storage.
- Peak power demand.
- Potential optimization of thermal grid through double use in intervals (short term hot water (90°C), short term warm water (50°C) with use of local small scale storage at different end-consumers.

2.1.3 Partners engaged

BEN delivered the installation. VITO has advised on and selected the sensors required in the circuit and in both storage vessels. VITO has also suggested a control strategy to optimize the operation of the system. Data was stored at BEN premises as well as BASN. VITO monitors the data and calculates the Key Performance Indicators (KPIs) (as part of WP6).

2.1.4 Booklet chapter

The chapter is added as Annex 1.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646426

Project STORY - H2020-LCE-2014-3

3 Acronyms and terms

ORC	Organic Rankine cycle
CHP	Combined Heat and Power
LTSV	Low-Temperature Storage Vessel
HTSV	High-Temperature Storage Vessel
RTD	Resistance Temperature Detector
SOC	State-Of-Charge
PVT	Photovoltaic Thermal collectors

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646426

4 Appendices

Annex 1: Report chapter on private multi-energy grid in Belgium

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646426

Project STORY - H2020-LCE-2014-3

STORY

STORY D5.8 | June 2020

Report Chapter on Private Multi-Energy Grid in Belgium

System description, monitoring results and State of Charge determination

Authors: Jad Al Koussa (VITO), Jan Diriken (VITO), Ana Gonçalves Soares (VITO), Carlo Manna (VITO), Jef Verbeeck (VITO), Johan Van Bael (VITO)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646426
Project STORY – H2020-LCE-2014-3

Table of Contents

1 Introduction

Being a cheap alternative to electrical storage, thermal energy storage provides an important tool to decouple heat production and demand and thus enhance the flexibility of an energy system. This is particularly valid when a Combined Heat and Power (CHP) unit is present in the energy system. Without thermal storage, the operation of a CHP is usually driven by the heat demand and the produced electricity can be considered as a by-product. The inclusion of thermal energy storage is crucial to unlock the flexibility of the system and allow for smart control to achieve certain goals. As an example, the electricity consumption can be increased during periods when electricity prices are high to gain an economic benefit.
At the private multi-energy grid in Belgium, a wood joinery has decided to use a combination of a waste wood boiler, an ORC (Organic Ranking Cycle, CHP unit) and two storage vessels to maximize the self-sufficiency in heat and electrical energy using the locally available waste wood.

2 The concept

At the demonstration site in Olen, Belgium, a wood fired boiler of 1.6 MW_{th} was installed. The waste wood from the general contractor Beneens is the fuel for this boiler. In case the amount of wood is insufficient to fulfill the heat demand, waste wood from other companies is also used. The high-temperature heat produced by this boiler is used in two ways: on the one hand to produce electricity using an ORC boiler, while valorizing the low-temperature residual heat; and on the other hand, this high-temperature heat can be stored directly in a large storage vessel of 50 m^3 for further use. The low and high-temperature heat is used for space heating (offices and the workshop) and industrial processes in the painting rooms, whereas the electricity produced is either used directly on-site or stored in batteries for later use. Any electricity surplus is sold back to the grid. Moreover, excess low-temperature heat is stored in a second storage vessel of 20 m^3. The installation has been operational since June 2016, monitoring of the thermal and electrical energy produced and consumed in the system has been taken place since September 2016.

3 The installation

In this section, a detailed description of the components of the installation is given in addition to a description of the system's operation.

3.1 Main components

3.1.1 Wood boiler

To produce the required heat, a wood boiler with a thermal power of 1.6 MW has been installed. Figure 1 shows a photo of the wood boiler (the red-grey installation on the left) next to the wood bunker where the waste wood is placed. The wood is transported to the boiler's burning chamber via a hydraulic feeding system. This wood boiler is one of the main components of the installation and its only thermal energy source.

Figure 1: The wood boiler (red and grey) installed in the technical room next to the wood bunker from which wood is fed to the boiler via a hydraulic feeding system.

Table 1 summarizes the technical specifications of this boiler.

Table 1: Technical specifications of the wood boiler.

Power [kW]	1600
Supply temperature [℃]	145
Return temperature	≤ 20 ℃ ΔT

3.1.2 Organic Rankine Cycle

An Organic Rankine Cycle (ORC) system allows the generation of electrical power using low heat-source temperature. This system involves the same components and principle as in a conventional steam power plant (boiler, work-producing expansion device, condenser and circulation pump). However, the working fluid is an organic component characterized by a lower boiling temperature than water. In addition to its application to low-temperature heat sources, another advantage of the ORC is that it can be used for local and small-scale power generation. Figure 2 depicts the working principle of an ORC: (1) the organic working fluid is evaporated in the evaporator using the (low-temperature) heat source; (2) then the vapor passes through the expander where electricity is produced via a generator; (3) after that, the low pressure vapor is then condensed in the condenser; (4) finally, the condensed vapor is pressurized using a pump and the cycle is then repeated.

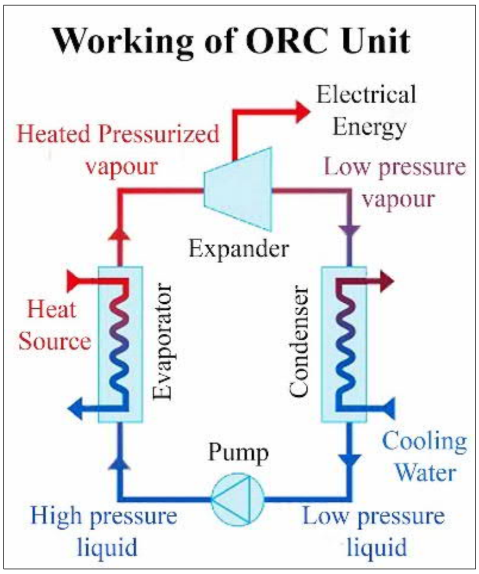

Figure 2 Working principle of an ORC unit [1].

To maximize the efficiency of an ORC installation, the cooling water for the condenser can be used for applications with low-temperature heat demand such as low temperature space heating. At the demonstration site, an ORC with a maximum thermal power input of 1 MW_{th} has been placed to produce a gross electrical power of 110 kW_e. Figure 3 shows the ORC installed in the technical room next to the wood boiler and Table 2 provides some technical specifications of that ORC.

Figure 3: The ORC installation (white box with blue frame in the middle) placed in the technical room next to the wood boiler.

Table 2: Technical specifications of the Organic Rankine Cycle (ORC).

Generator type	Asynchronous,2 pole, 3-phase
Maximum heat input [kW_{th}]	1000
Generator power [kW_e]	110
gross efficiency [%]	11.1%
net electricity production (Summer/Winter) [kW_e]	75/84
Temperature heat input [℃]	80-150

3.1.3 Storage

At the demonstration site, two storage vessels are installed.

High-Temperature Storage Vessel (HTSV)

The HTSV used has a capacity of 50 m^3 and it is made of P265GH pressure vessel steel. It is designed to store water at a temperature of 90 ℃. To limit the thermal losses, the storage vessel is surrounded by 100 mm of insulating mineral wool followed by a 1 mm of aluminium plating. This vessel has a height of around 5.85 metres and a diameter of 3.5 meters as shown in the schematic in Figure 4. Due to the large size of this vessel, it has been installed in the technical room during the construction phase.

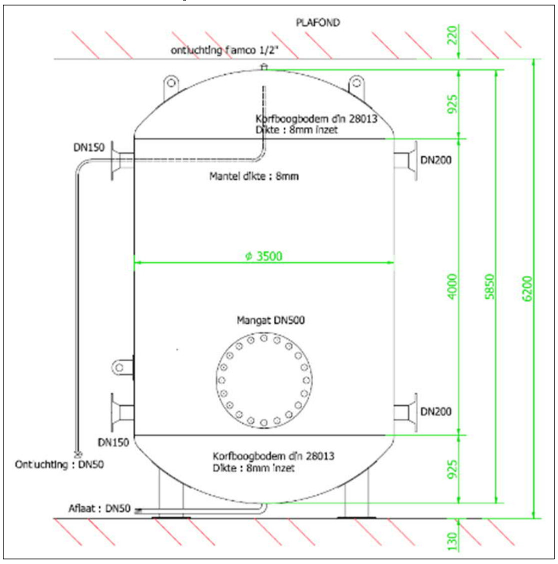

Figure 4: Schematic of the HTSV.

Figure 5 shows the storage vessel placed on its side on the truck used for its transportation and Figure 6 shows the vessel placed already in its dedicated location in the technical room during the construction phase, before installing the roof (insulation of the vessel was not present yet).

Figure 5: The HTSV placed on its side on the back of a truck for transportation.

Figure 6: The HTSV installed at its dedicated location in the technical room during construction phase.

Table 3 summarizes the technical properties of the HTSV.

Table 3: Technical properties of the HTSV.

Material	P265GH pressure vessel steel
Insulation material	100 mm, insulating mineral wool
Design storage temperature [℃]	90
Height [m]	5.85
Diameter [m]	3.5

Low-Temperature Storage Vessel (LTSV)

The LTSV has a capacity of 20 m^3 and it is made of P265GH pressure vessel steel. It is designed for water at a temperature of 45 ℃. To limit the thermal losses, it is surrounded by 100 mm of insulating mineral wool followed by 1 mm of aluminium plating. A photo of the LTSV is shown in Figure 7.

Figure 7: A photo of the LTSV (right hand side).

Table 4 summarizes the technical properties of the LTSV.

Table 4: Technical properties of the LTSV.

Material	P265GH pressure vessel steel
Insulation material	100 mm, insulating mineral wool
Design storage temperature [℃]	45
Height [m]	3
Diameter [m]	2.9

3.1.4 Dry Cooler

To cool away surplus heat produced by the boiler, a dry cooler with an adiabatic pre-cooler is placed on the roof of the technical room, as shown in Figure 8 (the blue rectangular shape), and connected to the secondary side of the ORC. It is designed to cool away 900 kW of thermal power at an inlet temperature of 44 ℃ and a flow of 23.4 L/s, for an outdoor dry bulb temperature of 31 ℃.

Figure 8: A photo of the technical room with the dry cooler placed on the roof (the blue rectangular shape).

The technical specifications of this dry cooler are summarized in Table 5.

Table 5: Technical specifications of the dry cooler.

Cooling power [kW]	900
Design inlet temperature [℃]	44
Design liquid flow [L/s]	23.4
Design dry bulb temperature [℃]	31

3.2 System description

As the main components were introduced in the previous section, the interconnection between them and the full system setup at the demonstration site is described in this section.

Figure 9 illustrates the system's architecture. Waste wood is transported from the wood bunker to the burning chamber of the boiler via a hydraulic conveyer system.

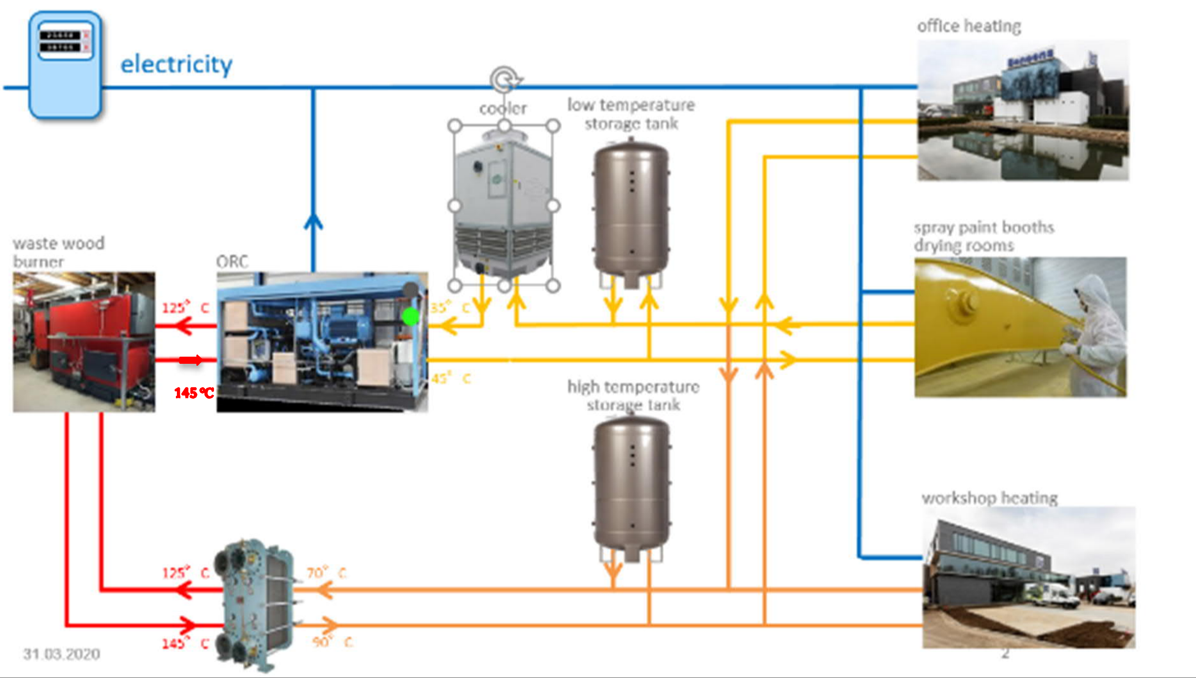

Figure 9: A representation of the system's architecture.

The high-temperature heat (1.6 MW at 145 ℃) produced by this boiler is used in two ways: on the one hand to produce electricity using the ORC, and on the other hand, this high-temperature heat can be stored in the HTSV (50 m^3) at 90 ℃ for further use in the workshops or for office heating. The cooling circuit of the ORC (secondary side of the ORC) is used for low-temperature heating (45 ℃) of the new offices and for the drying and painting cabins.

The excess low-temperature heat is stored in the LTSV (20 m^3). In case also this vessel is completely charged, the dry cooler can be switched on to cool down this circuit and subsequently the ORC. Low temperature heat can be used to heat the new offices because they are well insulated compared to the old office building which requires higher temperature for space heating. A connection has been made between the high and the low temperature circuits to allow the high temperature circuit to provide the required heat in case the low temperature circuit's capacity is insufficient.

4 Monitoring

4.1 Monitoring process

To assess the performance of the system, the different energy streams must be monitored during operation. For this purpose, a combination of temperature sensors and thermal and electrical energy meters have been installed throughout the circuit. Figure 10 shows the hydraulic circuit with the location of the sensors: as shown, energy streams in and out of the components and to the heating circuits are monitored (thermal energy meters indicated by the letter C). Additionally, the temperature of the water stored in the storage vessels is monitored at different positions along their heights. This is done to evaluate the amount of heat that is stored in these storage units, which is important to employ the flexibility of the system.

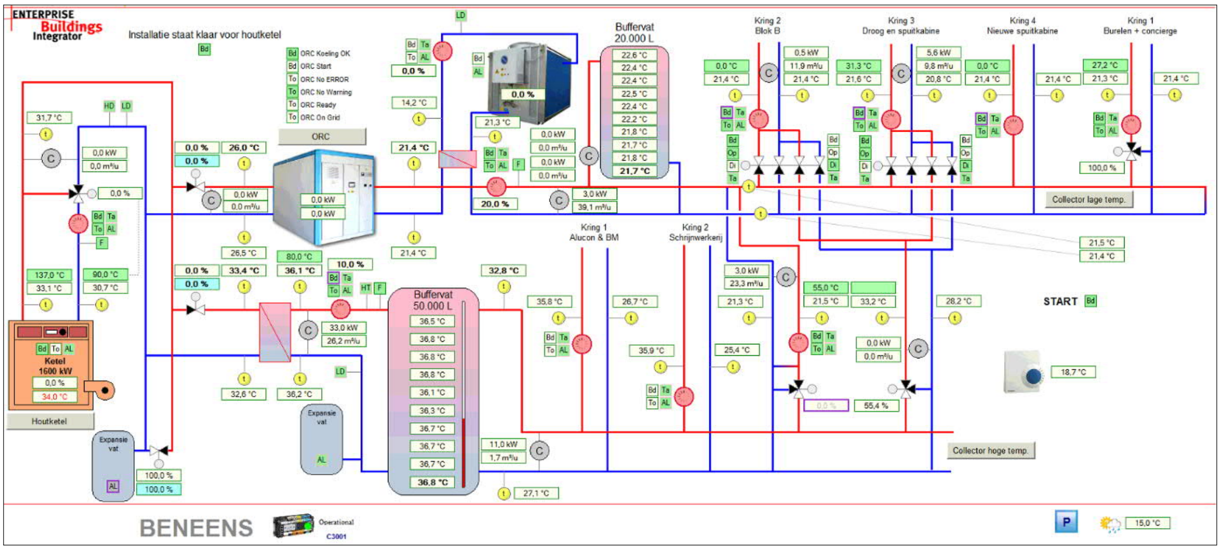

Figure 10: The hydraulic circuit and the location of the sensors throughout the system.

To monitor the thermal energy, around 63 temperature and energy sensors have been used. The flow has been monitored using the flow meters integrated in the thermal energy meters. The water temperature sensors used in the pipes or in the storage tanks are Resistance Temperature Detectors (RTDs), more specifically Pt100. Figure 11 shows a photo of the immersion Pt100's placed on different heights of the HTSV to monitor the water temperature in different layers. In Figure 7 the PT100's for the LTSV can be seen in addition to a number of temperature indicators.

Figure 11: Temperature sensors placed along the height of the HTSV.

In Figure 12, one of the thermal energy meters is shown (in the red circle) installed on one of the pipes. This energy meter typically has two temperature sensors and a flow meter allowing it to calculate different values such as power and energy.

Figure 12: A thermal energy meter placed on one of the pipes.

The parameters of the different sensors are logged in a database on a 6 minutes basis.

4.2 Monitoring results

The wood boiler has been operational since June 2016 and the installation has been monitored since September 2016. Figure 13 shows the energy produced by the wood boiler and the energy consumed by the ORC and the high temperature circuit, on a monthly basis, since the start of the monitoring until March 2020. From this figure the following can be noticed:

- Thermal energy produced and consumed at the demonstration site was considerably higher in 2016 and 2017 compared to 2018, 2019 and 2020.
- Thermal energy demands have a seasonal pattern, which is higher during winter and lower during summer.
- Electrical energy produced is a small fraction compared to the total thermal energy produced/consumed on the site.

To give a better view on how much of the energy was consumed by the high temperature circuit and how much by the ORC, Figure 14 can be examined. In that figure it is clear that the ORC was mainly operational in the years 2016 and 2017. In 2018, the ORC didn't consume any noticeable amount of thermal energy whereas it was partially operational in 2019 and 2020.

Regarding the heat consumption for the high-temperature circuit, the pattern was the same for the duration of the monitoring period: high consumption during winter and autumn and low consumption during spring and summer. It can be noticed that for the winter of 2019-2020 the amount of thermal energy demand was lower than the previous years, which can be

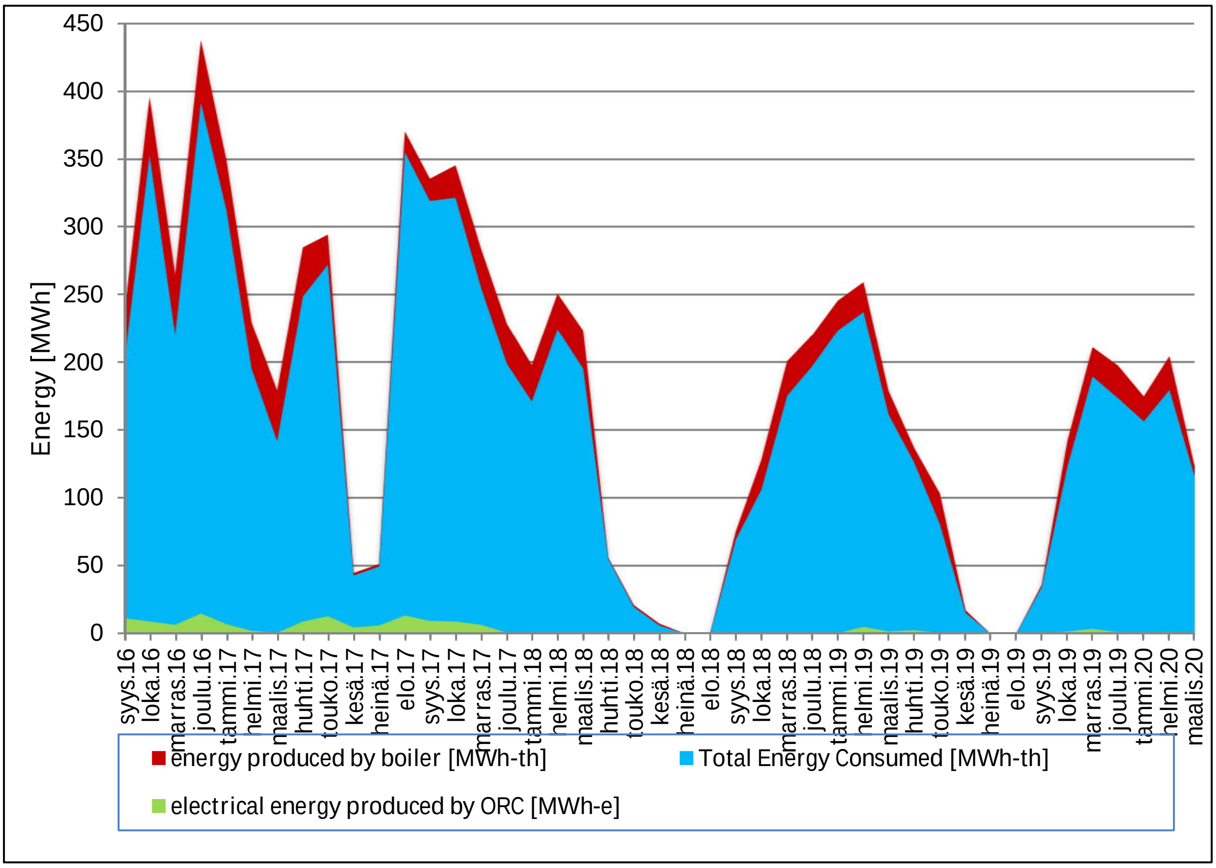

Figure 13: Energy produced by the boiler, total energy consumed by the high temperature circuit and the ORC, and the electricity produced by the ORC on a monthly basis during the monitoring period from September 2016 until March 2020.

attributed to the mild temperatures of that winter.

The decrease of operation of the ORC as well as of the boiler is attributed to a series of technical problems that occurred on both installations. Some of the control actions on the system were not convenient for the ORC and/or the boiler. So, some components had to be changed due to damage and others had to be adapted, which led to periods of downtime.

In addition, it can be noticed that the electrical production of the ORC is not always directly proportional to the amount of high-temperature energy consumed by the ORC. This occurs because the amount of electricity produced by the ORC depends not only on the inlet thermal energy, but also on the temperature of the inlet water (source) as well as the temperature of the cooling water: the smaller the difference between these temperatures, the lower is the electrical efficiency of the ORC and therefore the lower is the electricity produced. For example, if we compare August 2017 and December 2016, the electricity production is almost the same but the energy consumption of the ORC in August 2017 is much higher.

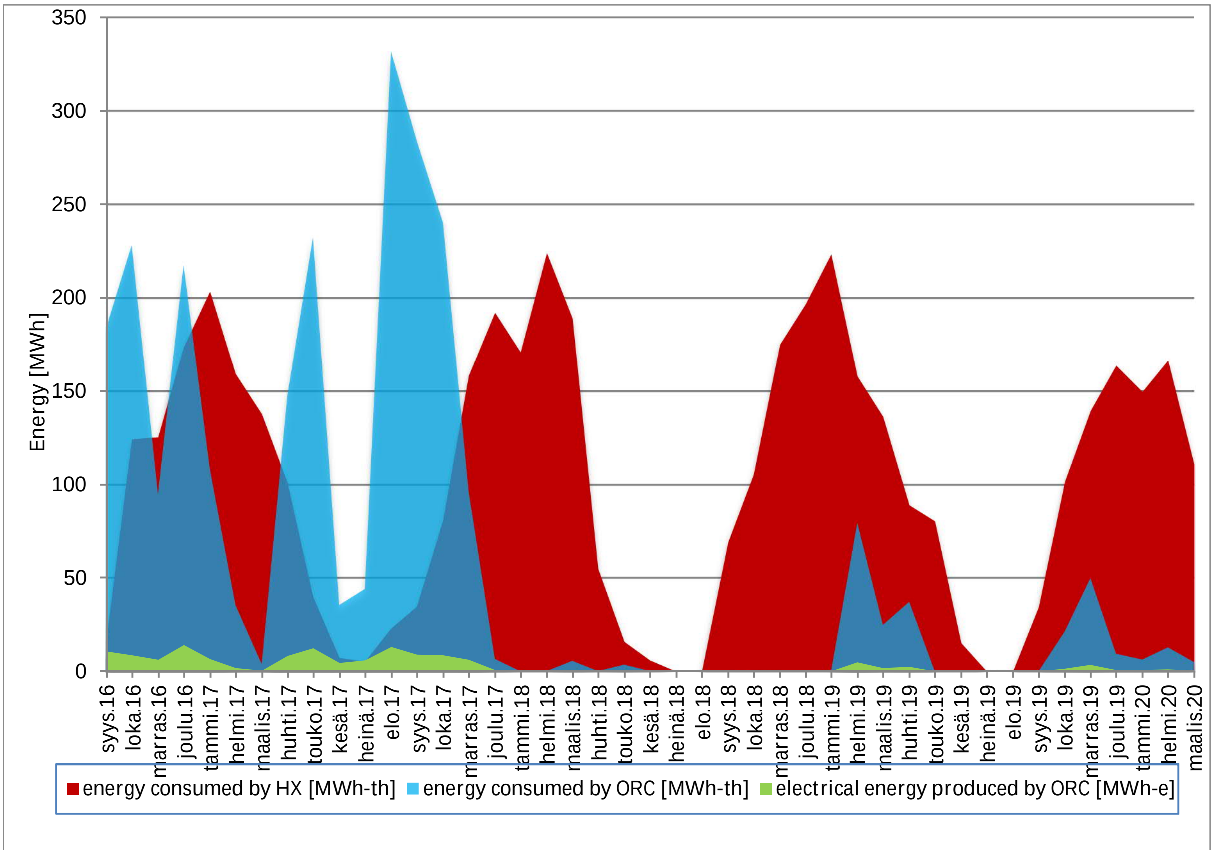

Figure 14: Energy consumed by the heat exchanger of the high temperature circuit (HX), total energy consumed by ORC circuit, and the electricity produced by the ORC on a monthly basis during the monitoring period from September 2016 until March 2020.

5 State-Of-Charge (SOC) Determination

Thermal Energy Storage (TES) alone is not enough to fully exploit the flexibility potential. Knowledge of the State-Of-Charge (SOC) of the TES, is necessary to perform intelligent control actions without affecting the user's comfort. Knowing the SOC at any given time is key to adequately design the suitable control strategies, namely when to charge and discharge the storage and how. The SOC is defined in the context of this report as an indicator giving information about the temperature stratification of the water inside the thermal storage under certain conditions which might change over time. Using this information, the amount of energy available in the TES can be deduced.

A classic example of a controller with a simple SOC estimation can be found in an electric boiler. These systems are typically equipped with a single temperature sensor that will activate the heating element if the temperature drops below a pre-defined set point. This can cause oscillations which can be solved by including hysteresis to limit the number of on/off cycles.
Within the H2020 STORY project, more sophisticated methods have been developed to provide quantitative SOC estimates. These are applied to the storage vessels in the multi-energy grid demonstrator.

5.1 Storage vessels monitoring and tests

In order to validate the SOC methods developed, experimental data for typical use cases of the storage vessels is needed. For this reason, multiple sensors have been placed on different heights of the storage vessel, as shown in Figure 15. Also, water temperature and flow on the inlets and outlets of the storage vessels are monitored.
The HTSV and the LTSV are characterized by direct charging and direct discharging: this means that the tank is charged and discharged by adding or removing hot water directly from/to it, so no heat exchanger is present inside the vessel.
Typical use cases of the storage vessels are charging, discharging, idling and simultaneous charging and discharging. Multiple of these use cases occurred during monitoring, which provides valuable data for the validation of the SOC determination. Figure 16 shows an example of charging the HTSV from 45 ℃ to around 80 ℃ during charging: the temperature of the different layers increases per layer sequentially from top to bottom (given that the storage vessel is charged from top).

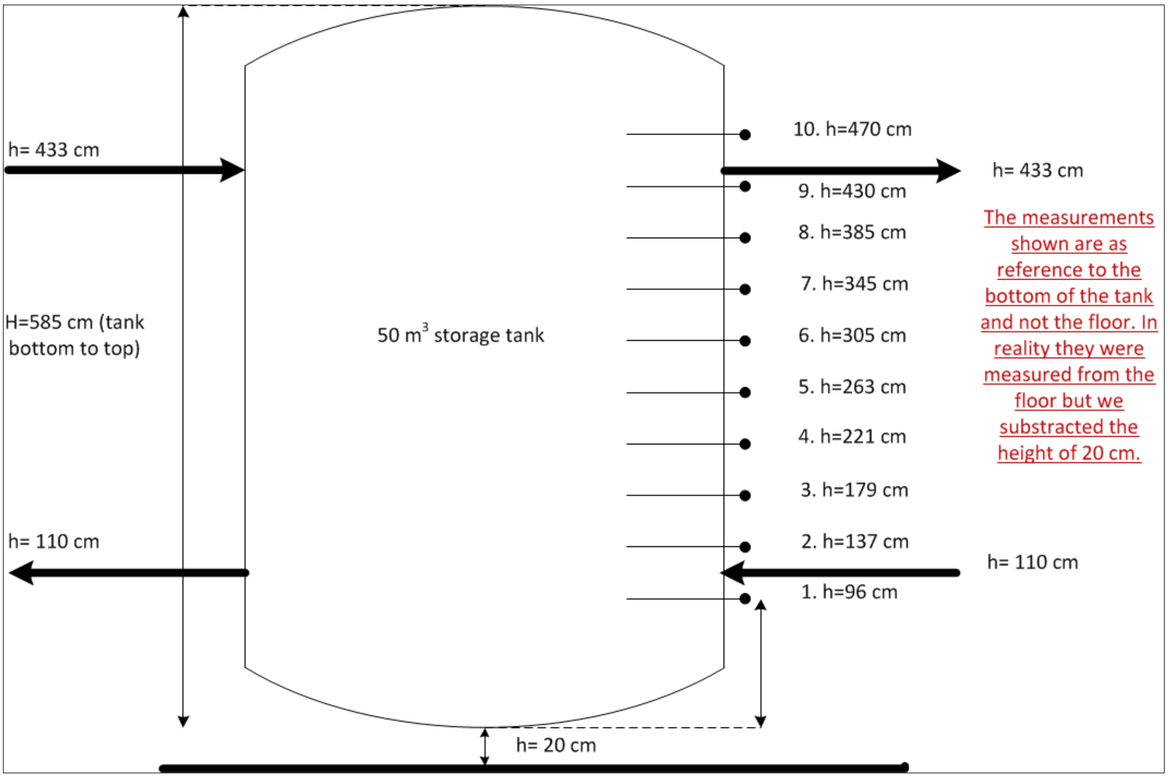

Figure 15 The location of the temperature sensors in the HTSV.

5.2 SOC determination method results

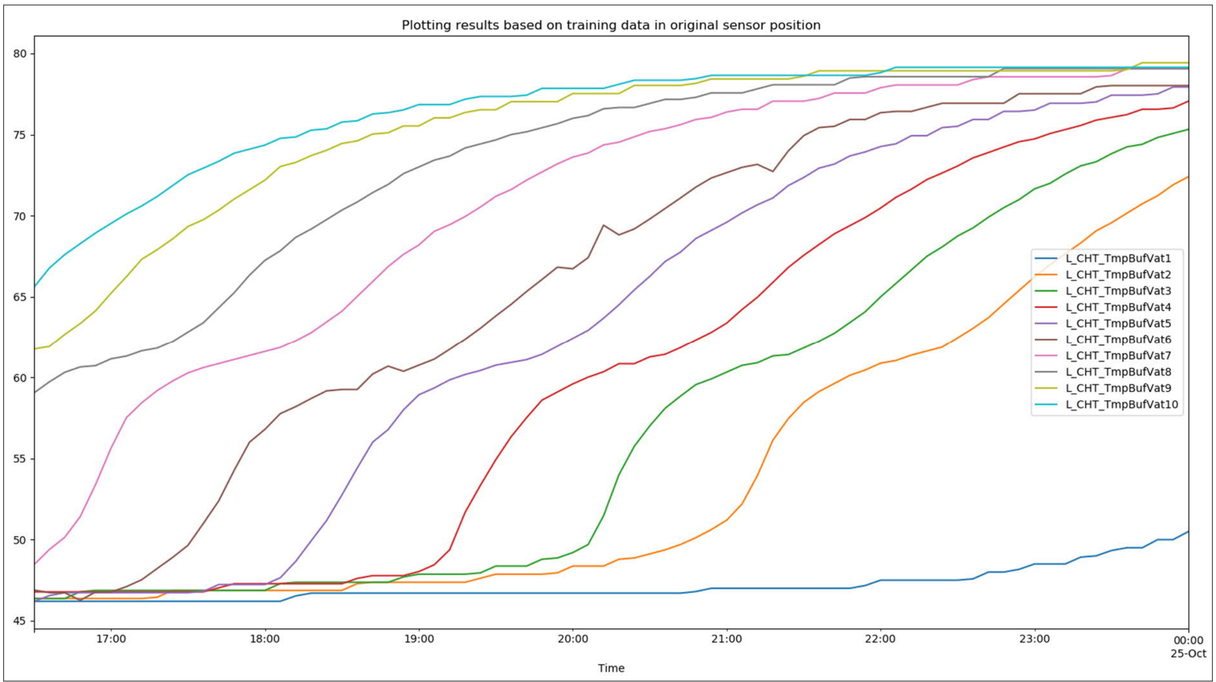

Figure 16: The temperature in the HTSV during a charging cycle.

The thermal behaviour of the storage vessels can be modelled starting from basic physical principles such as conservation of mass, momentum and energy. Turbulent flow present at the inlet and outlet ports, and the mixing of water at different temperatures are very complex phenomena. Fortunately, these are transient phenomena, and natural convection will eventually dominate these effects, displacing warmer and less dense water to the top of the tank and sinking of the colder water to the bottom.

This natural process of thermal stratification is desirable for a hot water storage vessel, as stratified vessels offer more usable energy (exergy) than a fully-mixed vessel containing water at the average temperature. Minimizing the mixing of water and reducing the turbulent flow from charging and discharging is one of the design considerations of state-of-the-art storage vessels.

The SOC determination methods were developed and applied to the HTSV for charging and discharging cases. Figure 17 and Figure 17 show the temperature estimated by the model at different heights of the HTSV and the corresponding measurements how accurately the model can predict the temperature at different heights during the two cycles respectively (simulations: dotted lines; measurements: continuous lines), for a given inlet water temperature and flow.

As shown, simulation corresponds well with the temperatures measured at different heights inside the storage vessel. Some deviations occur mainly for the sensors present near the top or the bottom, which is close to the inlets and outlets.

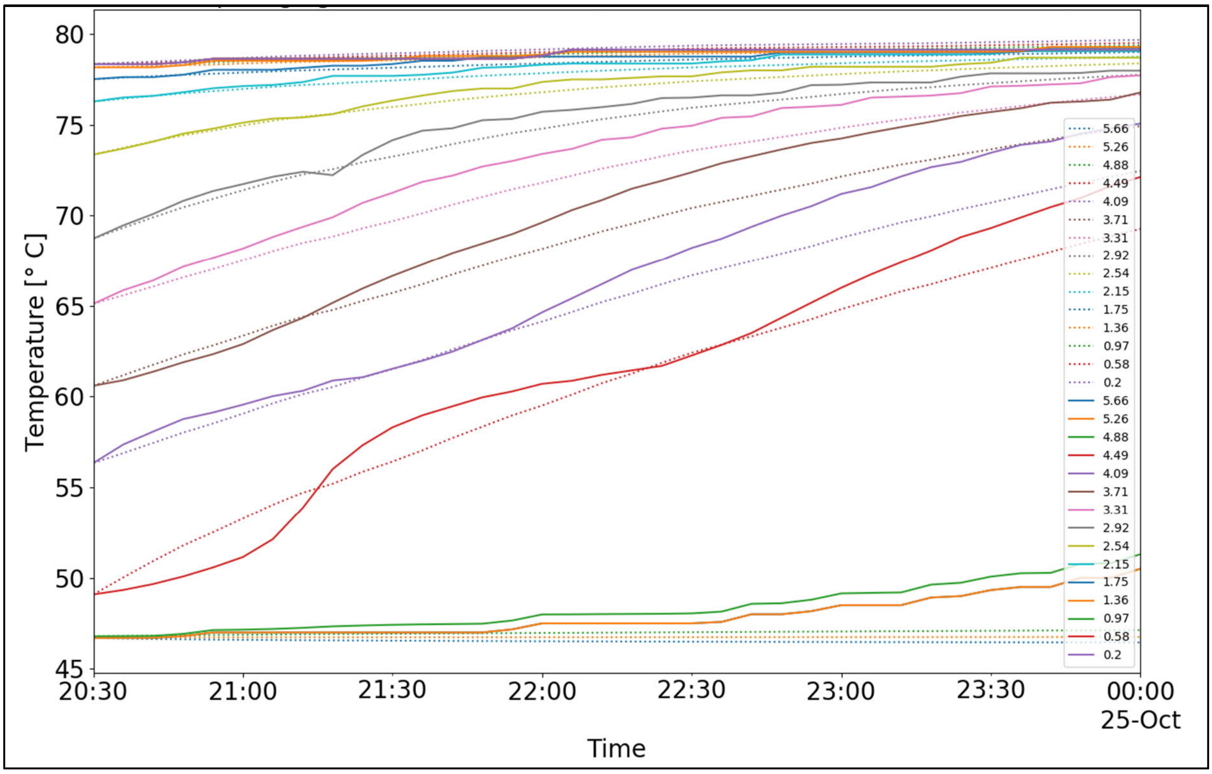

Figure 18 Temperature evolution inside the HTSV (positions in terms of depth) during a charging cycle: solid line: real measurements , dotted line: results from simulation.

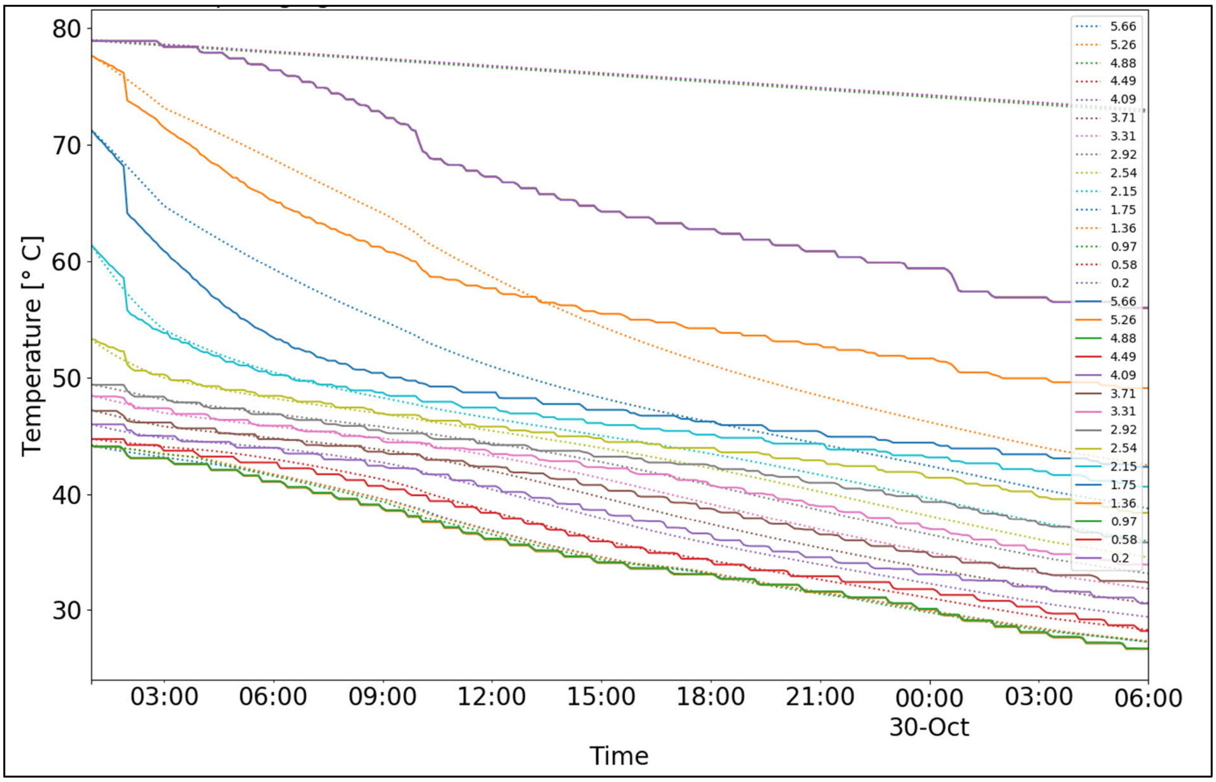

Figure 17: Temperature evolution inside the HTSV (positions in terms of depth) during a discharging cycle: solid line: real measurements , dotted line: results from simulation.

Although some of the errors were quite high ($> 5°C$), they do not occur at all heights at the same point in time. So, if there is not an absolute need for very high accuracy when calculating temperature for each height, at every single moment in time, then it is safe to assume that the model presented performs well. In the absence of temperature sensors at different heights of a storage vessel, this kind of model can be used by energy management software for a better control of systems using thermal energy storage. It can also be used in other contexts where the vessels are used to store thermal energy due to local energy surplus generation from Photovoltaic thermal collectors (PVT) systems, or reduce operational costs and increase self-sufficiency. The time step used in an energy management system varies according to the types of loads being managed, but a 15 minutes timestep is typically used for thermal loads. This model works with both smaller or higher timesteps, which makes it quite flexible to be used. The model also allows having different timesteps for the data collection and for the simulations.

6 Conclusions and lessons learned

A description of the system and the different components of the multi-energy grid has been presented. The use of an ORC allows the local production of electrical energy as well as the use of low-temperature heating. Moreover, including thermal energy storage on the high- and low-temperature circuits, increases the flexibility of the installation and allows a smart control of the system. Accurate knowledge of the SOC of the storage vessels during operation allows the control system to better optimize the control actions. This control can be optimized to for instance reduce operational cost and /or increase self-sufficiency: by knowing the SOC of the storage vessels, the control can know how much heat to produce at night and stored in the vessels to be used the next day. Also, by continuously monitoring the SOC, the control can forecast when the vessels should be loaded, or electrical production prioritized to avoid loss of comfort to the users.

The major lesson learned in this demonstrator is that when a combination of technologies is considered, good knowledge of the different systems and their limits is crucial. This can be done by for example having a “technology integrator/aggregator” that can integrate the different components together and setup clear responsibilities regarding any issues that may arise during operation. Also, it is important to develop a control system that considers the limits of the different components to guarantee the safety of operation and to avoid costly technical problems and long downtimes.

7 References

[1] https://contest.techbriefs.com/2016/entries/sustainable-technologies/6990