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STORY

added value of STORage in distribution sYstems

Deliverable 6.1
Report Chapter on Performance Evaluation

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1 Publishable executive summary

The European project STORY (Added value of STORage in distribution sYstems) demonstrates and evaluates innovative approaches for energy storage systems in the residential and industrial sectors.

Within WP6 activities, the demonstration sites set up as part of the project's activities have been equipped with monitoring systems to enable a detailed study of their behaviour. Each demonstrator was designed to respond to different needs, so the strategy for using the energy storage systems was different in each case. Similarly, the monitoring needs had to be adapted to the specificities of each demonstrator, to enable a proper evaluation of their behaviour throughout the project. Specifically, KPIs allow for the quantification of the the advantages (or disadvantages) of applying each evaluated solution.Thus, for each demo the developed comparisons of a base case (BC) or the initial situation and a case study (CS), which corresponds to the new situation with the solution developed and implemented, are described.

In summary, this report presents the main results obtained during the monitoring and evaluation of the use cases raised, described in six different Sections as follows.

Monitoring and evaluation of residential building level demonstrations (Belgium). Demo 1, a)

This Section is focused on the general Living lab, battery lab, thermal lab and control evaluation. The results from the monitoring and evaluation of this demonstration are explained in this Section.

First of all, it is worth noting that cost is a very important factor in a replicable solution for a residential building. Second, standardization and regulation can aid in the abundance of innovative technologies and the required use of components from different manufacturers. Therefore, interoperability becomes a great challenge to overcome and testing remains crucial.

Integrating a high-level control, such as predictive control model (MPC) in a real-life residential system, has proven challenging. Therefore, assumptions and simplifications were needed to arrive at a viable algorithm in terms of optimization and computational effort. And finally, the difficulty of knowing precisely the real limits of installation products in real life performance has been proven tha affect the result of the BESS capacity control operation.

Monitoring and evaluation of residential building level demonstrations (Belgium). Demo 1, b)

In this Section, the demo’s four residential buildings monitoring (loads, generation and storage) is detailed. The energy flow metering between the grid and the house (main meter metering is reported. An energy management platform deployed for accomplishing the demo’s objectives is evaluated through KPIs. The impact of the control on thermal confort of the end-user, the impact of the control on energy costs, the impact on local use energy, the impact of the control on CO2eq. emissions of the electricity consumption, and technical performance are reported.

In detail, the performance of the control was evaluated using a comparative analysis between BS and CS, which discriminates between5 different control periods, and taking place in the winter and autumn seasons.

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The evaluated performances results show strongly depency on the ability to obtain good levels of controllability. This situation proved with the reported KPIs analysis to reach higher effective shifted energy and associated cost reduction (values from 4% to 10%). Besides, the presented evaluation ofcontrol setup with an adaptive and robust central control system, able to learn from the few parameters received from the local devices and to take user feedback into account in some way.

In addition, the economic performance analysis is presented showing a limited potential for cost reduction. In terms of profitability, the evaluation performed indicates that may be necessary to increase the financial interest of the business case to make it more viable.

Monitoring and evaluation of neighborhood level demonstrations (Belgium). Demo 2

This Section sets forth the monitoring of the energy strategy to evaluatie impact grid balancing and flexibility in the Oud-Heverlee neighbourhood. Also the two applied technologies: EVs and Belgium's first neighbourhood battery are evaluated. Besides, and not less important, a model predictive control was evaluated in the task of ensuring the optimal battery operation.

The main evaluation results are described, such as that the neighbourhood BESS sizing was correctly performed. From monitoring and evaluation of this demo case, the main lessons learnt indicates firstly that improvement of power quality on the low distribution network can be done in a simple and cheaper way through low level control. Secondly, when focusing on local weaknesses and especially temporal situations and having multiple neighbourhood batteries acting in a coordinated manner, this can create benefits at medium and even high voltage level, and therefore an increase in the penetration of decentralized and centralized renewables can be achieved.

Monitoring and evaluation of industrial building (Spain). Demo 3

In this Section the KPIs are calculated and the performance is discussed. Also, a business case based on electricity bill savings lithium-ion battery at industrial level was analysed, in order to assess the system profitability. The values obtained from the KPIs allow for optimism about the suitability of these systems to reduce the costs of the electricity bill. The evaluation of the relative dimensioning of the PV system in relation with the experienced load demand, and also on the storage capacity of the ESS shows a dependence with scale of the reduction .

The main problems that affected the demonstration and thus the expected results are pointed out. The drawbacks detected reside in the integration of the different equipment present, especially with regard to the communication and control systems due to numerous failures. In addition, the low probability of possibility of guaranteeing adequate availability values for the installed system shows the difficulty of obtaining a return on investment, whether from an economic, environmental or operational point of view. Furthermore, as the operation of the system was strongly influenced by the evolution throughout the project duration of the Spanish regulatory framework for self-consumption installations, he presented analysis results evidence that regulatory framework limited the possibilities of the operation strategy.

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Monitoring and evaluation of medium scale storage unit (Slovenia). Demo 4

In this Section, the main achievements in monitoring and evaluation are summarised for the integration of a medium scale storage unit in a low voltage substation, connecting a residential area and photovoltaic production.

In detail, the technical KPIs are calculated and all BESS functionalities were successfully validated. As result, a confident grid consumption reduction is achieved. The demo evaluation showed a solid load peak shaving accomplished with the implementation of efficient BESS control algorithm. Reliable operation of the control and monitoring systems are developed within this high system complexity. Even when the BESS system evidences low efficiency.

Generally, all BESS predefined functionalities were successfully confirmed. The most important, load management functions, based on properly developed and optimized algorithms, proved to be efficient and well suited for future distribution network operations.

Grid KPIs are reported demonstrating that reliable operation of broadband radio is achieved with the disadvantage of encountering unexpected high frequency noise generation.

In addition to having a high investment cost in BESS, showing an unacceptably high number of different BESS faults and failures during the full demonstration, and added to the maintenance and operation problems, it means that this solution has disadvantages.

Monitoring and evaluation of private industrial grid roll out (Belgium). Demo 5

The demonstrated system is described as well as the main goal, which consists on evaluating the impact of the two additional thermal storages included in the CHP plant, from an economical and environmental perspective.

The heat demand upscaling demonstrated that, with the current installation and thermal load profile, a three-times extra thermal consumption can be added without the need to upgrade the installation. And this extra heat can provide additional revenue being an opportunity to improve the business case.

The calculated KPIs are reported and results are evaluated, showing that the integration of storage has a limited improvement on most of the technical KPIs, between 0.5 and 1.5%,and obtaining a reduction of 24% in the heat distribution losses.

In the simulation analysis reported for the industrial site, the reduction of the operational/running costs of the installation, demonstrates the reduction of the average cost of energy as well as owner savings on the annual electricity cost.

Additionally, the environmental KPIs calculation results are detailed and they revealed an increase of GHG emissions for the demo case compared to the reference case. that can be reduced if the demo case uses more than 20%.

Finally, **in the last Section** we focus on highlighting the main conclusions and lessons learned to be useful in potential future replications of such energy storage use applications. As an example, the main lesson learned from all demo evaluations is the importance of having a good knowledge of the different systems, that have a combination of technologies, and their limits.

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2 Introduction

The European project STORY (Added value of STORage in distribution sYstems) 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. STORY includes several demonstration sites, which range in size from individual buildings to the district level. They include different energy storage types, different renewable energy technologies, and target different project goals. All demonstration activities deliver input on technological performance, stakeholder acceptance and on the overall process of storage integration.

In “WP6 – Monitoring and Evaluation” the performance of the demonstration sites was monitored and evaluated using different measurement methods and performance criteria.

STORY addresses monitoring and evaluation for at least two purposes:

- Cover the technological, process, environmental, social and economic aspects of the demonstration cases.
- Focus on wider real-world storage deployment beyond STORY and elaborate solutions accordingly.

This report presents an evaluation of the results obtained through the monitoring process for the demonstration sites under study. The developed monitoring and evaluation methodology applied in each of the demonstration sites is reported in detail in the following sections.

For each demonstration site, the results obtained for the defined KPIs are presented, together with a discussion about the performance of the system according to its initial targets. Based on the experience gained during the operation of the systems, the lessons learned for each case of use are also presented.

CENER (CEN) led WP6 as well as the preparation of this document. To carry out this task, CEN worked in close cooperation with several other project partners, who provided foreground data on the demonstration sites, as well as interpreted the results.

The leading role of the activities regarding data interpretation and drawing of conclusions was taken by different partners for the different demonstration sites (see summary Table 2-1):

- Monitoring of building level demonstrations (Belgium) – Th!nk E (THNK) / Actility-Flexcity
- Monitoring of neighborhood level demonstrations (Belgium) – Th!nk E / Actility-Flexcity
- Monitoring of industrial building (Spain) – CENER / Exkal
- Monitoring of medium scale storage unit (Slovenia) – Elektro Gorenjska / University of Ljubljana (UL) / Technical Research Centre of Finland (VTT)
- Monitoring and evaluation of private industrial grid roll out (Belgium) – VITO / Beneens

BaseN implemented the project's central database management system, which allowed the centralized collection of monitored measures as well as the calculation of previously defined KPIs for each demo. Joaneum Research (JR) was also in contact with the demonstration leaders THNK, Beneens (BEN), Elektro Gorenjska (EG) and Exkal (EXL).

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Table 2-1Summary of demonstration plants covered and description based on objective and functions

Demo	Name	Location	Objective	Functions
1. a) **1. b)** **2.**	Demonstration in residential building Demonstrating the roll out of a neighbourhood	Oud-Heverlee, Belgium Oud-Heverlee, Belgium	- interoperability issues - demonstration of several technologies in buildings, - operation optimization of a neighbourhood - congestion management in the distribution network	- More RES integration (mainly solar) - Real-time load flexibility management - Reduction of energy consumption (from grid)/increase self-consumption - Improvement of network operation (congestion management) - Management of several assets operation
3	Demonstration of storage in factory	Navarra, Spain	- reduce the demand charge (power peak contracted) of the factory. - enhance the use of the solar resources, - increase the overall energy efficiency and sustainability	- Peak power reduction - More PV energy integration - Real-time load management - Reduction of energy consumption (from grid)/increase self-consumption
4	Medium scale unit connected to low voltage substation in residential grid	Slovenia, (TP Suha)	- demonstrate the flexibility and robustness of a medium scale battery - demo of the battery in a LV substation - demo using the battery in the headquarters of EG in an industrial grid.	- Increase of decentralised RES integration efficiency - Reduction of RES curtailment (and comparison with smart-inverters capabilities) - Increased reliability in blackouts - Better operation of transformer station and the complete systems - Peak demand control - Congestion management - Voltage control
5	Demonstration of roll out of private multi-energy grid in industrial area	Olen, Belgium	- operation of a private micro-grid in an industrial area	- Analysis of thermal storage capabilities - Support, control and efficiency enhancement of ORC operation - Peak power demand - Congestion management

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3 Monitoring and evaluation of residential building level demonstrations (Belgium). Demo1, a)

Authors: Leen Peeters, Frank Veltmans (Th!nk E), Christophe Van den Eynden, Christian Carelsberg (Viessmann), Francesco Reda (VTT), Topi Mikkola (BaseN), Jan Diriken, Jad Al Koussa (VITO), Edited by Andreas Tuerk (JR).

3.1 Introduction

The Living Lab has been operational the first part of the STORY project as stand-alone case, before being integrated in a neighbourhood level energy community. Data has been collected on local grid exchange as well on different aspects of the Living Lab demonstration. The Living Lab's main focus is on technology cooperation, including interoperability, and limitation of grid exchange. The data show interesting outcomes with regards to decisive residential load and hence control priorities as well as with regards to the energy consumption of data collection and control operation. Lessons learned clearly identify the need for a co-design of hardware and software, keeping control and data locally when possible and the added value of pre-testing technologies and software in a Living Lab.

3.2 The concept

The Living Lab was designed to demonstrate that a Nearly Zero Energy Building (NZEB) could be developed to minimize its impact on the public energy infrastructure. Building a NZEB is often done combining a good building design and adding enough local renewable production through thermal and electrical solar systems. The Living Lab was designed to minimise the exchange with the grid and provide maximum flexibility on when and how much energy to exchange.

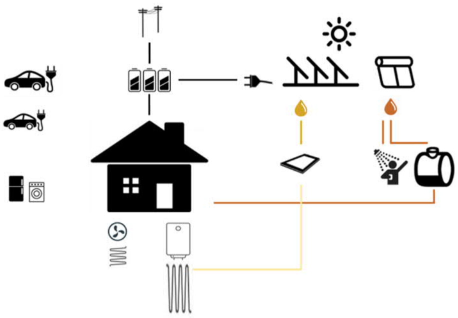

Figure 3-1: Schematic of the Living Lab energy concept. Local production is provided by solar thermal and hybrid PV. Storage is realized in hot water tanks and in electrical batteries, and by regenerating the geothermal system that feeds the heat pump. Electrical vehicles and all normal household electricity is considered in the energy balance.

Different operating modes can be selected. The below schematic (Figure 3-2) provides an overview of the thermal loops that can be activated.

Additionally, the electrical flexibility is provided through a battery set-up and electric vehicles: a total lead acid battery set-up of 46 kWh & 18 kW and one 33kWh & one 90 kWh electric vehicle.

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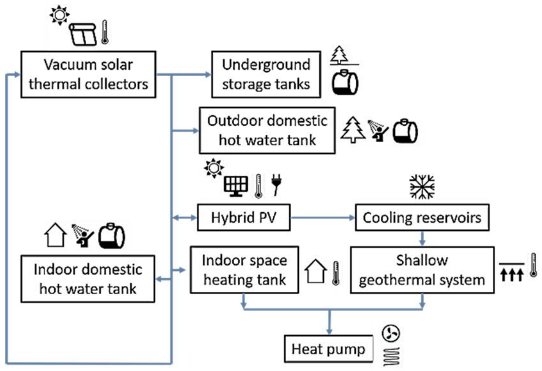

Figure 3-2: Schematic overview of the circuits and exchanges that can be delivered with the thermal lab set up.

3.3 Total grid exchange with electrical storage

3.3.1 Self-sufficiency levels

The KPIs that applies here were defined in the deliverable D6.2[1].The self-sufficiency level (%) indicates the ratio of locally produced energy in the overall energy consumption of the Living Lab.

The self-sufficiency level is shown in Figure 3-3. As expected, summer periods are easy to achieve a 100% self-sufficiency. Days with less solar radiation are more challenging. The break-down of the consumption reveals the following monthly values:

- 190 kWh for the heat pump;
- 106 kWh for mechanical ventilation with heat recovery and ground loop;
- 30 kWh for the fridge;
- 35 kWh for cooking;
- 37 kWh for washing machine and dryer;
- 460 kWh for the 2 electric vehicles.

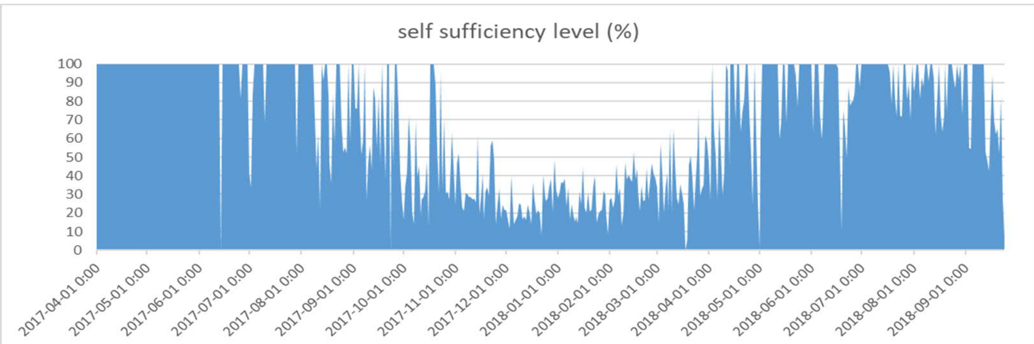

Figure 3-3: Self-sufficiency level as function of time.

[1] "Use cases and Key Performance Indicators (KPIs) of the STORY project" http://horizon2020-story.eu/wp-content/uploads/STORY-use-cases-and-KPIs.Publish1-1.pdf

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3.3.1.1 Energy aspect

The distribution of electric loads indicates the decisiveness of mobility in the overall energy consumption at building level. Non-flexible loads such as cooking and ventilation are small in overall energy consumption. A calculation based on extraction of car charging indicates the potential to reach a yearlong self-sufficiency level close to 100%.

While the solar thermal system is oversized, the option was selected to use the heat pump for sanitary hot water. In summer, there is an excess of electrical energy that, due to not being allowed to inject in the grid, would lead to curtailed PV production. The high temperature heat produced by the solar thermal system is instead stored in the seasonal storage system.

With regards to the energy consumed for heating, the 2017 winter includes no use of the thermal storage tank. Opposite to summer 2017 which also included a discharging test on the storage tanks, summer 2018 contained extremely hot periods leading to fully charged thermal storage tanks for the first time.

3.3.1.2 Power aspect

More important, and not directly integrated in the calculation of the self-sufficiency level, is the power component. Several occurrences with grid connection in sunny periods where related to a high power demand: when the demand for power exceeds the value that can be provided by the 3-phase invertors on the battery, automatic connection to the grid is activated. This is the case when charging the 2 electric vehicles at the same time and unthoughtfully activating cooking appliances without interrupting the charging. While energy is sufficiently available, power is the cause for reconnecting to the grid.

3.3.1.3 Self-sufficiency level as function of outdoor conditions

As self-sufficiency is strongly related to the local production, the relation between self-consumption level and solar radiation is to be expected (see Figure 3-4).

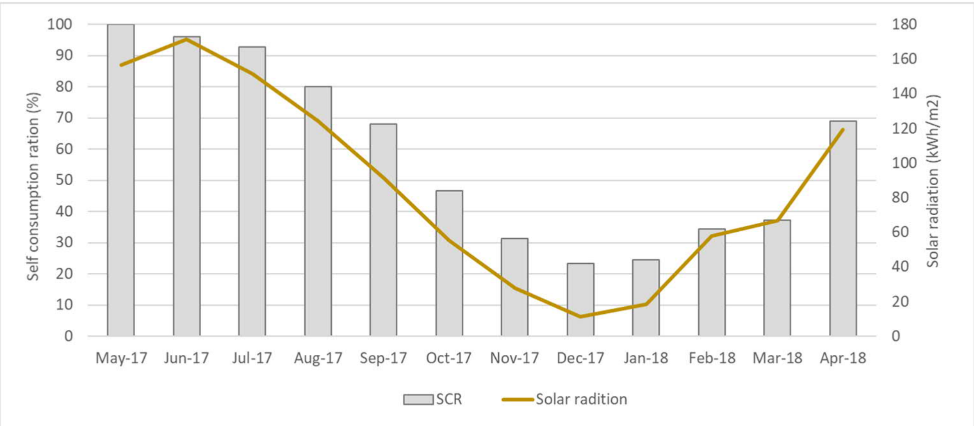

Figure 3-4: Self-consumption level as function of months and in relation to solar radiation.

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3.3.1.4 Self-consumption levels

The set-up with batteries between the grid meter and the energy consumption, was new in Belgium with the start of the Living Lab. The distribution grid operator prohibited injection in the grid. Consequently, the combination with 11 kWe of hybrid PV panels leads to a substantial share of curtailment in case of consecutive days with a high share of solar radiation.

Therefore, the self-consumption level is 100% during nearly the full experimentation period of the Living Lab. Longer periods with maximum State of Charge (SOC) during sunny periods are an indirect indication of curtailment.

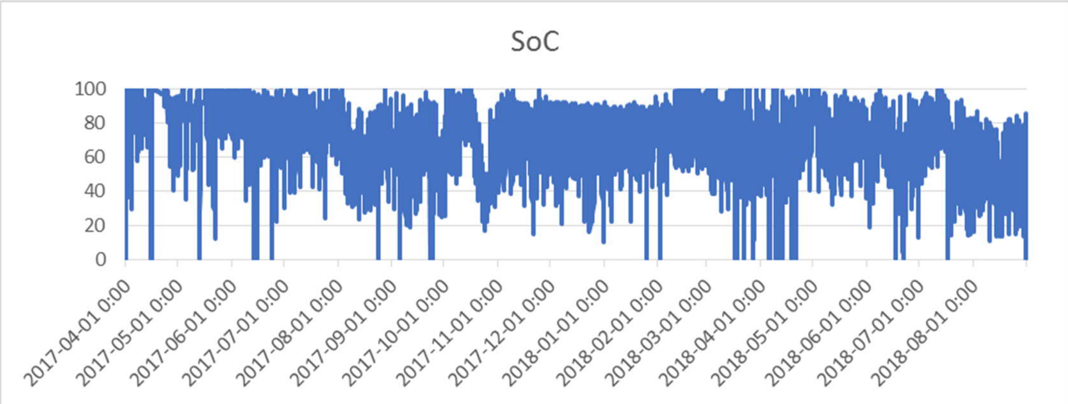

Figure 3-5: Battery State of Charge as function of time, effectively used is 32 kWh of the battery capacity (46kWh) hence 0 SOC in the graph corresponds to 30%.

3.3.2 The seasonal underground thermal storage

The combination of a well-insulated building and over-sized solar collector installation leads to a seasonal imbalance between supply and demand of heat. Seasonal storage can bridge this gap by capturing excess of solar energy in summer and saving it for use in winter when demand is high. In this way the share of on-site renewable energy use can be increased while, at the same time, curtailment can be reduced.

One can think of different technologies to achieve seasonal storage, depending on the application. In solar districts like Vojens, Denmark, 2000 households are connected to a district heating system including 52.500 m² of solar collectors and a 203.000 m³ water basin (pit storage). This solution leads to a solar fraction of 45%. In Drake Landing, Canada, 52 houses equipped with in total nearly 800 solar collectors store excess heat in summer in a high-temperature borehole field (BTES).

It reached a solar fraction of 97% in spite of its location in Alberta. Other solutions include aquifer thermal storage, (large-scale) tank storage and the use of gravel or rocks.

It is necessary to limit the thermal losses since a significant long timespan between loading and unloading, typically several months, must be bridged. In combination with the amount of energy that has to be stored, large-scale solutions, which have favourable volume-to-surface-area ratios are preferred. Thermochemical storage, which relies on energy stored in bounds of chemical

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compounds, allows to realize compact storage systems, ideally without thermal losses. However, these systems are currently in a prototype stage and still facing major technological and material challenges.

A final consideration are the economics of seasonal storage. Since the number of loading-unloading cycles per year is limited to one, it is of great importance that the cost of the storage is as low as possible to be economical viable.

Figure 3-6: Seasonal storage tanks during installation phase

To accomplish this at living lab premises, two 12.5 m³ hot water storage tanks have been installed underground. Considering a temperature delta of 40 °C, this corresponds to a potential 4.2 GJ storage capacity.

The seasonal storage tanks are hydraulically decoupled from the main collector circuit using an external heat exchanger. The water in the tanks is circulated over the secondary side of the heat exchanger to transfer heat to or from the collector circuit depending on the season. The charge or discharge mode also defines the flow direction in the tank loop: hot water is always injected at or extracted from the top to the tank, in case of cold water the bottom layers are used.

A decent amount of insulation is foreseen at the sides, as well as at the top of the tank to minimize thermal losses. Styrofoam board with a total thickness of 1 m at the top were installed at different times for each tank and analysis showed that losses from the top layer could be reduced by 45% when including the additional insulation.

Use cases for the seasonal storage tanks in the living lab were defined to recharge one of the two domestic hot water tanks, or to provide space heating, either directly or in combination with the solar collectors. A secondary use that was proposed is to use the stored heat to heat up hybrid PVT panels in case of snow coverage.

The two tanks have been equipped with 10 temperature sensors each. These measurements can be used to develop methods to accurately determine the energy content, or state of charge, of these storage tanks, which can be used as input in intelligent control algorithms.

In the summer of 2017, the tanks were charged up to temperatures of 70 and 67 °C, reached between early July and August. The tanks were left idle during the fall and winter to assess the thermal losses to the ambient soil. After a short charging period in the spring of 2018, a dedicated

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discharge test was conducted in early May before recharging the units to maximum temperatures of more than 80 degrees.

The seasonal character of the storage units could be first assessed using the data from the fall and winter in 2017. It was found that the temperature declined rapidly and became quickly insufficient to prepare DHW, where a minimum temperature of 50 °C is required. Since low-temperature floor heating is used in the building (supply temperature of 33 °C), part of the stored energy can be used to directly heat the building. If the temperature in the seasonal storage tanks become too low to provide space heating directly, it can in principle be used as a heat sink for the heat pump. This mode of operation competes with the shallow geothermal source and the extracted temperatures thereof.

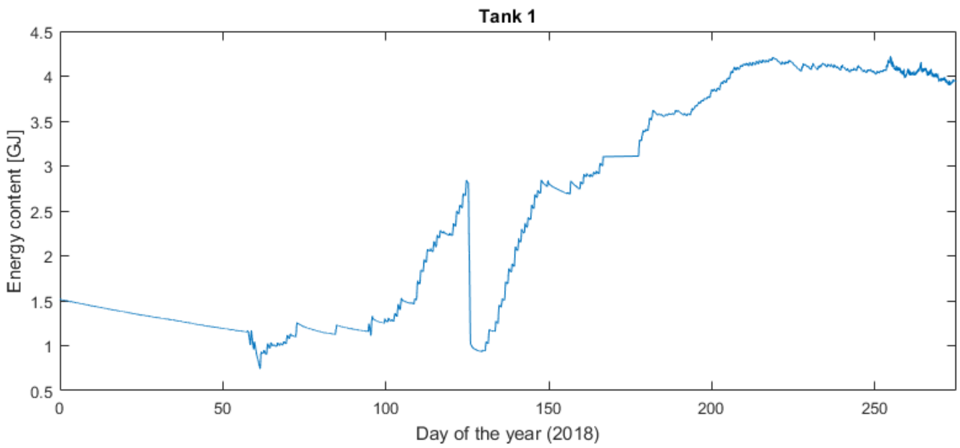

Figure 3-7-Energy content evolution in 2018 in one of the seasonal storage tanks. The sharp decline around day 125 is the effect of the dedicated discharge test. Energy is relative to uniform 0 °C storage temperature.

Tank 2 was indeed used for heating purposes between November 30th 2018 and January 15th 2019. In total, 1.6 GJ was recovered from the tank.

With respect to the measurement and related equipment, it was found that the harsh environmental underground conditions impacted the quality of the measurements. High humidity levels have affected electrical contacts and led to the loss of data. Special care should be given to both the choice of sensors and DAQ equipment (IP rating) and installation procedure. Since the installation is located underground, accessibility is poor and interventions are also depending on the temperature of the storage tank.

3.3.3 The small-scale thermal storage

The 400-litre solar boiler (Vitocell-140E[2],Figure 3-8) is placed in a technical room and equipped with an immersed coil tube heat exchanger (1.5 m2 surface). It is used for DHW purpose. VITO has installed a custom-made temperature measuring device containing 7 equally spaced point sensors along the height of the tank (1458 mm).

[2] https://www.viessmann.co.uk/products/domestic-hot-water-cylinders/heating-water-buffer-cylinder/vitocell-140-e

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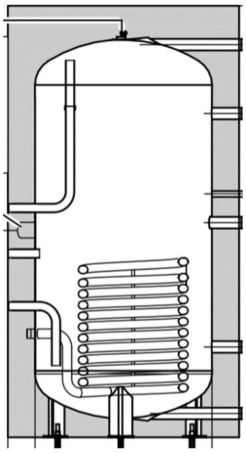

Figure 3-8-The storage tank with the immersed coil tube heat exchanger in its lower part

An energy meter, with built-in temperature sensors and a flow meter, is installed on the secondary side (freshwater draw). On the primary side, no dedicated energy meter is installed. The energy that is transferred to the solar boiler is determined based on the readings of the temperature sensors situated before and after the internal heat exchanger, combined with the total flow in the circuit measured by a flow meter.

This storage tank has not been often used because it is not the main DHW storage for the house as it is placed in the guest area. However planned charging, idling and discharging tests have been performed for the validation of the state-of-charge determination methods. Given that the solar boiler can only be charged using the solar collectors, charging has been performed during a sunny day. For the discharge tests, a pipe has been installed connecting the DHW tank to the swimming pool instead of discharging the water in the sinks, to reduce water consumption and energy losses.

Figure 3-9 shows the temperature variation in the tank for the charging and the idling tests. As can be seen, even though the storage tank is being charged using a heat exchanger, all the layers get warmed up homogeneously and no stratification occurs. After charging, the tank was left idling for a week. The stratification in the tank is clearer in this case. Also, the lower layers of the tank cool down at a higher pace than the upper layers. This is because of the ground's temperature effect on the bottom of the tank. Moreover, daily variations in the rate of heat losses can be seen due to the day/night temperature variations inside the technical room.

Figure 3-10 shows the variation in the tank's temperature at different layers for a discharge test. As can be seen, the tank is initially slightly stratified. Given that hot water is withdrawn from the top of the tank and cold water enters from the bottom, the heat layers propagate from the lower layer all the way to the top, to exit the tank from the discharge point, and they are replaced by fresh cold water. The hot water temperature at the discharge point was not measured but it can be taken as that of p7 because the hot water is withdrawn from that layer.

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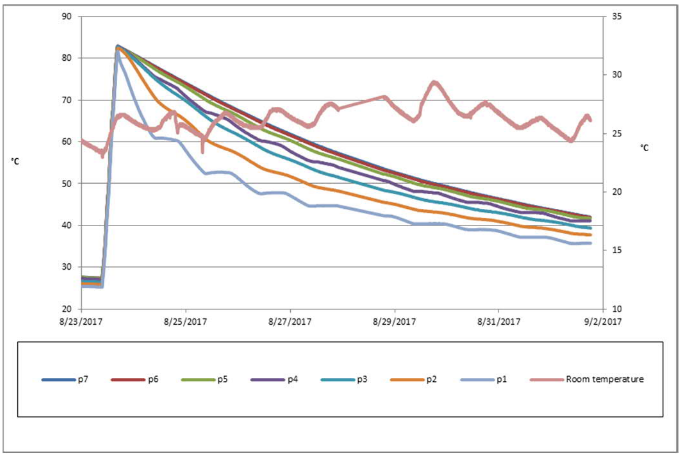

Figure 3-9- Temperature variation at different heights (p7=top and p1=bottom) within the storage tank (left axis) and the room temperature (right axis) for a full charging test followed by a heat losses test.

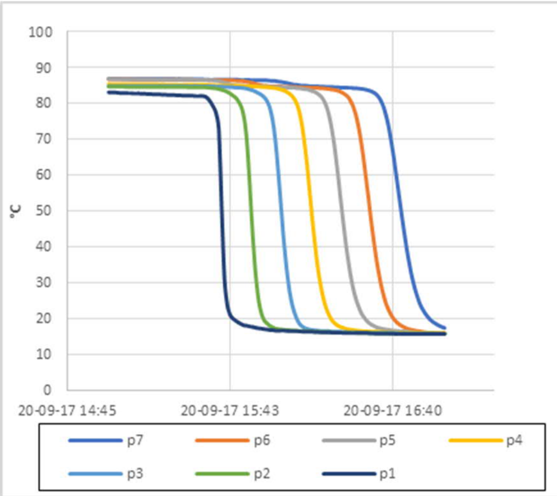

Figure 3-10 Temperature variation at different heights (p7=top and p1=bottom) within the storage tank during discharge.

3.4 Hybrid PV

The hybrid panels have been composed using the best performing PV panels on the market and adding a tailormade back composed of an aluminium plate with tubes, high and low temperature resistant insulation and an aluminium finishing. A mixture of di-ethylene glycol with freezing temperature at -18°C is circulated through the tubes.

3.4.1 Behaviour of hybrid PV

Figure 3-11 shows the behaviour of the hybrid panels separately for the thermal and electrical yield. When the battery is reaching a higher SOC, the electrical production of the PVT panels is

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curtailed, until an additional load (in this case an electric vehicle) is connected and the produced electricity can be delivered to the load instantly. The thermal side, however, continues to produce, independent of any interruption of the electric side and reaches higher values in power as well as energy for that specific sunny day.

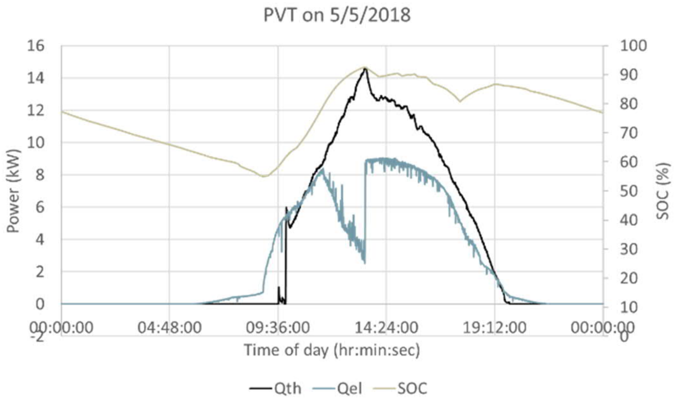

Figure 3-11- Temperature variation at different heights (p7=top and p1=bottom) within the storage tank during discharge

3.4.2 Efficiency of hybrid PV

Hybrid PV cools the panels continuously, i.e. as long as a cooling source is available. The set-up installed in the Living Lab has 33 panels of 335 Wp electrical with the backside as described earlier.

Table 3-1 Net extra yield for PVT set-up (W_{el})

	Solar radiation			
ΔT (K)	>1000W/m²	≈1000W/m²	>800W/m²	>600W/m²
5	**203**	**102**	**86**	**20**
10	**455**	**254**	**223**	**91**
15	**708**	**406**	**359**	**161**
20	**961**	**558**	**495**	**232**
25	**1213**	**710**	**632**	**302**

Table 3-1 shows the additional yield when cooling the panels as function of the temperate difference between a cooled PVT panel and a normal PV panel. Due to the continuous cooling, a warm summer day showed to lead to an increase in electrical yield equal to 36%.

It is important to identity the impact of the cooling: the temperature difference has a more positive impact if the inlet temperature is lower. Although the living lab has 2 different cooling reservoirs, the extreme summer of 2018 used the cooling capacity up to its limits with basin temperatures close to 38°C for the deep basin and above 40°C for the second basin (average depth of 0.5 meter, large surface area and 5 waterfalls to maximise natural cooling).

Figure 3-12 shows that the system is used to its limits with low electrical yield, nearly fully charged batteries and temperatures too high to regenerate the shallow geothermal system.

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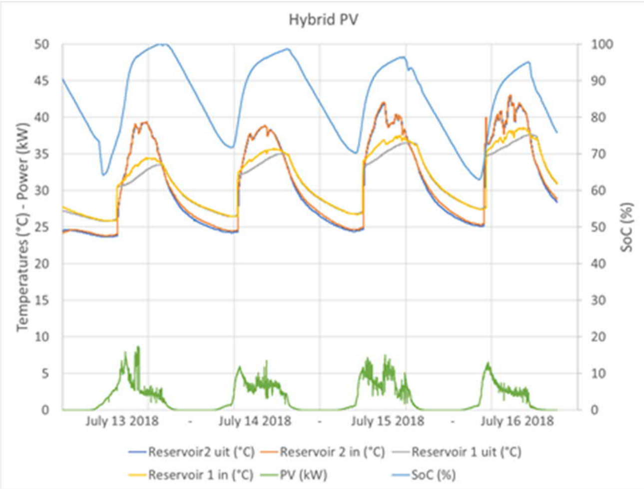

Figure 3-12: Temperature of cooling reservoirs and production of PV as function of time of the day summer days with extreme temperatures.

3.5 Control

This paragraph is a concise summary of the main findings of deliverables D3.4 and D3.5[3] where control algorithms and algorithms performance have been reported for what concerns this specific demo.

3.5.1 Model Predictive Control

Concept

Model predictive control is an advanced control method, in which both the intermediate (related to a future time horizon) and final states of the controlled system are modelled and evaluated to choose optimal control inputs, which regulate the energy flows between energy generation, storage and consumption, at every intermediate time step. The control inputs for the actual operation are chosen using a continuous procedure that emulate the performance of the system until the last time horizon step (rolling horizon approach).

Theoretical savings

In order to estimate potential savings from the use of model predictive control, initially it was tested using a detailed dynamic simulation model of the thermal system of Living Lab demonstration site. The findings regarding the thermal system are reported and published in D3.3[4] and they have been partially published in a paper presented at EuroSun 2018 conference[5]. Anticipating

[3] Deliverable 3.4 “Streamlined control algorithm for storage integration”, Deliverable 3.5 “Report on performance evaluation of control.

[4] Neighbourhood simulation models for input in extrapolation (WP7).

[5] Korvola, T., Abdurafikov, R., & Reda, F. (2018). Control strategies for a residential property with solar building, thermal and electricity storages. In A. Häberle (Ed.), EuroSun 2018 Conference Proceedings (pp. 77-88) https://doi.org/10.18086/eurosun2018.06.01

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some of the D3.3 content, the MPC allowed over 30% saving in both operating energy consumption and costs during cold periods of the year compared to a conventional rule-based control. Electric vehicles were initially excluded from the analysis of the thermal system and were considered later. In a later study, the controlled system consisted of uncontrolled loads (13 MWh/a), electric vehicle loads (3.5 MWh/a) and uncontrolled PV/T production (8.2 MWh/a), stationary electricity storage with usable capacity of 32 kWh and external power supply from grid. Given the weight of the vehicles on the energy consumption, the application of MPC has been focused on shifting the charging start times, within certain time constraints connected to when vehicles were expected to be present on-site and connected to the charger. These time constraints as well as charging energy requirements were identified using machine learning techniques based on measured consumption data.

Two versions of MPC system were considered: one featuring a constant rate of charging and another smarter one, where charging power could be varied. Results of both MPC versions were compared to real measurement. It was found that the annual energy consumption from grid as well as costs did not differ significantly. The measured electricity consumption from grid was 9038 kWh and costs have been estimated to be 2678 €. Using model predictive control with constant charging rate these were: 9023 kWh and 2663 €, and with varying charging rate: 8920 kWh and 2636 €.

Practical implementation: The effects of curtailment in PV production data

The effects of curtailments were evaluated using a trained machine learning model, using Gradient boosting ensemble method. The used input data for machine learning have been retrieved from BaseN platform. They include yearly series of:

- PV production data
- power AC (house total power consumption including EV charging demand)
- SoC data
- Weather station data

In order to detect PV curtailment periods (possible timespans when PV curtailment may occur) along one year, the following conditions have been considered:

- Full house battery (SoC data values corresponding to 100%)
- PV production value achieved with machine learning is greater than measured electricity consumption

The aim is to use machine learnings to filter out the timespans from the measured data where PV production may be curtailed. Thus, in order to properly train and create the machine learning model only the data segments where curtailment cannot occur have been used. This has ensured that the PV production estimations, done by the trained machine learning model, do not consider potential period where curtailment could have occurred.

To summarize, the analysis of potential curtailment of PV production consists of three steps:

1. Train the machine learning model using only the time segments where PV production curtailment cannot occur.
2. Use the machine learning model to estimate the non-curtailed PV production, and generate the estimated PV production data.

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3. Compute the volume of PV produced energy curtailed as the difference between machine learning model generated PV production data and the PV production measured data.

The accuracy of the PV production machine learning model estimated considering periods, when curtailments do not occur, is about 0.0302 (mean absolute error). The picture below shows the accuracy of the machine learning model in terms of deviance as a function of the training iteration (boosting iterations).

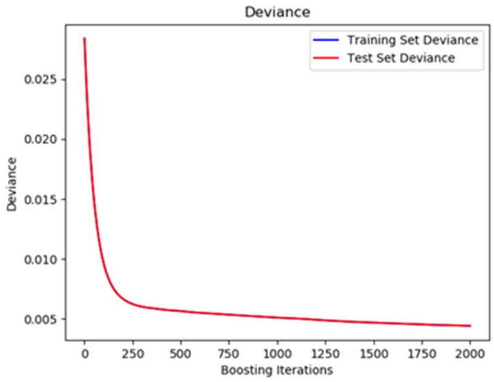

Figure 3-13- Accuracy of the machine learning model in terms of deviance as a function of the training iteration (boosting iterations).

The figure below shows the difference between machine learning model generated PV production data and the PV production measured data considering a single day.

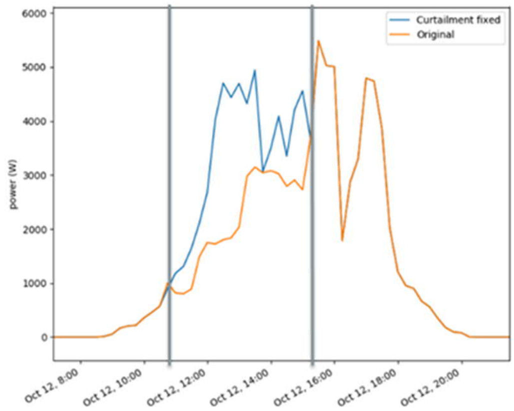

Figure 3-14-Measured PV production curve (original) and the machine learning generated PV production curve.

The estimated effects of curtailment is 179 kWh/year. The yearly measured PV production is 8195 kWh.

3.5.2 Decisive loads determining control effectiveness

It has been observed that the electric car is a disruptive load and controlling the charging has the biggest impact on the energy performance of the system. Please refer to deliverables D3.4

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“Streamlined control algorithm for storage integration”, where the algorithms for storage integration have been described for each demo, and to D3.5 “Report on performance evaluation of control”, where simulation based performance evaluation of the control algorithms developed for different demos have been presented.

3.5.3 Sensitivity as a function of storage sizes

Table 3-2- Summary of the sensitivity analysis of annual energy costs and curtailed electricity to sizes of the PV system and stationary energy storage.

		Energy (kWh)			(€)
		fromGrid	PV	Curtailed	Energy bill
PV(kW$_p$)	BESS (kWh)				
20	64.4	*5613.1*	*16390.2*	*4570.7*	*1653.4*
	32.2	*5976.8*	*16390.2*	*4998.1*	*1760.3*
	16.1	*6766.3*	*16390.2*	*5929.8*	*1994.7*
10	64.4	*8958.6*	*8195.1*	*91.0*	*2652.7*
	32.2	*9037.7*	*8195.1*	*184.0*	*2678.3*
	16.1	*9174.8*	*8195.1*	*345.4*	*2721.6*
20	0	*10453.1*	*16390.2*	*10267.4*	*3104.0*
10	0	*11717.1*	*8195.1*	*3336.3*	*3492.3*
5	16.1	*12596.4*	*4097.5*	*0.0*	*3762.5*
	32.2	*12596.4*	*4097.5*	*0.0*	*3762.5*
	64.4	*12596.4*	*4097.5*	*0.0*	*3762.5*
	0	*13265.8*	*4097.5*	*787.5*	*3968.6*

Table 3-2 summarizes the results of sensitivity analysis of annual energy costs and curtailed electricity to sizes of the PV system and stationary energy storage in a case when electric vehicle charging follows the pattern identified from historical data. The sizes of installed equipment are 10 kWp of solar (PV/T) panels and 32.2 kWh of effective battery capacity. As can be noticed, halving the size of PV/T system has very little effect on energy bill, no PV output is being curtailed as any surplus can be accumulated by the battery.

The results suggest that existing battery is over dimensioned: for the PV/T system of the same size, halving or doubling the battery size leads to at maximum 2 percent change in annual energy costs. More significant annual energy cost savings appear to be possible when increasing the size of the PV system, for example, results suggest that doubling its size would result in ca. 34 percent reduction in annual energy bill. The results show that with larger solar power installations, curtailment of significant amounts of PV output may prove economically justified with existing electricity pricing scheme, with zero price for exported electricity.

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3.6 Control integration

3.6.1 General – Living Lab

Figure 3-15-The Living Lab of the Oud-Heverlee demo site with vacuum collectors (VC) and PVT panels.

Integrating a high-level control, like a Model Predictive Control (MPC) in a real-life residential system has proven a challenge.

The practical computation of the MPC requires that the real-life system be simplified to reduce computation time. From the MPC designers' point of view, having hundreds of parameters for optimization requires a lengthy and often impossible calculation. Thus, assumptions and simplifications are necessary to arrive at a viable algorithm. Afterwards, when this algorithm is given to the (lower level) system integrator, there are still many degrees of freedom. Leaving many blanks and decisions to take before arriving at a working system.

Two examples to illustrate this:

1. A pump is ON/OFF for the MPC. In real-life each pump has a variable speed (RPM) with different lower and upper limits.
2. Temperatures are inputs for the MPC. Gathering these in the real-life system implies running pumps for several minutes to circulate fluid and get a stable measurement. This logic should not be in the MPC and thus implies the need for an intermediate layer.

While this may seem trivial for the given examples, the complexity of the living lab gives rise to a great many of these situations. Often these issues are only identified during the implementation and require a lot of time to be resolved.

The Living Lab consists of two major controllable parts: thermal lab and battery lab. Both are discussed separately, however, the MPC also deals with the prioritization between thermal and electrical energy transfers. E.g. heating the residential building can be done via the thermal lab (PVT, vacuum boilers, storage tanks, etc.) or via the heat pump that uses electrical energy from the battery lab (PV or BESS). The optimal choice from an energetic point of view might not always be the most economical one, indicating a multidimensional trade-off with sometimes conflicting interests.

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3.6.2 Battery Lab

Figure 16. The Battery Lab of the Oud-Heverlee demo site, a 3-Phase on / off grid installation with 46 kWh battery.

After computation, the high level MPC algorithm provides a set of optimized control parameters or setpoints (e.g. charge current). These are generally computed over a larger time frame and available every hour. Next, they are communicated to the EV chargers and battery energy storage system (BESS). This BESS has a faster internal control loop with its own capabilities and limitations. Both will differ significantly from between manufacturers and are also dependent on the battery chemistry.

First, the difference in speed between both control loops presents some challenges that must be solved:

- Failure of the hourly MPC computation due to a sensor failure or software issue. In this case the lower level system still requires new setpoints to remain functional.
- Allow manual override and recovery from disruptive events. E.g. the immediate need of the EV for driving to the hospital and thus interrupting the scheduled charge cycle.

Second, characterizing the internal control of the BESS before purchase is also a challenge. Mainly due to the lack of detailed, technical information from manufacturers. The information that is available is mostly marketing material with numbers that are only valid under ideal lab conditions. This makes it also difficult to determine upfront compatibility, functionality, and performance in a real-life setup.

Commonly used battery energy storage systems (e.g. Tesla Powerwall) do not even allow the external control that is necessary for integration into system with MPC optimization.

Also, for batteries, cycle life is given for scenarios with fixed charge or discharge currents. However, when used in a PV setup the charge current will be highly variable due to cloud coverage. What effect this has on cycle life and charge efficiency is thus difficult to determine before the system is operational. An external control will vary the charge / discharge current of the battery and thus has a significant impact on the lifetime of the battery. General predictions can be made based on the BESS chemistry but in optimization scenarios more detailed information is the key to success.

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3.6.3 Thermal Lab

Figure 3-16-VC part of the Thermal Lab at the Oud-Heverlee demo site.

The Thermal Lab consists of individual circuits, interconnected by heat exchangers to allow thermal transfers. The control is built up in layers, starting from the individual components, grouped into circuits and finally the whole thermal system.

First, looking at the bottom layer, there are all the individual components in the Thermal Lab (e.g. pumps, valves, flow & energy meters, temperature sensors, heat pumps, etc.). The main challenge is to build them into a system that can be controlled. Components like valves and pumps are relative dumb parts, so low-level interfacing components must be added, like relays for switching valve positions, or motor controllers to drive the pumps.

Second, integrating all these low-level components into a viable, economical, or even practical system is often underestimated. A motor controller for example has a specific control interface (e.g. Modbus RTU) that allows you to power a pump on/off, controls the start-up and RPM of the motor. By itself it does not interface to a meter that measures the generated flow when the motor is powered on.

Today, many protocols and interface standards exist, e.g. Modbus TCP/RTU, RS232, RS485, CAN Bus, KNX bus, OPC, OCPP, 4-20 mA, pulses etc. These are all commonly found in a smart building, in addition to some proprietary protocols like Studer SCOM for inverters or SMA bus for PV and battery systems. Thus, when building a control system for a smart home it needs to be able to bridge multiple protocols and interface standards. This gives rise to interoperability issues on multiple levels.

There is no common, uniform way of connecting components together without relying on intermediate converters. Often this implies that multiple devices are needed between the sensor and device storing the measurements or the actuator and controller.

While these converters, gateways and interfacing components are needed to make the system controllable, they also add to the energy consumption. Given the example of an MPC, requiring many input parameters before it can determine an optimum. The energy cost of gathering, transporting, and processing these input parameters before the optimization is often overlooked.

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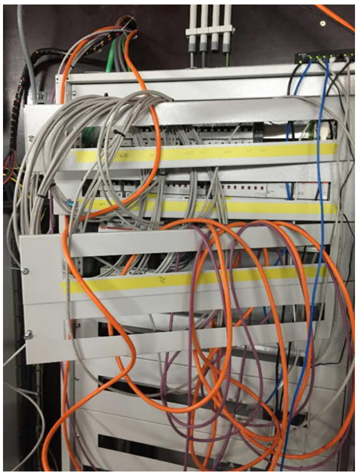

Figure 3-17-One of the electrical boards during installation of the labs, showing different coloured cables for multiple protocols.

Figure 3-18-. An IT cabinet of the Living Lab, able to control 100 output channels and do logging of 600 different measurements.

Given the current tendency to run optimizations in the cloud, e.g. on a central server, energy consumed for data transport and computation on the remote site is never considered. For an optimization to be useful, it should never consume more energy than it can potentially save. This may seem obvious though often forgotten along the way when building a system.

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4 Monitoring and evaluation of residential building level demonstrations (Belgium). Demo 1, b)

Authors: Actility-Flexcity.

4.1 Introduction

An energy management platform has been deployed into four residential buildings (houses). The houses are situated within the same residential neighborhood in Belgium. This reports highlights results obtained in two houses.

The houses were or have been equipped with smart appliances that are associated to a certain storage capacity in the form of thermal energy. The appliances are connected to specific energy meter.

Control devices are installed to influence their state (e.g., ON or OFF). Thereby, their power consumption can be remotely controlled to serve different purposes.

This demonstration evaluates the impact of **dynamic pricing**, i.e. the response of appliances to hourly day-ahead market price of Belgium. An optimisation algorithm minimises their energy costs by consuming in the hours when prices are the lowest. A **Model Predictive Control** framework runs in real-time, updated every 5-15 minutes, over a time horizon of 24 hours.

The main contributions of this document are listed below.

- **Methodology:** a comparative analysis method is proposed used to determine the evolution of performance indicators (e.g., electricity cost) following the introduction of optimisation & control infrastructure.
- **Robust Optimisation:** The MPC optimisation framework exploits data metered in real-time as well as forecast of those data. In case real-time value of a certain parameter is missing (communication problems, etc.), the MPC framework allows to replace it with its last forecast. In case of long run communication problems, local control can take back the lead. The robustness is evaluated in the form of availability of control command.
- **Comparing Direct & Indirect control:** It is well known that Interoperability is the key obstacle to the roll-out of smart-house solutions at a large scale. We have shown that interfacing with minimal interaction (smart plugs, indirect control via temperature set point in thermostat) is a simple but efficient way to control the smart appliances at stake. Furthermore, we show that indirect control (control via thermal set-points) is possible under the condition that user's feedback is considered properly.

4.2 The concept

The Demonstration setup is at residential building scale (Oud-Heverlee, Belgium). Figure 4-1. Four houses are in the scope of this report. The fifth one is not in the scope, the Think-E Living Lab.

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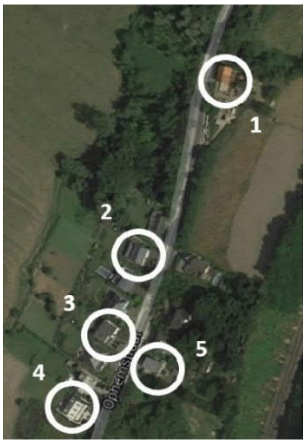

Figure 4-1-The Neighborhood

The objective of the demonstration is to:

- Go through interoperability challenges.
- Evaluate the controllability of the electricity consumption of thermal appliance.
- Understand End-user acceptance.

The reason behind is that flexibility from residential appliances in Belgium are still largely untapped mostly due to technical and economic barriers.

A single building is modeled as a subset of a few possible components, listed below and shown in Figure 4-2.

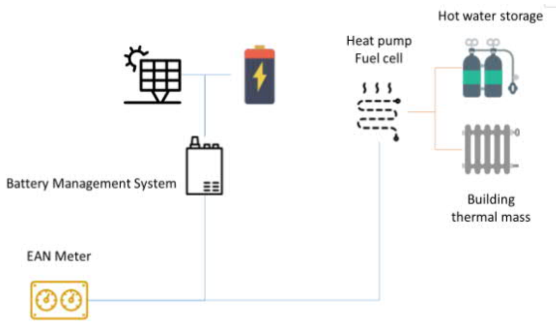

Figure 4-2 -A single house and it's components

- Battery system
- Heat pump
- PV installation
- Fuel cell
- Hot water storage
- Building thermal mass

For each building, the power **consumption/generation** of the most important appliances are **monitored** (loads, generation and storage). The energy flow between the grid and the house (main meter) is also metered.

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Appliances’ **energy consumption is controlled** via actuators either directly (on/off, state control) or indirectly (thermostat).

This report studies the control of heat pumps for house and water temperature control, as shown in Table 4-1.

Table 4-1- Overview of the thermal model exploited in the optimisation (heat pumps)

Model	State variable	Storage capacity	Boundaries
Building house 4, 3 & 2	Inside temperature	Building thermal mass	Temperature comfort
Boiler house 4	Water temperature	Thermal mass	Temperature comfort

The **states** of the appliance/building (temperature of room, temperature of water, water flows, etc.) are measured and exploited in an **energy model**. This model can **predict/simulate** the energy consumption of the appliance based on desired temperature profile, water demand, solar gains, etc.

Communication with the external world is established via **multiple canals**: fixed internet line, mobile technology (2G/3G) and LoRaWan Gateway is also used on the energy metering part.

The software consists in solving **model predictive control** (MPC) problems that are based on **mixed integer linear programming** (MILP) models of controllable systems which is solved for every time step k over the horizon p, as illustrated on Figure 4-3.

Horizon	24 to 48 hours
Timestep	Hour
Control step	15 minutes

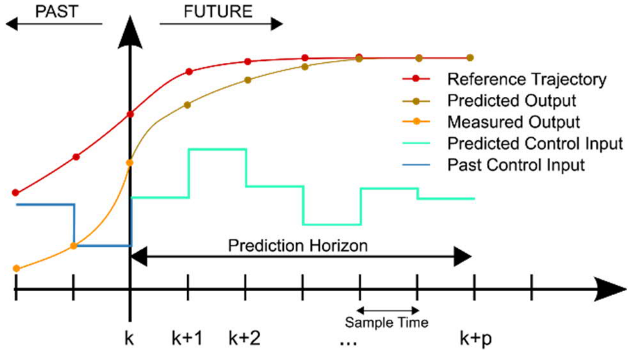

Figure 4-3 -Illustration of MPC and moving prediction horizon with current time k

The **energy model** of appliances and building is a physical model that can later be exploited in different use case (objective function) by formulation of an adequate objective function (Figure 4-4).

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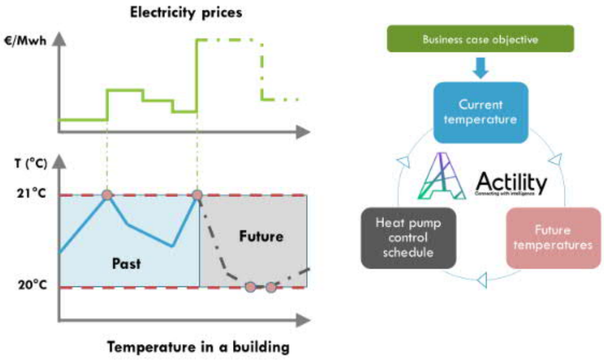

Figure 4-4 -The control setup and link with electricity prices

4.3 Use cases evaluation

4.3.1 Dynamic Pricing

The use case at stake is dynamic pricing. It is formulated within the optimization framework as the objective function of the MPC. The control algorithm minimizes the total cost of heating the thermal mass of which temperature is being regulated based on an hourly price profile (Table 4-2).

Table 4-2- Optimisation setup

Objective	Minimize cost of sourcing electricity
Parameters	Hourly price profile (Day ahead price in Belgium), Outside temperature, PV generation forecast, (Non-flexible electricity consumption)
Models	Thermal mass evolution, Electricity consumption of the heating appliance
Control step	15 minutes

At the moment this report is written, residential end-users are not exposed directly to day-ahead market prices in Belgium. As such, these day-ahead prices were only used as a proxy for the residential electricity prices available to the neighborhood consumers.

In order to **compare the behavior** of the houses **under the control** (Control case) to other days **without control** (Base Case) in a relevant way in comparable terms, **one set and two subsets of days** are defined based on specific criteria. Firstly, the **set of valid days** is the set of days during which measurements could be done at an adequate rate, high quality and precision. The **Control** and **Base Case** days are a **subset of the valid days** respectively situated within days where control was performed by the central optimisation (Control case) and within days with local control only (Base Case).

In this demonstration, five **Control Periods are studied**, representing a certain scope for the optimization (Table 4-3).

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Table 4-3 -The Control Periods

Period	House	Storage	Optimized load
1 & 2	4	Boiler	Electric water boiler
3 & 4		House	Heat pump (space heating)
5	3	House	Heat pump (space heating)

For each control period, valid days are defined. The Control and Base case are selected according to three quantitative comparison criteria:

- Daily electric consumption, in kWh
- Outside temperature average, in °C
- Solar irradiance, in Wh/Day

Comparable days are selected by defining maximum and minimum limits on the quantitative comparison criteria (Table 4-4). The resulting selection is illustrated on Figure 4-5 (solar irradiance vs temperature).

Table 4-4– Min./Max. value of Selection Criteria

Period	Criteria	Unit	Min.	Max.
1	**Energy consumption**	kWh/d	-	3.6
	Outside Temperature	°C	9	-
	Solar Irradiance	Wh/m²/d	837	-
2	**Energy consumption**	kWh/d	0.4	4.3
	Outside Temperature	°C	-	13.5
	Solar Irradiance	Wh/m²/d	1000	25000
3	**Energy consumption**	kWh/d	-	27.2
	Outside Temperature	°C	10	-
	Solar Irradiance	Wh/m²/d	700	3700
4	**Energy consumption**	kWh/d	30	51
	Outside Temperature	°C	5.3	11.5
	Solar Irradiance	Wh/m²/d	1400	4152
5	**Energy consumption**	kWh/d	11.5	26.8
	Outside Temperature	°C	-0.65	11.4
	Solar Irradiance	Wh/m²/d	887	3905

Table 4-5– Resulting number of days to compare

	Control case	Base case
Period	Number of Days	
1	20	**20**
2	8	**8**
3	20	**20**
4	8	**8**
5	20	**22**

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Days with low data quality are excluded and weekdays type are considered (same repartition of week/weekend days in both sets). The electricity price is used as a normalization factor in the performance analysis. Table 4-5 highlights the number of days in each set of Control periods 1 to 5.

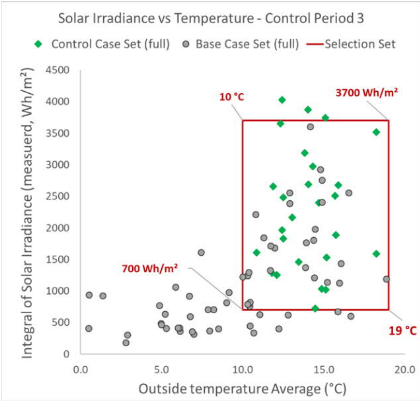

Figure 4-5- 2D Days selection illustrated

Advantage of the Days selection method

The days selection methodology allows to estimate the benefit that the presented control framework brings in some comparable terms. This is a challenge as the 5 different control periods lasts 8 to 20 days, with temperatures ranging from 0°C to above 15°C and take place in the winter and autumn seasons.

Limits of the the Days selection method

This method leads to the exclusion of days within both control and non-control periods based on exogenous (i.e., outside temperature) and endogenous (i.e, electricity consumption) criteria. Yet, the methodology tends to exclude extremes (i.e., <0°C) simply as an extreme value observed during the periods with external control could not always be found in the days where only local control was used.

As illustration, the energy consumption in all days of Control and Base Case of period 3 are shown on Figure 4-6.

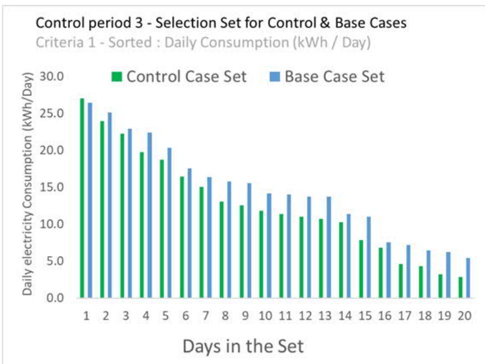

Figure 4-6- Electricity consumption comparison in Base and Control Case (Period 3)

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The behaviour of the control linked to thermal limits and to price response are illustrated respectively on Figure 4-7 and Figure 4-8.

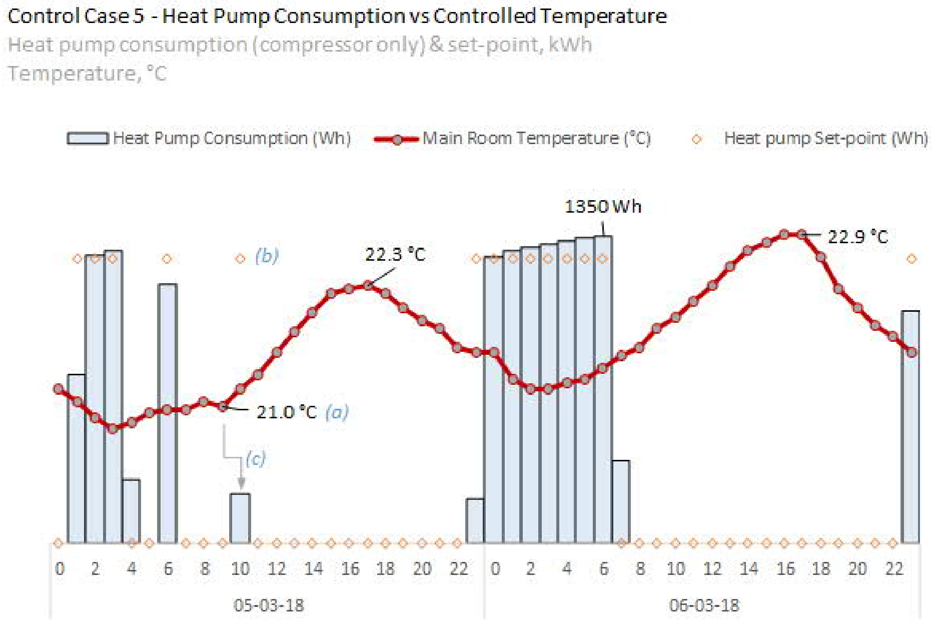

Figure 4-7- Heat pump consumption vs Controlled Temperature. The control set-point varies between zero and maximum heating power following price and temperature forecast with real-time feedback on temperature. On the 5th of march, a sudden temperature drop (a) leads to a short start command (b) then to electricity consumption at 10 am (c). This occurs within high price period.

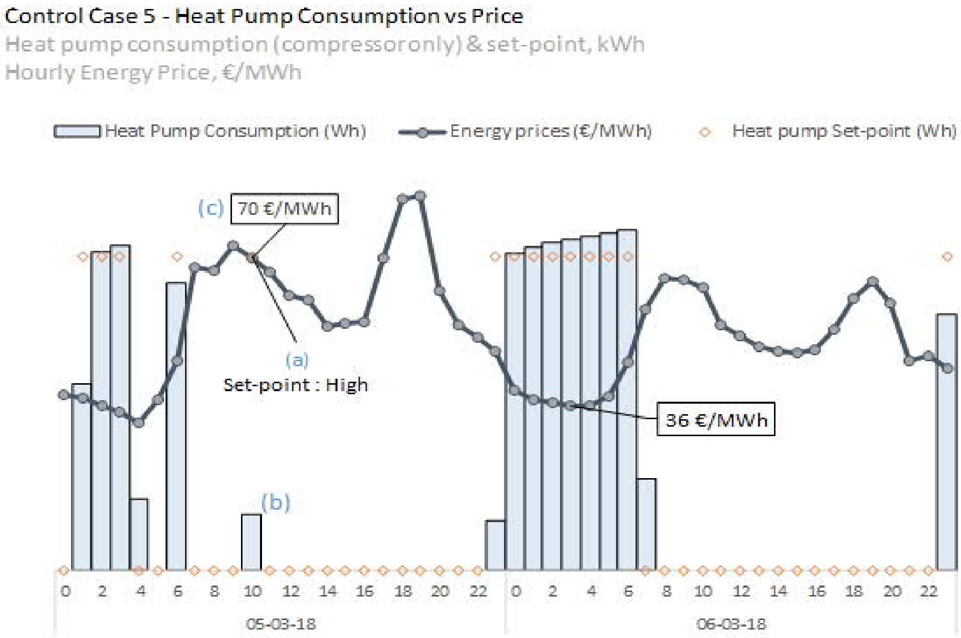

Figure 4-8- Heat pump consumption vs Energy price. The consumption occurs mainly at low-price period. Thermal constraints may force the control (a) to consume electricity (b) at higher prices (c).

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The uncontrollable part of the load **is considered** in the rest of this text for performance analysis. This means that reduction in power consumption is relative to both controlled and uncontrolled part of the consumption of each participating house/appliance (Figure 4-9).

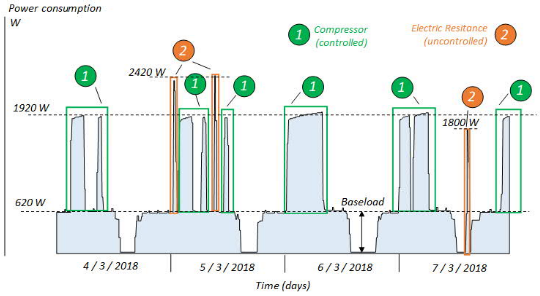

Figure 4-9- Uncontrollable part of consumption.

The technical and economic performances are evaluated via 3 KPIs listed below, according to D6.2[6].

- ***KPI 1.1: Energy Costs have decreased***
  - Consumption in control case should lead to lower energy costs.
- ***KPI 1.2: Energy is used locally (self consumption and self sufficiency levels)***
  - Auto-production should not be negatively impacted.
- ***KPI 1.3: Infrastructure is available***
  - The measurement-communication-control chain works >95% of the time.

KPI 1.2 is only applicable to the house of control period 5 as the only house with local generation.

Table 4-6 -KPI list (technico- economic performance)

		Applicable control period				
KPI	Name	1	2	3	4	5
1.1	Energy Costs have decreased	x	x	x	x	x
1.2	Energy is used locally					x
1.3	Infrastructure is available	x	x	x	x	x

The storage performance and environmental impact are described respectively in section 4.4 and 4.5.

4.3.2 KPI Description - Energy Cost Decrease

By selecting the most appropriate hours to heat the thermal mass at stake, the control in the dynamic pricing use case has an impact on the cost of the thermal appliance's consumption.

The control **score** is the reduction in cost that we can attribute to the control. It is expressed below, where cont and base stand for control and base cases.

[6] "Use cases and Key Performance Indicators (KPIs) of the STORY project" http://horizon2020-story.eu/wp-content/uploads/STORY-use-cases-and-KPIs.Publish1-1.pdf

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$$1 - \left(\frac{C_{cont}}{B_{cont}}\right) / \left(\frac{C_{base}}{B_{base}}\right)$$

The score factor exploits the ratio (C/B) between the **total daily costs** (C) on the day-ahead market (i.e., =consumption per hour x price per hour) divided by the **baseload daily cost** (B) (i.e., = baseload price x daily consumption). The **baseload price** is the hourly average of the day-ahead market price, epex spot BE.

4.3.3 KPI results - Energy Cost Decrease

Dynamic pricing essentially leads to a concentration of electricity consumption within hours where the price is the lowest. The consequence of the control is that the consumption will in some way mirror the daily price profile. The effect of dynamic pricing on consumption profiles is detailed for each period in Table 4-7.

Table 4-7 -Profile impact and energy shift results

Period 1 - 2 (Water Boiler)
Profile change: shifted mostly in **early morning** (<6 am) except after water draws.
Average shift: 4**0% of the daily consumption**
Period 2 - 3 (house 4)
Profile change: heat pump's consumption shifted **partly in the early morning** (<6 am) and **partly in the late evening** (>8 pm).
Average shift: 1**0% of the daily consumption** (5% in morning, 5% in evening)
Period 5 (house 3)
Profile change: shifted mostly in **early morning** (<6 am).
Average shift: **14% of the daily consumption**

The score factors for each period are computed on Table 4-8.

Table 4-8– Cost Reduction (score factor)

Period	Season	#Days	Score
1	Autumn	20	13.5 %
2	Winter	8	2.6%
3	Autumn	20	4.3%
4	Winter	8	0.9%
5	Winter	20	6.3%

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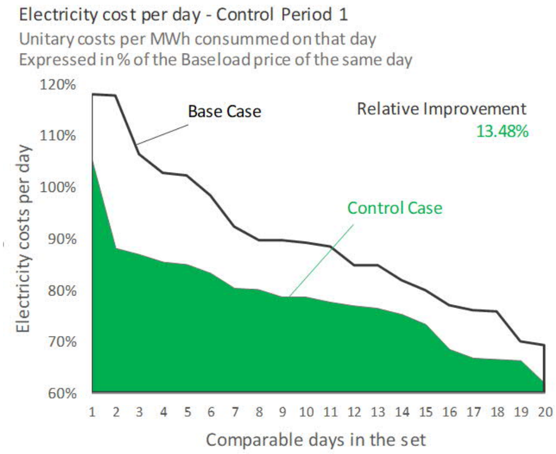
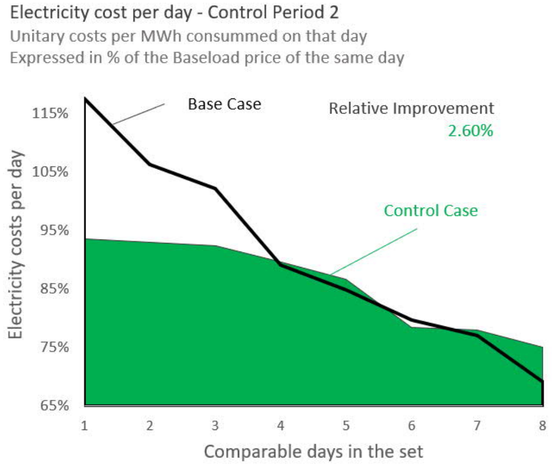
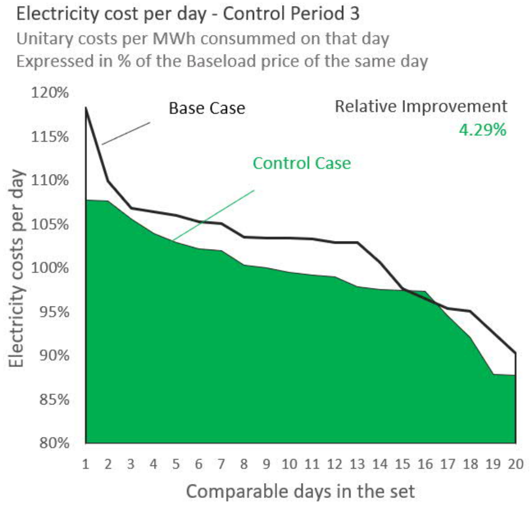
Daily costs are illustrated in Figure 4-10. Cost reduction is highlighted by the area between the base and control case lines.



(a) Control Period 1



(b) Control Period 2



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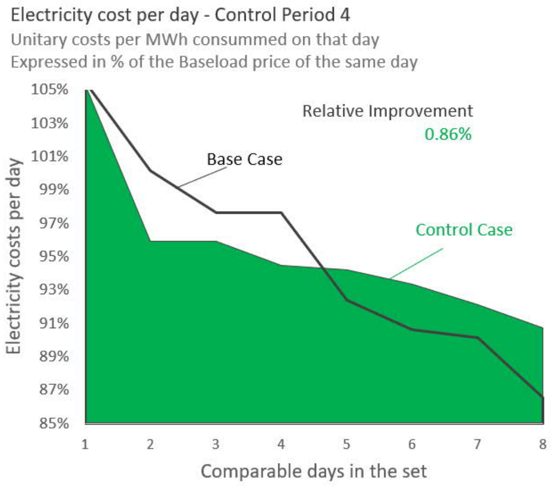
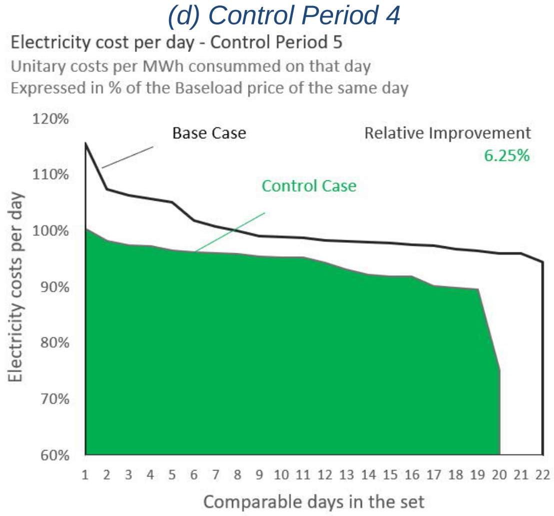
(c) Control Period 3



(d) Control Period 4



(a) Control Period 5

Figure 4-10-Electricity Cost per day, relatively to an equivalent consumption of the same amount of energy at the daily baseload price in Base and Control Case

The daily average energy profile also shows the impact of the control (Figure 4-11, Figure 4-12, Figure 4-13).

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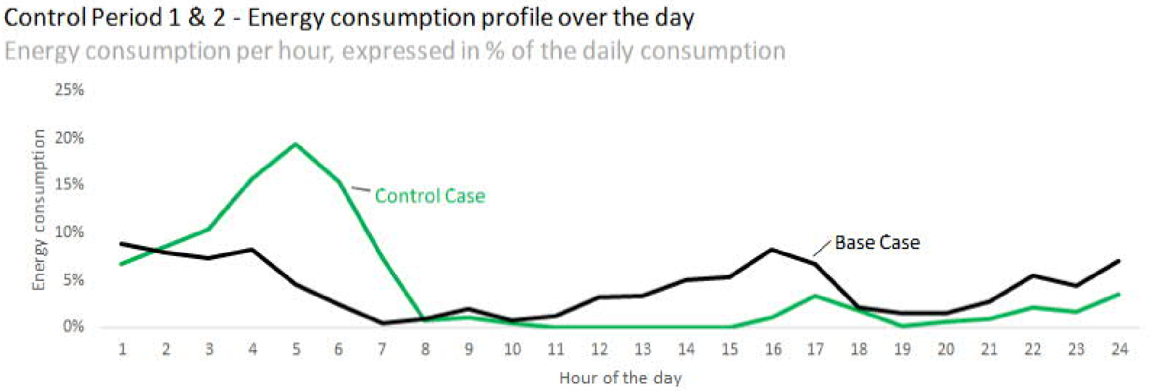

Figure 4-11- Daily energy consumption for control period 1 & 2 (water boiler). The consumption shift corresponds to 46% of daily consumption.

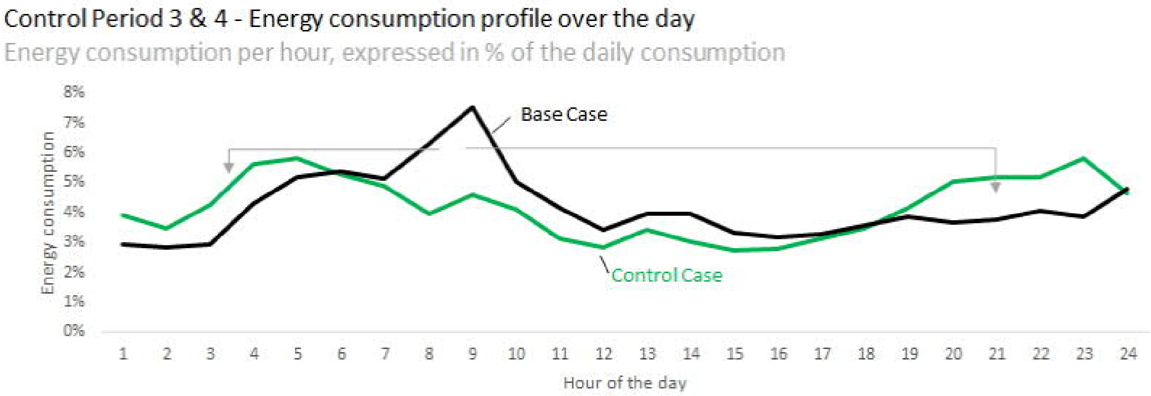

Figure 4-12- Daily energy consumption profile for control period 3 & 4 (house heating). The consumption shift corresponds to 11% of daily consumption.

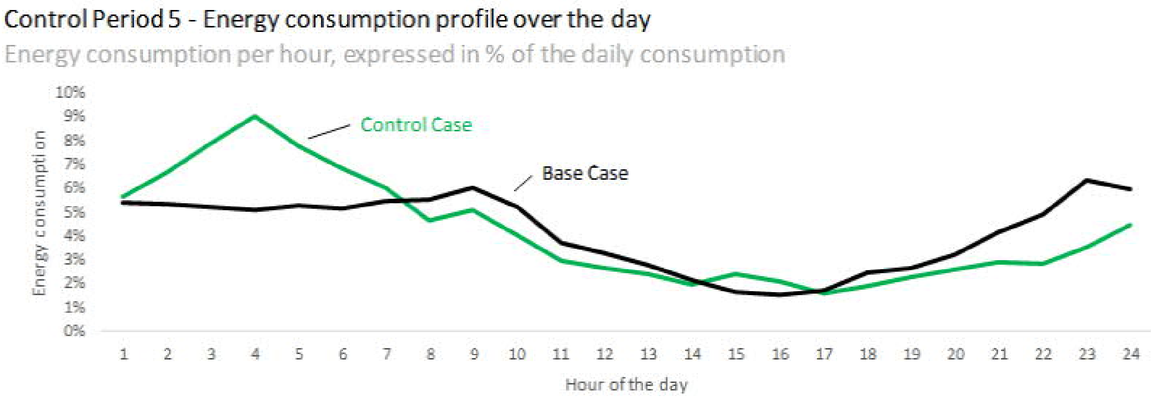

Figure 4-13- Daily energy consumption for control period 5 (house heating). The consumption shift corresponds to 14% of daily consumption.

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The consequence of controllability is reported on Table 4-9**Error! Reference source not found.**. Appliances with good controllability have higher realised shifted energy and associated cost reduction.

Table 4-9– Overview of the Impact of controllability

Period	Appliance	Control	Shifted energy	Cost Reduction
1 - 2	Water Boiler	Direct, Good	**40%**	**10.3%**
3 - 4	Heat pump (space heating)	Indirect, Poor	**10%**	**3.8%**
5		Direct, Good	**14 %**	**6.3%**

4.3.4 KPI Description – Local Energy use

Dynamic pricing may have an impact onn the consumption of locally generated energy. The applicability of this KPI is limited to house with local generation (house 3).

As illustrated on Figure 4-14, self-consumption and self-sufficiency levels are evaluated and computed on a certain interval T for this house. Self-consumption level SCL (%) is defined as a ratio between self-consumed locally produced energy (C) with the total amount of locally produced energy (C+B), of which the surplus is injected into the main grid. Self-sufficiency level SSL (%) is defined as a ratio between the consumption covered by local production (C) with the total consumption (C+A) over certain monitored interval.

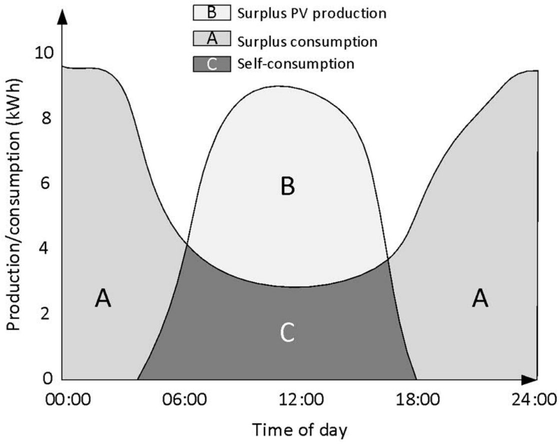

Figure 4-14 -Visualization of SCL and SSL (SCL=C/(C+B); SSL=C/(C+A)) [7]

We will observe two cases with T = 1 day, and T = all comparable days in the control & base cases.

[7] S. Cao, A. Hasan, K. Sirén, On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections. Energy and Buildings, Volume 64, 2013, Pages 423-438, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2013.05.030.

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The installed PV generation is 10 kWp. Let's note that the Daily PV generation (average per day) is a bit higher in the control case than in the base case, respectively 17.4 kWh/day and 14 kWh/day.

4.3.5 KPI results – Local Energy use

As shown on Figure 4-15, the Self-consumption and self-sufficiency levels tend to increase slightly following the introduction of external control.

This is somehow counterintuitive as the consumption is shifted in the early morning for house 3, where there is no PV generation (see previous discussion). Yet, two elements explain this result: (1) for this house, most of the consumption that is shifted before 6 am in the optimized case is sourced from hours before 11.00 and after 20.00, hours where there is little PV generation, and (2) consumption tends to increase in the hours 13.00 to 17.00, where the PV generation is high.

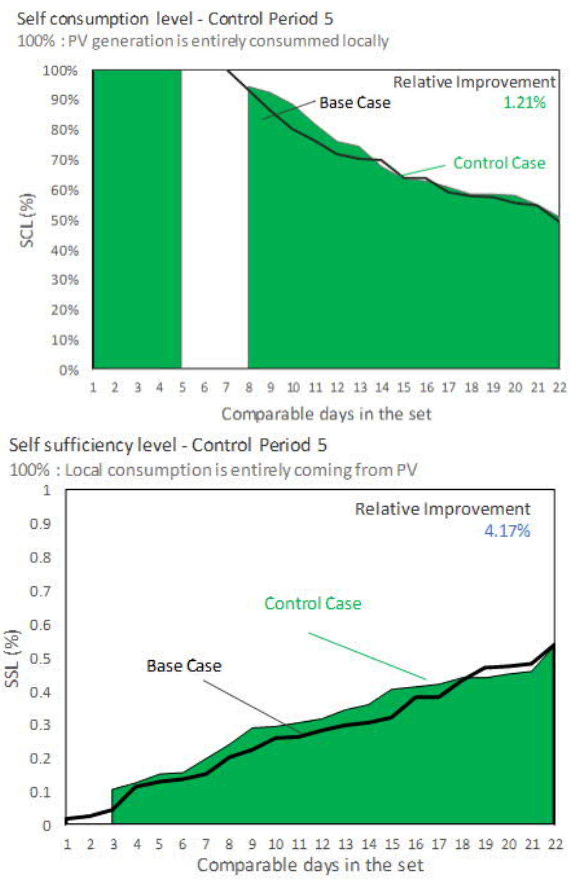

Figure 4-15- SCL (Top) and SSL (Bottom) evaluation in control and base case. The self consumption in the control case is lower relatively to each daily average but not in absolute value.

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4.3.6 KPI Description – Availability of device and data

The control infrastructure block diagram is represented on Figure 4-16. The different blocks are representative of appliances, controllers or software that must be kept functional most of the time for our control chain to reach good overall performance. In order to take correct decisions in real time, it is necessary to (1) have access to all necessary data (states, external disturbances, reference input), (2) send control commands, (3) compute states, (4) keep track of the recent past and (5) forecast future states/etc.

To this end, five components must be made available to the model by the technical infrastructure (Table 4-10, Table 4-11).

The availability of each component is computed separately as the ratio between the number of data received in hour, h, with the expected refreshment rate of data per hour, capped at 100%. The availability the whole chain in hour, h, is the minimum availability of each component.

Table 4-10–Control chain's components (Water)

Symbol	Description	Hot Water (Periods 1,2)
y	Appliance Output(s)	Electricity consumption
		Water temperature
u	Control Command(s)	On/Off Status of Appliance
x	**Model State(s)**	Energy content
d	**Disturbance(s)**	Electricity price
		Outside temperature
r	**Reference(s)**	Comfort constraints

Table 4-11– Control chain's components (Building)

Symbol	Description	House (Periods 3-5)
y	Appliance Output(s)	Electricity consumption
u	Control Command(s)	Temperature set-point on thermostat
x	**Model State(s)**	Energy content
		Inside temperature
d	**Disturbance(s)**	Electricity price
		Outside temperature
r	**Reference(s)**	Comfort constraints

The expected rate is either technical (i.e., maximum rate allowed by the infrastructure) or functional (i.e., minimum rate required to for the control to run properly and effectively). Technical and functional rates are defined below (not applicable to reference input).

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Table 4-12– Data Rate per period/component

	Technical / Functionnal rates (per hour)	
Symbol	Periods 1,2	Period 3,4,5
y	12* / 4	60 / 4
u	4* / 4	4 / 4
x	12 / 1	6 / 1
d	1 / 1	1 / 1

* Smart Plug (LoRa) refreshed once per hour.

Note: One of the appliances of control Period 1-2 is equipped with a Smart Plug. The Smart plug is a class C LoRa control-measurement device with dynamic data rate. Measure: data are refreshed every 6 hours when no substantial change is measured (e.g., the appliance is idled) and every 5 minutes if data evolve significantly. Control : control signals may be sent at any moment in real-time.

4.3.7 KPI results – Availability of device and data

Functional availabilities are reported on Table 4-13. The results show that the infrastructure was able to compute and send a command (u) around **95% of the time** even with imperfect vision of the situation. This is thanks to the robustness of the real time implementation. Guaranteeing a perfect availability all source of data at the same time is relatively difficult. This is the consequence of the nature of the data streams originating from a broad number of sources using multiple communication protocols.

Table 4-13– Functional availabilities

Periods	**1-2**	**3-4**	**5**
y	89%	99.9%	100%
u	**100%**	**92%**	**97.6%**
x	95%	92%	91%
d	99.8%	99.9%	100%
Global	**88%**	**84%**	**88%**

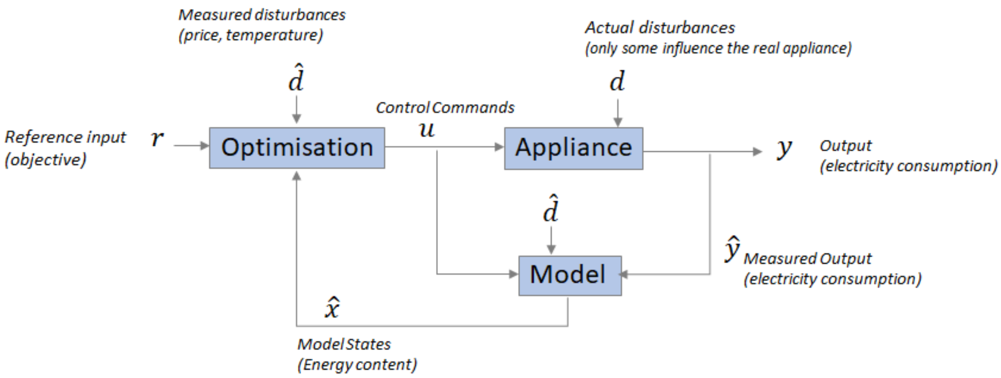

Figure 4-16– Control Block Diagram

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Table 4-14- Monitored temperatures, Thermal model and associated controlled temperature

Control Period	House	Storage System	Monitored temperature	Thermal Storage Model	Controlled temperature
1	4	Water Boiler	(3) **Top, Center and Bottom** temperatures	Energy content Model based on the 3 monitored temperatures (Vito)	Top temperature
2					
3		House	(5) **Living room**, kitchen, office, hall, bathroom temperatures	Hours without heating (see below)	Living Room
4					
5	3	House	(5) **Living room**, kitchen, office, bedroom, bathroom temperatures	Hours without heating (see below)	Living Room

4.4 Energy storage systems performance evaluation

4.4.1 KPI - Comfort

The most important constraint of the thermal storage exploited in this demonstratin is to maintain the comfort within acceptable limits (Table 4-15). The temperature under control should stay within acceptable limits.

Table 4-15– Storage means and comfort limits

Period	Storage	Controlled Temperature	Min.	Max
1-2	Water	Top Temperature	10°C	60°C
3-4	Space	Living Room	19°C	23 °C
5			20°C	24 °C

Yet, the control of the thermal storage (water, space heating) will have an impact on the temperature distribution.

4.4.2 Performance evaluation - Comfort

Water temperature (Period 1,2)

The water boiler (control period 1-2), the distribution shows a general reduction of temperature from 54°C in the base case to 44°C in the control case.

House temperature (Period 3,4,5)

In control period 3-4, the temperature increases in the house during the control from an average of 20.5°C in the base case to 21.1°C in the control case. The heat pump of house 4 is only

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indirectly controlled. Our commands are not always applied immediately (delayed response) but they tend to influence the average profile. The consequence of this is that, according to the occupant's feedback on first control days, the thermal comfort within the house was not ideal. Consequently, it was decided that the average temperature set-point should be increased

In Control Period 5, the **average** temperature in the house **does not change** (21.7°C in both control and base case). However the **variation** of temperature is **higher**, as the standard deviation in control case reaches 0.67°C, compared to 0.47°C in the base case (no control).

Link to outside temperature

The difference in variability of the temperature inside the house is also driven from the temperature profile outside the house. In Control Periods 3&4, the mean and standard deviation of the outside temperatures are respectively 8.8°C and 4.2°C in the base case, and 11°C and 4.18°C in the control case. Those values are 15°C (mean) and 3.9°C (standard deviation) in the base case and 18°C (mean) and 4.2°C in the control case of control period 5.

4.4.3 KPI – Storage Use

For each thermal appliance, an energy model is used in order to follow the evolution of the state of **charge of the storage**.

Hot Water boiler model (Period 1,2)

The boiler energy content is derived from the measurement of 3 temperatures: top, center, bottom. This reported on Table 14 and illustrated on Figure 17. The model is provided by Vito, partner of the project, and exploits the real-time measurements of the temperature in the boiler.

House thermal model (Period 3,4,5)

The thermal storage of the house is modeled as a virtual battery with a time varying capacity, since thermal losses depends on the varying outside temperature. The controlled temperature $T(t)$ evolves with time following a time-delayed discrete time model.

$$T(t+1) = T(t) + \frac{\Delta t}{C}\,[\eta \times u(t-d) - k \times (T(t) - T_{out}(t))]$$

C is the thermal capacity [kWh/K], k is an equivalent conduction factor [kW/K] and η is thermal power of the heating system [kW].

Time t is expressed in hours and $u(t)$ is a variable representing the heating state of the appliance under consideration [-]. Time delay d express a form of delay between the change of state of the heating system and its effect on temperature. Finally, $T_{out}(t)$ is the external temperature.

In order to represent the storage capacity, let's introduce three concepts: (1) the maximum number of hours of storage, (2) the actual hours of stored energy and (3) the instantaneous state of charge, being the ratio between (2) and (1), with $A = \Delta t \times \frac{k}{C}$.

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$\overline{H}(t)$ - *Maximum hours of thermal storage*

Definition: $\overline{\mathrm{H}}(\mathrm{t})$ is the time (in hours) that would be necessary without heating for the controlled temperature to go from his maximum $\mathrm{T_M}$ to minimum $\mathrm{T_m}$ acceptable levels assuming constant thermal losses.

$$\overline{\mathrm{H}}(\mathrm{t}) = \max\left[0\,;\,\frac{\mathrm{A}\,(\mathrm{T_M}-\mathrm{T_m})}{(\mathrm{T_M}-\mathrm{T_{out}}(\mathrm{t}))}\right]$$

$\mathrm{h}(\mathrm{t})$ - Hours of thermal storage

Definition: $\mathrm{h}(\mathrm{t})$ is the number of hours required, without any source of heating, for the temperature to reach its minimum acceptable value starting from its actual level.

$$\mathrm{h}(\mathrm{t}) = \max\left[0\,;\,\frac{\mathrm{A}\,(\mathrm{T}(\mathrm{t})-\mathrm{T_m})}{(\mathrm{T}(\mathrm{t})-\mathrm{T_{out}}(\mathrm{t}))}\right]$$

$\mathrm{SoC}(\mathrm{t})$ – State of Charge

Definition: $\mathrm{SoC}(\mathrm{t})$ represents the ratio between current and maximum hours of storage.

$$\mathrm{SoC}(\mathrm{t}) = \frac{\mathrm{h}(\mathrm{t})}{\overline{\mathrm{H}}(\mathrm{t})}\ \text{, if } \mathrm{T_M}, \mathrm{T_m} > \mathrm{T_{out}}(\mathrm{t})$$

The model is usable only for low outside temperature (when heating is required), or more properly when $\mathrm{T_M}, \mathrm{T_m} > \mathrm{T_{out}}(\mathrm{t})$.

The Table 4-16 lists all parameters of both houses.

Table 4-16– Thermal Model Parameters (houses)

Period	T_m [°C]	A [-]	T_M [°C]	Average max. hour $\overline{H}$	Average storage hours h
3 & 4	19°C	40.5	23	14h	7h30
5	20°C	54	24°C	12h	5h30

4.4.4 Performance – Storage Use

The evolution of the energy content for each control period is shown below on Figure 4-18, Figure 4-19 and Figure 4-20.

Control should introduce a larger variability of the storage level in the control case than in the base case. Indeed, the energy content should in theory be spread across a larger band. This is a marker for the storage being exploited in a larger extent when external control is in place. This behavior is observed in Control Period 1,2 and 5. Due to a lower controllability, the control cases of Control Period 3 and 4 show a lower variability in energy states.

This is confirmed by the mileage comparison below. The daily mileage measure is a way to compute the daily use of storage. Let $\mathrm{SoC}(\mathrm{t})$ be the state of charge of the thermal storage asset on time t. Then the change in SoC between two successive time steps is defined below.

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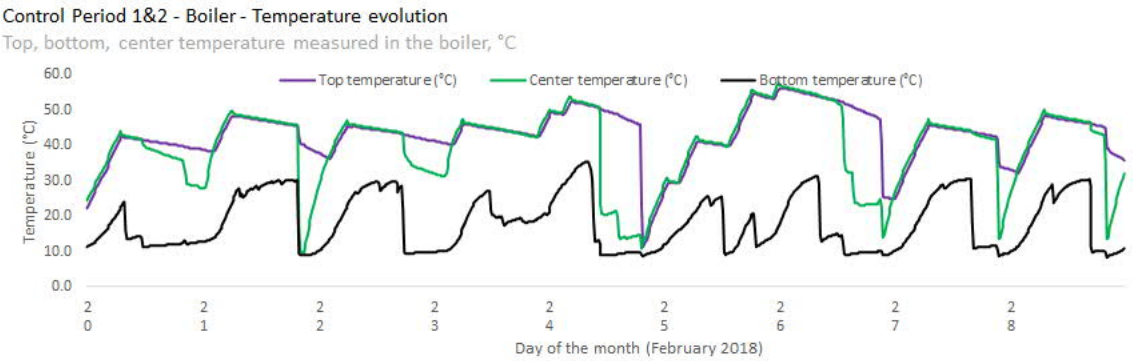
$$\Delta SoC(t) = SoC(t) - SoC(t-1)$$

The Mileage M on day D is expressed as the sum of the absolute value of the change in SoC.

$$M(D) = \sum_{t \in D} |\Delta SoC(t)|$$

Table 4-17– Mileage in Control and Base Cases

Period	Base Mileage	Control Mileage	Change
1-2	75%	80%	**+5.3%**
3-4	102%	77%	-25%
5	45%	52%	**+15%**



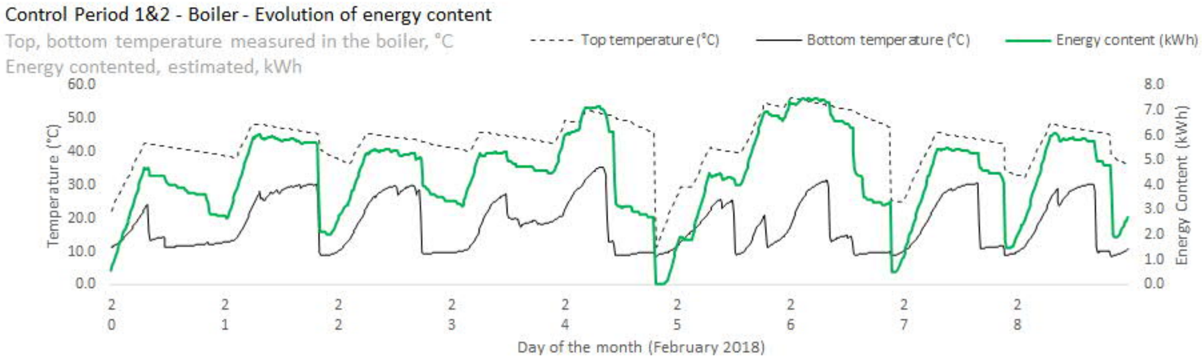


Figure 4-17– Temperature Top, Center, Bottom, and Energy content (Boiler)

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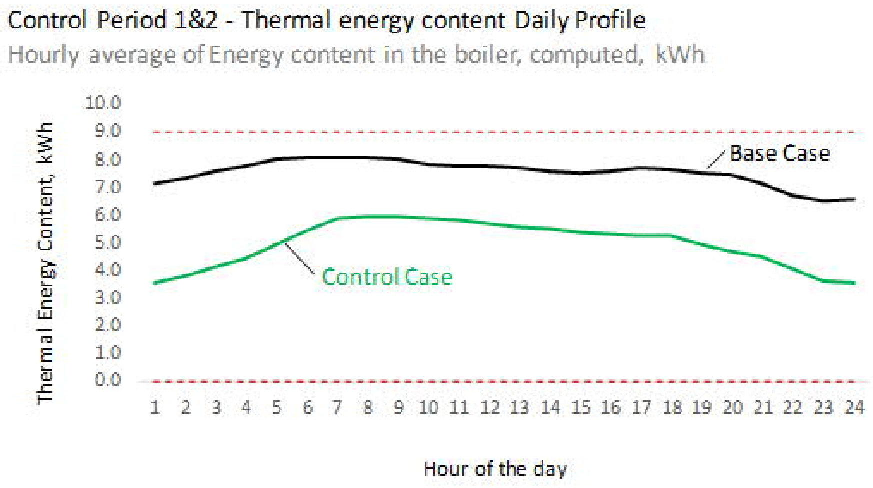

Figure 4-18– Thermal energy content profile in Control and Base Case (Period 1-2)

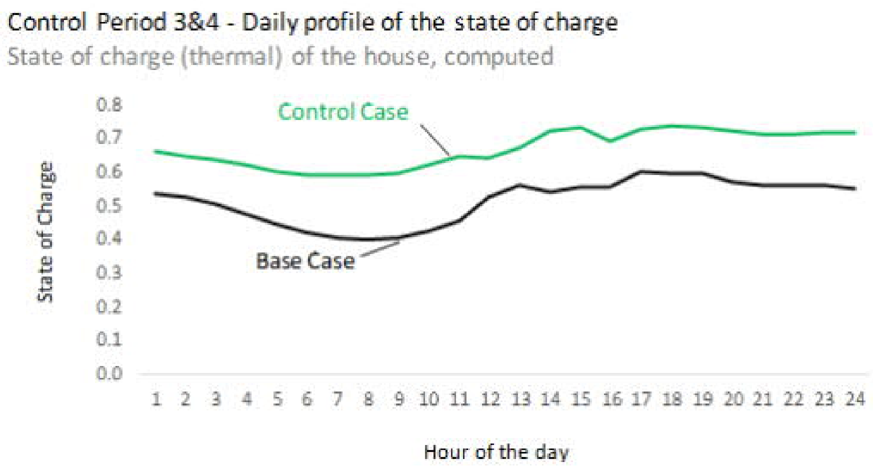

Figure 4-19– Thermal energy content profile in Control and Base Case (Period 3-4)

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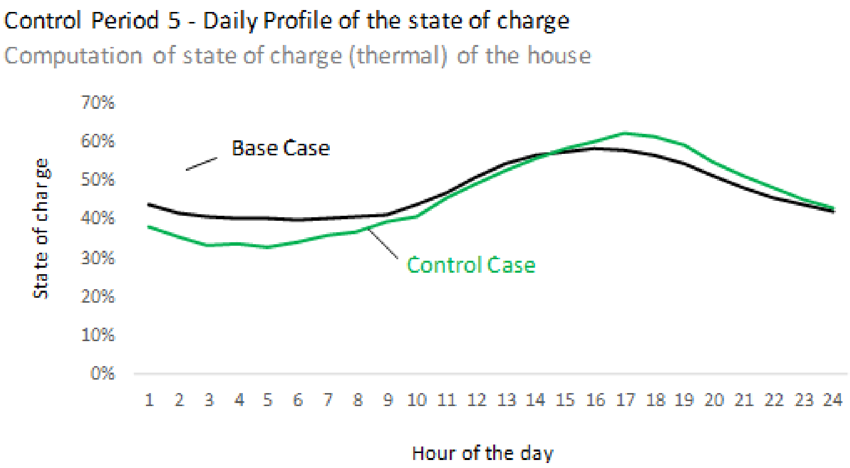

Figure 4-20– Thermal energy content profile in Control and Base Case (Period 5)

4.5 Environmental analysis

4.5.1 KPI

The CO2 equivalent emissions in the base and control cases are compared using the ratio between the actual **CO2eq. emissions per kWh** consumed by the appliance on one day with the **baseload emissions** of the same day. This ratio is denoted as the **real to baseload emissions ratio.**

To this end, the marginal CO2eq. equivalent emissions of the Belgian electricity system are modeled based on publicly available data of production per fuel (largest units8) as well as some typical CO2eq. emissions per generation technology[9].

4.5.2 Performance evaluation

The emission ratio in the base and control case is reported on Table 4-18.

Table 4-18– Emission Reduction

Period	Base	Control	Relative reduction
1-2	96%	92%	4%
3	102%	101%	0.93%
4	98%	96%	2.35%
5	99%	96%	2.41%

[8] http://www.elia.be/en/grid-data/power-generation
[9] Source : Tranberg, B., Corradi, O., Lajoie, B., Gibon, T., Staffell, I. and Andresen, G.B., 2018. Real-Time Carbon Accounting Method for the European Electricity Markets. arXiv preprint arXiv:1812.06679.

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The **difference in emissions** between control and base case period is linked to: (1) the hourly variation in CO2 eq. emissions of the generation mix and (2) the potential increase use of locally generated energy (PV, in control case 5).

Emission reductions are relatively more pronounced for appliances with higher control capability (Period 1,2 and 5). The driver of emission reduction is the fuel mix of the belgian system being less carbon intensive at night on average (nuclear power). The actual consumption of the heat-pump in control period 3 leads to higher CO2eq. emissions per kWh than a baseload consumption, both in base and control case. The control case leads to slightly less emissions.

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5 Monitoring and evaluation of neighborhood level demonstrations (Belgium). Demo 2.

Authors: Leen Peeters (Th!nk E), Frank Veltmans (Th!nk E), Arnor Van Leemputten (Th!nk E), Lucija Rakocevic (Th!nk E), Christophe Van den Eynden (VIESS).

5.1 Introduction

The Oud-Heverlee neighbourhood demonstration has been implemented in the second part of the STORY project. This demonstration focuses on the energy strategy to impact grid balancing and flexibility. Grid balancing and flexibility is achieved utilizing two technologies: electric vehicles (EVs) and Belgian's first neighbourhood battery.

In this chapter, the technical concepts for the use of both of these technologies to assure low voltage grid flexibility are elaborated. The chapter concludes with lessons learned from the application and installation of the technologies.

5.2 The neighbourhood concept

The Oud-Heverlee demonstration site consists of 13 residential buildings that are located on the low voltage grid. Power quality of the local grid is non-optimal due to two factors: the neighbourhood being located at the end of an old distribution line and high share of EVs by these households (7 EVs and HEV for 13 households).

Monitoring and management of each household and its associated installed technology (PV, heap pumps, battery storage or EVs) can solve the problem. However, such an approach requires installation, interoperability and communication of numerous devices and imposes ethical challenges. While complicated to implement, it also requires additional energy to assure operation and communication of these devices.

Therefore, in this report we present a novel approach. The solution is to monitor line voltage levels and manage flexible device performance based on this parameter only. Here this concept is applied on the control of EV charging and neighbourhood battery separately. It is specifically the characteristics of this local grid that enable such control: a long and overused cable that shows clear voltage swings. It is further an ideal case to show the added value of the neighbourhood battery system: in this particular case it enables an improved quality of supply.

5.3 EV charging

Electric vehicle (EV) charging is a decisive load in this residential environment. A vehicle plugged in to a residential charger requests between 3 kW and 7 kW power. When multiple chargers are installed on the same line, the local grid can become unbalanced. This results in a lower power quality, power interruptions or in extreme cases even possible damage to household appliances. The STORY demonstration in Oud-Heverlee has a high uptake of EVs (6 EVs at the start of the demonstration, 8 by the end of 2020). By aligning EV charging times on neighbourhood level, stress can be relieved from the local grid resulting in higher power quality.

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5.3.1 Concept

Alignment of EV charging within the neighbourhood can be considered on different levels. A first approach is to consider a high-level algorithm which controls the different chargers in the neighbourhood. Such a controlling algorithm could make use of predictions in neighbourhood load profile and user behaviour to schedule EV charging throughout the neighbourhood. Previous lessons learned within STORY have already showed practical issues with such a high-level control algorithm.

- Residential chargers do not provide access to the state of charge of connected vehicles which reduces the effectiveness of a scheduling algorithm.
- Insulation of buildings towards zero energy is good for minimizing thermal losses, but wireless sensor communication (4G, WiFi, Bluetooth, LoRa, etc.) becomes almost impossible without additional devices, increasing costs and energy consumption.
- For real time balancing of the local grid no data transmission delays can occur. Sending data towards a high-level platform and receiving the answer causes execution delays. Additionally, loss of data can occur, especially when taking into account the low connectivity of wireless networks within zero energy buildings.

Additionally, practice in previous projects has shown that interrupting power supply to the charger might prevent it to restart, i.e. some charger brands consider this equal to a grid supply interruption and request a manual restart. Furthermore, such approach would be susceptible to consent from the home owners which could be a challenging and costly aspect in case of upscaling. Therefore, a high-level platform is not ideal. Instead, a solution without an overarching algorithm is preferred. The congestion levels within a neighbourhood can also be observed when measuring the voltage on the grid. When the voltage drops below 230V there is a high load on the grid (for example multiple EVs charging or several heat pumps working at full load), similarly a rise of the voltage above 230V translates to an excess of energy (for example high PV production on a sunny day combined with low demand). By measuring the voltage on the grid in real- time “neighbourhood” load balancing can be implemented.

Some residential charging solutions already provide load balancing functionalities for a single house. This is to prevent too much current being drawn from the grid when the EV is plugged in together with household appliances like dryers, washing machines or heat pumps. Load balancing on a single house is based on current measurements. It is implemented to avoid a breaker to trip of a fuse to blow when using too many household appliances simultaneously. When the current drawn by the rest of the house becomes too high, the load balancing makes sure the EV charger’s power is reduced.

Neighbourhood load balancing can be achieved by measuring the voltage on the grid and aligning this with the EV charger load. This implementation is based on household voltage measurements that directly influence the EV charger. No data transfer towards an external controlling algorithm is required and therefore the downsides of a high-level solution are not applicable. This low-level implementation helps to balance the local grid real-time by reducing the load of the chargers in the neighbourhood once a low voltage (< 230 V) is observed.

User preferences need to be considered. The controlling algorithm cannot simply stop the charging process of an EV because the vehicle needs to be sufficiently charged when the EV

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user wants to leave his home. However, it is possible to slightly slow down the charging process without influencing user comfort. On average an EV charge takes about 2h each day while the EV is usually connected overnight. Users should have the option to choose for "fast charging" mode where full power is guaranteed in case of emergencies. This implementation requires the collection of user preferences which was not considered for the first prototype.

5.3.2 Implementation

Voltage based load balancing requires voltage measurements and charging stations that can be remotely controlled. The Oud-Heverlee demonstration uses the ABB A43 energy monitor to collect energy data throughout the demonstration houses. This data includes voltage measurements on three phases. A custom gateway developed by Th!nk E will allow this data to be read out (over modbus protocol) with a time resolution of 1 measurement per second. They have a hardware-based connection (Figure 5-1). The gateway contains the load balancing logic and transfers the data to a central data storage to monitor and evaluate the algorithm. This data transfer is only necessary for the project, not for the operation of such control. This data is transferred over TCP/IP (standard internet protocol) as illustrated in Figure 5-2.

Figure 5-1-ABB A43 (bottom) and Th!nk E gateway right (top)

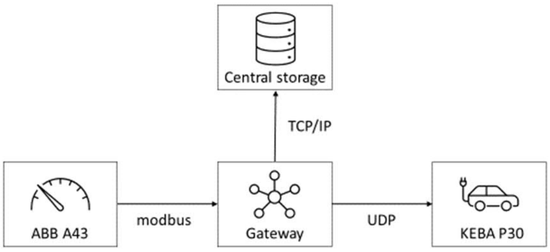

Figure 5-2: Setup low-level voltage controlled load balancing

Once data has been collected the gateway needs to be able to communicate with the charging infrastructure. In the Oud-Heverlee demonstration the ABB EVLUnic Pro (Figure 5-3) is installed. This charging station can be remotely programmed over UDP as depicted on Figure 5-2. It is possible to request status reports and push new setpoints to the charging station If the gateway

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and the charging station are connected to the same local network. One of these setpoints is the maximum allowed current. By regulating the maximum allow current of the charging station, the gateway is able to control the requested power.

Figure 5-3-ABB home charger.

The load balancing logic is implemented on the gateway. The time resolution of one voltage measurement (each second) allows for real-time load balancing of the local grid. The algorithm can evaluate once every second if the setpoints of the charger need to be modified. The only transmission delays that can occur are between the KEBA charging solution and the gateway, no external data transfer is necessary.

The first prototype has been developed in the living lab at Oud-Heverlee. The gateway was successful in controlling the charge profile of one electric vehicle. The prototype was in the process of being tested before the COVID-19 pandemic forced the country into lockdown and cars were only exceptionally used.

5.3.3 Consequences due to covid-19

The first Belgian lockdown in March 2020 delayed the roll-out of the controlling algorithm to the demonstration houses. Not only was the testing process of the prototype delayed, EVs were no longer used because participants were not allowed to leave their homes. Furthermore, it was not possible to enter the homes at the demonstration site to solve technical issues.

Up until several months after the first lockdown the traditional EV consumption profile could be recognized. The implementation of a low-level load balancing algorithm would have little influence on the local grid as EVs and other mobility solutions were still rarely used. Because of this the roll-out of the low-level voltage controlled load balancing has been suspended and few lessons could be learned from the implementation and operation.

5.4 Neighbourhood battery

The concept of neighbourhood energy operation assumes energy loads and capacity can be managed to assure balancing of the grid. This can be achieved by aggregation of flexible loads available in each household.

When it comes to home battery energy storage systems, their current prices and typical use for increase of self-consumption do not offer a viable busines case for a large scale roll-out of this

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technology. Therefore, a neighbourhood BESS is a way to scale up and ensure an adequate and well-orchestrated behaviour.

5.4.1 Concept

As discussed for EV changing before, the concept followed for the neighbourhood battery was also based on the lessons learned earlier in the Story project. It was clear that the complex and high level control of all the loads in the neighbourhood was hard to implement (communication and control issues). The potential dependency on consent of the end-consumers connected to the line

High voltage variations were due to the connection of a number of high loads (EVs and other household loads) and the injection of PV production. To fix the problem, we turned again to a point-based control with voltage measurements. Voltage measurement at individual houses could have been used but would still require coordinated local load control to assure the power quality on the distribution line is assured for the whole neighbourhood.

Therefore, the neighbourhood battery was installed in the middle of the line, having 13 households on one side towards the end of line and additional 27 before the connection to the substation. The voltage on all three phases is measured at the neighbourhood battery and a control algorithm is used, as will be explained below, to control voltage variation for this 230 V lines to be between +/- 5 % as is needed for normal operation.

At moments when too many loads are connected to the line and the voltage is dropping below this limit, the neighbourhood battery is used for discharging to balance the line. Likewise, in case of a high amount of injection, the battery charges to balance local demand and supply. A model predictive control was developed to ensure the battery started its charging and its discharging optimally.

5.4.2 Implementation

The concept of the neighbourhood battery has been discussed and analysed from a technical and economic perspective over the past few years. However, this installation represents the first installed neighbourhood battery in Belgium.

Implementation of this installation represented a learning process for all involved stakeholders. Due to this, significant amount of time and effort was spent on raising awareness, discussion and knowledge transfer with various Flemish institutions. The implementation of the neighbourhood battery involved challenges with land use regulation, permitting process, developing electrical connection contracts as well as appropriate electricity pricing.

5.4.3 Location

Existing legislation on building permits in Belgium does not include a neighbourhood battery. In order to assure experts on building permits on the societal value of the neighbourhood battery, we needed to first explain concepts such as electricity markets, power quality and curtailment of small scale PVs. Hence, it took several months to discuss with the local and Flemish level. Once

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the procedure was clear, the location in the Oud-Heverlee neighbourhood was decided and approved by the first notarial property act that mentioned a neighbourhood battery.

5.4.4 Permitting

Since this represented the first neighbourhood battery in Belgium it was not clear if special permitting procedure was needed. Moreover, multiple workshops were organized with local, regional and Flemish government representatives to clarify if such object can be considered to be part of the distribution infrastructure, if it is public or private and what are the permits that could apply in this case. The conclusions, after several months, were that neighbourhood batteries do not need a building permit and that there are no restrictions with regards to the duration of the battery being on the site. In order to install the neighbourhood battery, an environmental notification was needed.

5.4.5 Electrical connection

In order to define the optimal operation and electrical connection, a good collaboration with distribution system operator (DSO) was needed. Being the first of such installations, the default procedure would have been to connect the battery as any other consumer. However, such connection would limit the potential benefits from the battery installation.

The focus with the DSO was on the balance of encouraging a grid-supporting behaviour on one hand and restricting potential actions with unintended impact on the other hand.

Due to the fact that the distribution line in Oud-Heverlee neighbourhood has already been used to the maximum of its capacity, measured voltage variations could be used as a good indication of the actual load or injection on the line. The battery is to compensate for low voltages with discharging and for high voltages with charging. The DSO therefore developed a clear and logical addendum to the connection contract, emphasizing the need for grid-support in the operation of the neighbourhood battery and restricting specific behaviour that would not align with this goal.

5.4.6 Electricity price

A standard low voltage connection with over 10 kW injection power has a separate supply and injection tariff. The supply tariff includes the price for energy used, DSO and TSO grid costs and all levies and taxes (including societal contributions). In contrary to this, the injection tariff includes only what the electricity supplier is willing to pay for the energy that is injected in the grid. In practice, this implies that around 28 cent euros is to be paid for every kWh that the battery takes from the grid, while only about 4 cent euros is received for every kWh injected back into the grid.

Services that the neighbourhood battery can offer to the grid are not yet remunerated. The European Clean Energy Package foresees such services and market to be established as part of article 32 of the recently amended Internal Market for Electricity directive. With such market DSOs could give a price signals based on the local grid needs and would be obliged to develop some kind of remuneration schemes.

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5.5 Neighbourhood battery operation

Due to lengthy preparatory procedure, the conditions for the neighbourhood battery were only met at the end of 2019. The neighbourhood battery was installed and started operation mid February 2020. To assure the safe functioning of the battery in the distribution network an additional safety relay anda high frequency power quality meter are installed on the side of the DSO.

Figure 5-4-ABB Neighbourhood battery installed in Oud Heverlee demonstration site.

The neighbourhood battery is a Lithium polimer ABB battery of 90 kWh and 90 kW capacity (Figure 5-4). The design and implementation of the battery was done by partners Th!nk E, and ABB. Belgian Enervalis implemented the control as per the requirements, Imtech Belgium did the onsite construction and connection work. Fluvius, the Flemish DSO, was collaborating very constructively to enable this test.

Following are an explanation of the neighbourhood battery control and operation, along with the comparison of the distribution line power quality before and after battery implementation.

5.5.1 Control

To assure that the power quality of the distribution line is maintained using the neiighbourhood battery, the EN 50160 Standard on Voltage Characteristics in Public Distribution Systems was followed. Therefore the battery control had to respect the voltage requirements given in Table 5-1.

To assure these requirements are respected, the following controls are implemented:

- No injection with high voltages
    - 230 V + 7% or 246 V
- No consumption with low voltages
    - 230 V – 7% or 214 V

If approaching the limit of 93%-107% mean 10 minute rms values, the load is kept the same and not suddenly changed.

When the values of voltage on the grid change, the load will be adapted slowly.

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Table 5-1-Voltage requirements based on EN 50160

Voltage magnitude variations		
Mean 10 min rms values	± 10 %	95% of time
Mean 10 min rms values	85.0% ≤ x ≤ 110.0%	100% of time
Voltage unbalance		
Mean 10 min rms values	x ≤ 2.0%	95% of time
Flicker severity		
Flicker Plt mean for 2h	x ≤ 1	95% of time
Total harmonic distortions		
Mean 10 min THD	x ≤ 8.0%	95% of time

5.5.2 Grid operation improvements

The neighbourhood battery has been installed in February 2020 in Oud-Heverlee. Implementing the control based on the voltage measurements has been shown to be successful in improving the power quality of the distribution line.

While, through the STORY project there are measurements of the line voltage in the Oud-Heverlee neighbourhood for the period from 2017 to mid 2019, it is important to mention that the time resolution of these measurements is on hourly bases and with time interruptions for the mentioned period.

In order to show the difference in the distribution line power quality before and after the neighbourhood battery is installed, voltage measurements of the three phases for April 2018 are presented in Figure 5-5. Analysis of the voltage variations show that due to the use of multiple high loads (EV charging at the same time), there is a decrease in the line voltage below 10 % optimal value.

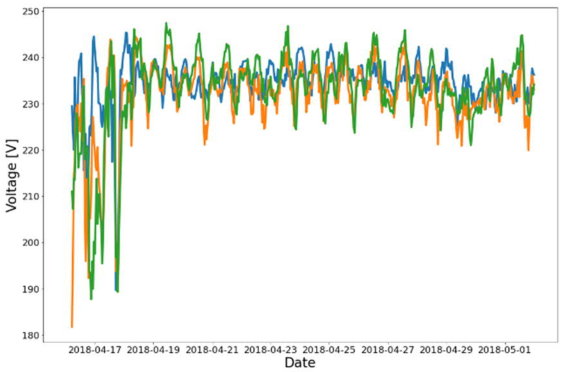

Figure 5-5- Example of voltage variations on three phases (blue, green, orange) of the distribution line in Oude Heverlee in April 2018.

Installation of the neighbourhood battery improved the power quality of the line, as can be seen from example voltage variation for three phases for April 2020 (Figure 5-6).

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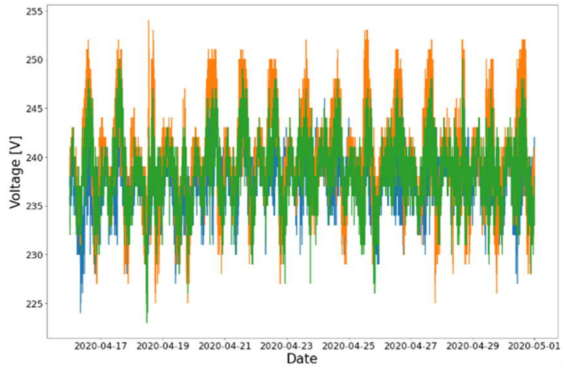
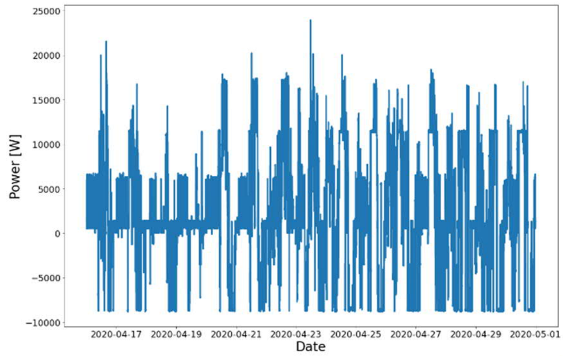


a)



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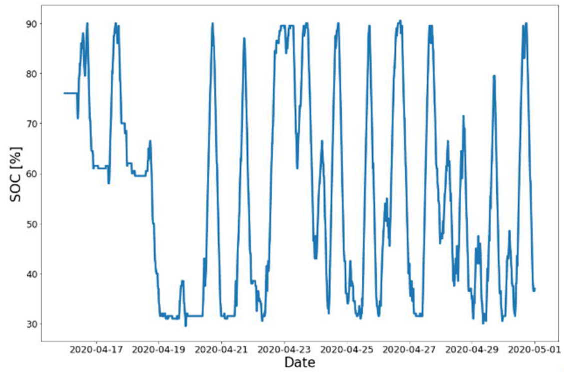

c)

Figure 5-6- Voltage variations on three phases (blue, green, orange) of the distribution line in Oude Heverlee, b) neighbourhood battery charging and discharging behavior and c) battery state of charge in April 2020, after the neighbourhood battery has been installed.

As can be seen from Figure 5-6, a) the implemented control keeps the line voltage between 10 % variation from 230 V. In cases when the voltage decreases to – 7% the battery is activated to discharge (Figure 5-6, b)) and SOC decrease (Figure 5-6, c)). On the other hand as the line voltage increases to + 7 % of 230 V, or to 246 V, the battery is used for charging and SOC increases.

Based on the variation in the state of charge (Figure 5-6, c)) it can be seen that **the sizing of the neighbourhood battery is optimal for the Oud-Heverlee application**.

The Oud-Heverlee neighbourhood presented here is an ideal case of weak distribution line where installation of the neighbourhood battery can lead to improved end of line power quality and

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potential for increase in flexible technology installation (renewable energy, EVs etc.) However, the complex installation procedure as well as the comparison of the price of the battery to the distribution line improvement makes for a non-optimal busines case.

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6 Monitoring and evaluation of industrial building (Spain). Demo 3

Authors: Raquel Garde (CEN), Gabriel García (CEN) and Clemente López (EXL).

6.1 Introduction

Globally, industry is the largest energy consuming sector and in 2016 accounts for about 37% of final energy consumption (IEA 2008). Improvements in energy efficiency in the industrial sector offer major advantages for environmental goals achievement because it is more concentrated in terms of entity numbers and often a small number of big energy-intensive enterprises consume the majority of energy in the sector. Achieving improvements in energy efficiency in industry can make a significant contribution to solving local, national and global energy problems.

Additionally, competitiveness of industrial sector is also dependent on the energy prices since manufacturing costs can be largely affected by energy prices mostly for energy intensive industries.

Both goals, environmental and economic, can be achieved by using local renewable energies optimally managed to maximise their contribution to the overall consumption and to improve their reliability. Energy Management Strategies, to match the renewable generation and industrial consumption at the lowest price, are supported by energy storage systems (ESS). These allow an optimal energy balance between generation and loads and additional grid services, such as peak shaving or congestion management, to improve the overall energy system efficiency.

6.1.1 Objectives

The main goal of the Spanish pilot plant is to demonstrate the added value of energy storage by reducing the demand charge of the factory, which in occasions rises up to 60% of the electricity bill. To achieve this main goal, a peak shaving strategy is applied in the demonstrator comprising a Li-Ion battery of 50 kW/200 kWh and a PV plant of 112.70 kWp and demand charges in the range of 250-280 kW. Additionally, PV energy is managed in order to optimise its use according to the electricity tariff periods.

The business case based on electricity bill savings is here analysed in order to quantify the energy storage's added value and to assess the system profitability.

6.2 The concept

6.2.1 Overview of the plant

Previously to the STORY project, a PV plant was operative in Exkal factory for self-consumption purposes. In order to improve the local resources use and increase the profitability of the plant according to the STORY goals, a Battery Energy Storage System (BESS) has been installed (Figure 6-1).

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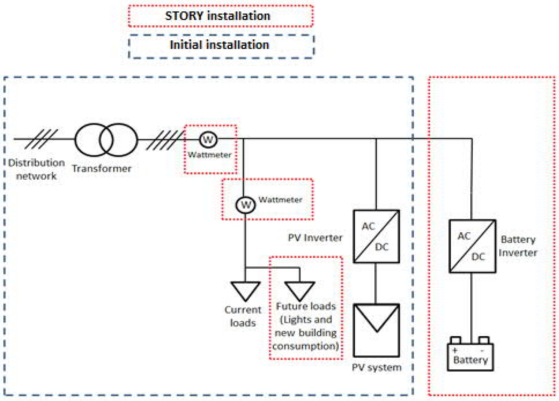

Figure 6-1 -Scheme of the STORY demonstrator in Exkal factory (Spain).

Thus, the STORY demonstrator comprises a PV plant for electricity production, a Li-ion battery including the associated power electronics system, a PLC which is the controller of the plant and supporting infrastructure related to communications and monitoring.

6.2.2 PV plant

A PV plant of 112.70 kWp was already installed in Exkal factory for self-consumption purposes since 2013. The PV plant comprised 23 strings of 20 modules in series, adding a total of 460 modules (LW 245, Lightway) and a surface of 747 m2. See Figure 6-2.

The inverter was an Ingecon Sun 100 from Ingeteam with a voltage range of 405-750 V and rated power of 100 kW AC. The plant was managed by an Energy Management System (EMS) of Ingeteam implemented in the inverter which was removed for the STORY demonstrator development.

Figure 6-2 -View of the Exkal factory and the PV plant installed in the roof

6.2.3 Battery Energy Storage System (BESS)

The sizing of the Li-ion battery (50 kW/200 kWh) was performed according to the annual Exkal loads and PV generation, with the aim of covering as many power peaks as possible using the locally generated PV energy.

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Figure 6-3 -Li-ion battery by SAFT in the Exkal factory demonstrator

The selected Li-ion battery of SAFT is composed of two Intensium Mini E 26S, each of them consisting of 26 modules, which are divided into 4 strings or blocks (4 units BMM), controlled by 1 master manager (MBMM). Figure 6-3. The main characteristics of the battery are listed in Table 6-1.

Table 6-1-Characteristics of the Li-ion battery in Exkal factory demonstrator

Intensium® Mini E with 2 x 26 Synerior 24E modules	2 units
Installed Energy (Beginning of Life) C/3 rate, +25°C	222 kWh
Maximum Continuous (over 30s) discharge power at +25°C, 50% SOC	408 kW
Maximum Continuous (over 30s) charge power at +25°C, 50% SOC	112 kW
Rated nominal DC voltage, 50% SOC	655 V
Minimum DC voltage	546 V
Maximum DC voltage	728 V
Lifetime at +20°C perm	> 15 years
Operating temperature	-20°C to +55°C
Storage temperature	-20°C to +55°C
Weight	1,950 kg

The battery is connected to the network throughout a Power Converter Supply (PCS) by Cinergia (60 kVA) which operates the battery according to the setpoints defined by the Master Control.

The main characteristics of the PCS are:

- Three-phase network side converter (400V @ 50Hz)
- Nominal power 60kVA
- Power factor between 0.9 and -0.9
- One single DC channel for connection of Lithium battery with BMS
- Limits voltage in the DC channel from 50VDC to 700VDC.
- DC 150A maximum current side
- Maximum power side DC 50kW

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- Power overload capacity on AC side (25% for 10 minutes, 50% for 1 minute)
- Power overload capacity on the DC side (25% for 10 minutes, 50% for 1 minute) as long as current limits are respected
- There is no type of galvanic isolation in the converter.
- Battery charge / discharge management is done from the master of the micro network together with the BMS.
- Specific BMS protocol for the lithium battery determined by the customer (isolated CAN).
- The converter is a gateway for CAN messages between the master and the battery.
- Communication protocol with the system MASTER (MODBUS TCP / IP)

6.2.4 Master Control, ICTs and monitoring system

The overall plant, including PV generation and energy storage, is managed by a Master Control (General Controller) that corresponds to the second level or local control in the STORY project and visualized in a SCADA, both developed by CENER (Figure 6-4). Additionally, ICTs and monitoring systems allow the supervision and operation of the plant in real time and the analysis of KPIs.

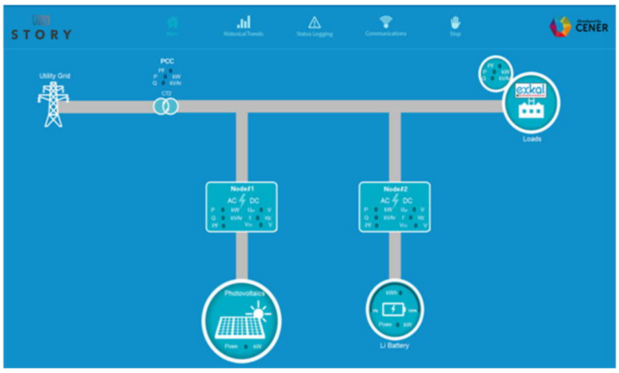

Figure 6-4 -SCADA of Exkal factory's demonstrator

The General Controller acts as a gateway and it is formed by one PLC (Programmable Logic Controller) and two workstations that accomplish server tasks.

The battery inverter, the battery system and the photovoltaic inverter integrate their own primary control to maintain the stability of critical processes of the individual systems. In a second control level, if a critical situation is detected in the overall system, the most suitable action will be taken by the PLC.

All the variables of the components are acquired by the PLC and shared with the OPC server through the specific driver for Siemens S7-300 series. The SCADA server integrates an OPC client that reads data from the OPC server. Data is logged into the database, and both historical and current values are published for SCADA clients. See Figure 6-5.

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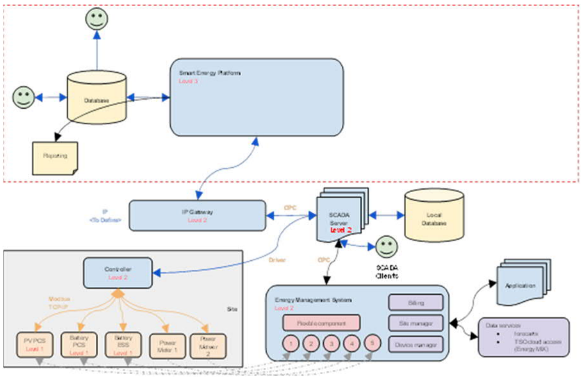

Figure 6-5 -ICTs and monitoring systems architecture in Exkal factory demonstrator

SCADA server logs data to the STORY database by BaseN to accomplish the KPIs analysis. STORY database management system includes web services for both logging and database queries purposes. The gateway developed by CENER logs data to the database through HTTP protocol and JSON format. SCADA clients and server have been developed on LabVIEW.

The communication inside the site is Modbus over TCP/IP with bandwidth requirements of 60kb/s, with 10Hz (100ms) measurement and control cycle. The system is bi-directional, with the general controller handling and setting the control variables (write registers) on the actual devices which support bi-directional data flow.

The external access from the system to both STORY database and DSO is over Internet. Estimated reachability SLA for site is 99.9% (8.75h downtime/year) with the system providing a local backup logic for safe operation during communications downtime.

Power generation hardware and General Controller communicate through MODBUS TCP/IP. The General Controller acts as master while other devices act as slaves. So as to right energy management, the General Controller also communicates with watt-meters/grid analysers to know loads demand.

The Li-ion battery has its own BMS (Battery Management System) which communicates with other devices through CAN bus. The BMS shares with the PCS necessary data for safe and proper system operation. Furthermore, the PCS acts as a bridge between CAN bus and MODBUS, publishing all relevant data of the battery system and sharing it with the General Controller.

6.3 Operation strategy

Due to the Spanish regulatory framework regarding self-consumption and energy storage systems application, the management strategy has been developed gradually starting from a simple electric energy balance formulation, called the basic energy management strategy, to a more complex management based on genetic algorithms. The major objectives of the strategy are:

- To increase renewable energy usage: to rationally maximise the use of renewable energy produced on-site through the Li-ion Battery.

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- Daily predictive identification of energy supply flows (energy production systems) based on energy costs and weather data.
- Peak shaving: energy demand over a threshold is withdrawn from the Li-ion Battery.
- Energy schedule prediction (time shifting): shifting energy (production, storage and consumption), considering tariffs and weather forecast, to the most convenient time.

The main aspects as well as some simulation results are discussed in the following sections.

6.3.1 Energy management strategies

According to the Spanish Royal Decree 900/2015, the charge of BESS from the grid in self-consumption plants is forbidden and depending on the plant type, the excess of energy (PV generation) cannot be fed into the grid. The basic energy management strategy is defined to comply with these restrictions and takes into consideration the tariff periods to make decisions regarding the charge and discharge processes of the battery. Essentially the battery is charged during valley hours with the PV energy excess while it is discharged during peak hours to reduce the demand charge as much as possible. Additionally, a better use of the PV energy is carried out when possible by applying a time shifting strategy.

Along 2018 changes in the Spanish regulation have been proposed to approve a new Royal Decree for self-consumption. Major modifications include the backup toll elimination, simplification of administrative burdens, cooperative self-consumption and most important, the capacity of applying peak shaving with storage and charging BESS from the grid. In accordance to this, CENER developed an advanced energy management strategy including renewable generation and power demand forecasting, and the additional possibility of BESS recharging from the grid.

This strategy has the same main goals than the basic one, peak shaving and time shifting, but the new features allow optimising the PV energy use according to the electricity price to maximise the bill savings.

6.3.2 Simulations

Both strategies have been simulated to check their suitability previously to be implemented in the plant.

For the basic strategy, considering the original 200 kW peak demand in Exkal, results reveal that the BESS is charged along the week-end and fully discharged in the beginning of each Monday. During working days the PV energy excess available to charge the BESS is only a 3.5 %.

The advanced strategy was developed and simulated under different case studies with the demand charge (peak power) reduction goal. In Figure 6-6 the results obtained for the two working shifts case is presented.

The Li-ion Battery power setpoint value is established by calculating the amount of power that the battery has to release in order to avoid exceeding a maximum power value (cut power).

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The cut power of each tariff period is calculated at the beginning of the month using the renewable generation and the demand profile predicted for the first seven days. If the cut power of any period is exceeded, the value of this new peak power is set as cut power threshold in this period for the rest of the month.

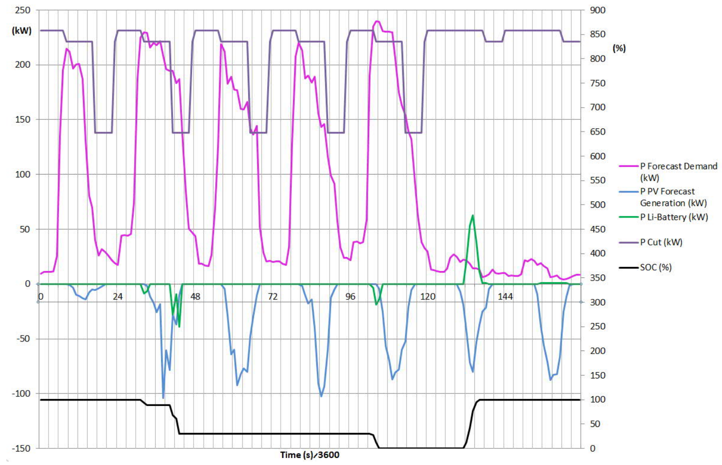

Figure 6-6- Power and SOC evolution (28th-3th November2013) of case study (two working shifts in Exkal factory)

The strategy aims to keep the demand charge of each period below the values of their cut power, giving a special priority to cover overconsumptions in the high tariff periods of the day. The cut power values computed for each different tariff periods are presented in Table 6-2.

The cut power value for the peak tariff period is reduced to 138 kW which corresponds to a reduction of about 50%.

Table 6-2 -Values of cut power applied in case study

Cut Power (kW)		
Valley	Flat	Peak
231	**221**	**138**

6.4 Use case evaluation

To evaluate the performance and to assess the efficiency of the control strategies taken, an evaluation methodology based on KPIs was designed. The KPIs were defined in the deliverable “Use cases and Key Performance Indicators (KPIs) of the STORY project”.

The KPIs are divided into two categories: economical and technical. Some of the KPIs are general while others are demo specific. In this report, the KPIs are calculated and the performance is discussed.

Since the incorporation of the Li-ion battery system to the factory, data has been registered in BaseN’s database. This data included information about all the elements of the system: PV generation, Li-ion battery, load demand and PCC.

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However, several communication and control issues between the battery BMS and the power converter resulted in discontinuous operation of the energy storage system. Consequently, the overall system availability factor and data registration were highly impacted.

Nevertheless, using the data available a valuable assessment has been carried out.

6.4.1 KPI: Change of revenue associated to power

According to the data obtained during the monitoring process, the use of the battery represents almost a 6% reduction in the maximum monthly power registered during the period from January to March, as it is capable of storing surpluses in the hours prior to the peak period that can be used later as defined by the strategy set.

As a result, the demand charge obtained is shown in Table 6-3. According to Spanish regulations, the cost of the bill is not always proportional to the power, as there are different calculation values depending on thresholds above or below the contracted power.

The values shown correspond to three reference cases, which are also used in the following tables. The first case corresponds to the initial situation of the factory, before the installation of the renewable generation. The second case corresponds to the system prior to the start of the project, which already included the photovoltaic installation. Finally, the third case corresponds to the complete system, including the energy storage system.

Table 6-3- Peak period demand charge (Jan-Mar)

	Jan	Feb	Mar	Average reduction
Loads (€)	384.44	367.34	429.87	
Loads-PV (€)	384.44	365.56	428.77	-0.24%
Loads-PV+Bat (€)	355.95	357.45	398.91	-5.87%

The operation during the second half of the year is shown in Table 6-4 and Table 6-5. In this case, it is possible to see two different cases attending to the different timetable seasons. As the tariff changes with the time change at the end of October, a different behaviour is obtained in November.

The first two months in the table belong to the summer semester, with the peak period happening during the afternoon and coincident with the PV generating hours. Consequently, the values of the second case, with photovoltaics, achieve a significant reduction, which no longer occurs in November.

Table 6-4 -Peak period maximeter power values (Sep-Nov)

	Sept	Oct	Nov	Average reduction
Loads (kW)	75.0	89.0	99.9	
Loads-PV (kW)	54.4	70.3	100.4	**-14.70%**
Loads-PV+Bat (kW)	65.0	71.5	100.4	**-10.23%**

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As for the third case, which includes the storage system, its operation achieves higher values of maximum power during September and October. This is due to the use that the battery makes of this photovoltaic energy during the central hours of the day, in order to reduce both the power and energy terms in the flat period that follows.

Finally, the demand charge values for these months in the peak period are listed in Table 6-5.

Table 6-5 -Peak period demand charge (Sep-Nov)

	Sept	Oct	Nov	Average reduction
Loads (€)	365.00	447.13	486.00	
Loads-PV (€)	264.47	353.26	488.34	-14.80%
Loads-PV+Bat (€)	316.13	359.10	488.34	-10.37%

Figure 6-7 shows a comparison of the total demand cost calculation for the three reference cases over the year 2018.

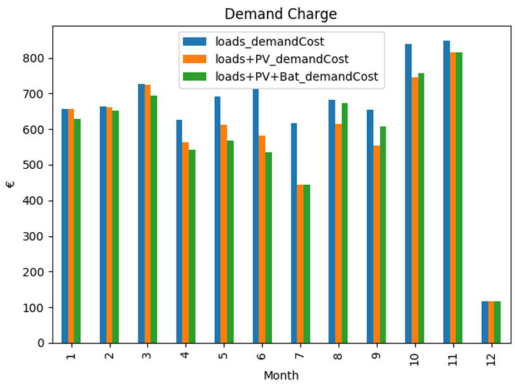

Figure 6-7- Total demand charge over 2018

It can be seen that, in this case, the impact of the photovoltaic system is much greater than that of the energy storage system, especially in the months of the summer semester due to the time coincidence with the peak period. Of course, the positive impact of the battery has been drastically penalised by the low availability suffered.

In addition, it should be noted that certain tests carried out on the battery may have impacted the result of the powers registered. Since a single power value recorded during 15 minutes may mark the monthly maximum, certain specific tests carried out during system maintenance operations may have altered the data finally obtained.

6.4.2 KPI: Change of revenue associated to energy

Figure 6-8 shows the energy term values of the bill obtained for the three reference cases. Although the third case obtains some savings in certain months, it again suffers from the reduced number of cycles experienced by the energy storage system.

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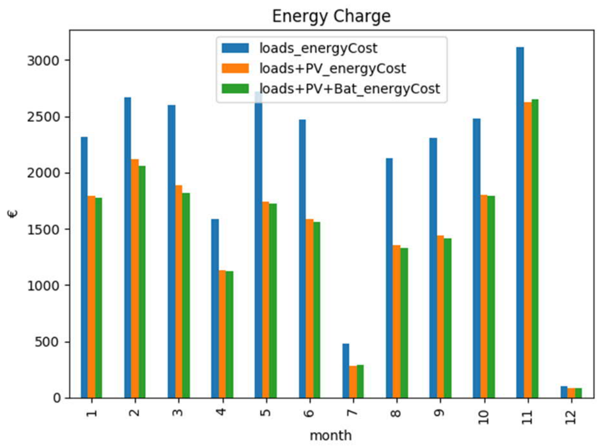

Figure 6-8 -Total energy charge over 2018

In this case, the energy charge should be reduced due to the incorporation of the battery. In normal operation the battery would store PV surplus energy for later use, reducing the dependence from the grid and accordingly the energy charge in the bill.

The size of the reduction would depend on the relative dimensioning of the PV system in relation with the experienced load demand, and also on the storage capacity of the ESS.

6.4.3 KPI: Self-consumption

First, regarding the PV self-consumption values, Table 6-6 lists the monthly averages over 2018. Due to regulatory framework in place, PV generation was being limited by the inverter during the first half of the year to avoid energy exports. As a consequence, higher values of self-consumption were obtained due to the absence of energy exports.

Table 6-6- PV self-consumption monthly average values in 2018

Self-consumption			
Month	Without battery	With battery	diff
1	98.0%	99.8%	1.8%
2	97.2%	100.0%	2.8%
3	96.2%	99.9%	3.7%
4	96.5%	98.9%	2.4%
5	97.7%	99.3%	1.6%
6	96.5%	98.4%	1.9%
7	86.0%	86.7%	0.7%
8	90.6%	92.8%	2.2%
9	92.3%	95.8%	3.5%
10	94.8%	96.9%	2.1%
11	96.5%	96.7%	0.2%
12	96.1%	96.3%	0.2%
Average	**94.9%**	**96.8%**	**1.9%**

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In the second half of the year, these values were lower because PV surplus energy could be regularly fed into the grid.

In general, the incorporation of the battery meant an average annual increase of about 2% in self-consumption values for the locally generated PV energy.

6.4.4 KPI: Self-sufficiency

On the other hand, self-sufficiency values for 2018 were around 30%, although no variation could be identified due to the inclusion of the battery.

6.5 Energy storage system performance evaluation

6.5.1 KPI: Full Cycle Equivalents of Storage

Problems experienced with system availability greatly reduced battery operation, resulting in a total annual accumulation of 70 cycles only. As Table 6-7 shows, in some months only a few operating cycles were achieved which has impacted on the possibility of obtaining representative data for the calculation of some KPIs. However, with the available data, it has been possible to calculate consistent values for system efficiency, which are shown in Table 6-7.

Table 6-7- Li-ion battery equivalent cycles and round-trip-efficiency

Month	Equivalent cycles	RTE
1	6.4	62.8
2	8.2	69.8
3	10.5	68.3
4	2.7	59.4
5	3.0	57.2
6	2.8	74.5
7	0.0	
8	6.8	78.3
9	12.2	69.8
10	14.6	77.4
11	3.0	60.6
12	0.0	

6.5.2 KPI: Storage Efficiency

Although there is a certain deviation, especially in the months with the greatest lack of data, it can be concluded that the average efficiency of the system, including the consumption of the converter, is close to 70% as seen in Table 6-7.

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Despite the high DC-DC efficiency of the Li-ion battery, with typical values over 90%, both the efficiency of the converter, and its passive consumption throughout the 24 hours of the day, suppose an important penalty for the final calculation.

Figure 6-9 shows a histogram of the battery SOC values obtained in the August-September studied period. In it, we can see how the most repeated values correspond to the maximum and minimum permitted states of charge.

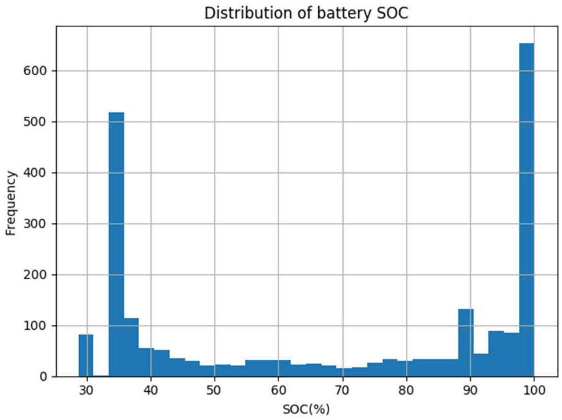

Figure 6-9- Battery SOC histogram

This behaviour is logical, given that when the battery is fully charged or discharged, it normally waits several hours to do the opposite cycle when required.

6.5.3 KPI: Storage Capacity Factor

Due to the problems experienced, it was not possible to carry out the necessary test of nominal charge-discharge to obtain a reliable update of the capacity factor of the installed battery.

However, given the limited number of equivalent cycles performed, it is expected to remain practically the same as the day of commissioning.

The only impacts that it can have suffered would be related to long duration periods at a low state-of-charge or to the influence of the so called calendar life.

6.6 Environmental analysis

More details on the LCA are provided in the STORY report "Environmental analysis of demo-scale storage implementation" as Additional Deliverable to WP6 as output of Subtask 6.2.8.

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7 Monitoring and evaluation of medium scale storage unit (Slovenia). Demo 4

Authors: Andrej Gubina (UL), Marjan Jerele (EG), Jernej Zupančič (UL).

7.1 Introduction

Rapid emergence of distributed energy resources (DER), installed mainly in low voltage networks, poses new challenges to distribution system operators (DSO). Besides regular voltage quality provision, new load balancing solutions are becoming one of the most important future DSO operational concepts.

Rapidly developing storage technologies are with no doubt one of the future load balancing measures and already paving its way into distribution low voltage networks. Elektro Gorenjska d.d. (EG) is an active partner of STORY H2020 project and strongly contributes to demonstration of a flexible and robust use of a large-scale battery energy storage system (BESS). The storage is currently installed in residential type of low voltage network with high penetration of distributed generation.

7.2 The concept

A medium scale storage unit for the demo case was connected to a 20/0,4 kV MV/LV transformer station supplying the Suha village residential grid in the vicinity of city Kranj. Suha village LVN is an example of a 0,4 kV rural cable network (no overhead lines) with high penetration of PV generation. The cable network topology, the locations of PVs and 20/0,4 kV MV/LV transformer station is depicted in Figure 7-1.

A number of power network analysers is already installed within the network for on-line monitoring and control purposes (the data is registered per one-minute time period).

Due to expected STORY project requirements, additional power network analysers were installed on the two remaining PV locations.

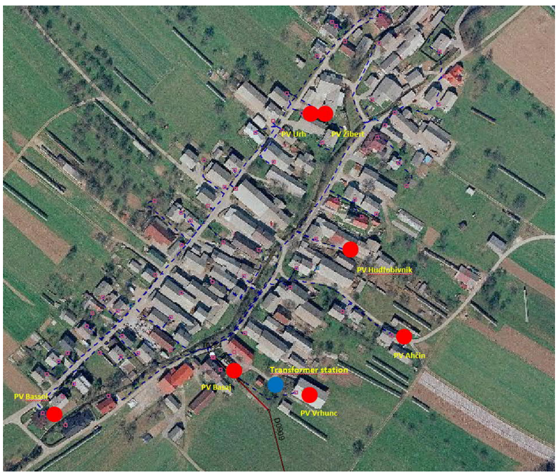

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Figure 7-1: LVN SUHA topology, PV and transformer locations.

Power plants nominal power data:

Table 7-1- PV data.

Photovoltaic power plant	Active power
PV Basaj	29 kW
PV Ahčin	22 kW
PV Bassol	15 kW
PV Žibert	22 kW
PV Vrhunc	50 kW
PV Urh	22 kW
PV Hudobivnik	50 kW
Total nominal power	**210 kW**

T0248 Suha transformer station (TS) is a representative of a standardised EG 20/0.4 kV transformer station. TS comprise:

- Transformer concrete casing TSN TPR-C type
- 20/0.4 kV, 400 kVA OLTC transformer (Schneider - Minera SGrid)
- 20 kV Siemens ring main unit 8DJH with motor
- 0.4 kV switchboard
- TS remote control system

The BESS unit is connected to one of the spare low voltage feeder connections via a Point of Common Coupling (PCC) cabinet. PCC consists of main circuit breaker with network protection relay, remote control terminal unit and main system process controller. Main controller unit (MCU), with implemented control algorithm, is also installed in PCC in order to bring system calculations and process control as close to BESS as possible. MCU and BESS programmable logic control unit (PLC) are directly connected via network cable in order to minimise connection failure risks during operation. PCC is remotely controlled by remote terminal unit (RTU), general layout.

The BESS is designed to provide nominal power of 170 kW, an installed gross energy capacity of 552 kWh (net 450 kWh) and a typical roundtrip efficiency of > 85 %, and it is ready for outdoor installation. The BESS system main functionalities are as follows:

Table 7-2- BESS functionalities

Functionality
Peak Shaving (Main functionality)
Islanding (not applied in Suha demo)
Black Start (not applied in Suha demo)
Reactive power compensation*
Harmonic Compensation* - specific for 5th Harmonic
Load Balancing*
Tertiary Reserve

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* - Reactive power compensation, harmonic compensation and load balancing functionalities require current signals from the distribution transformer.

A simplified BESS connection scheme is presented in Figure 7-2.

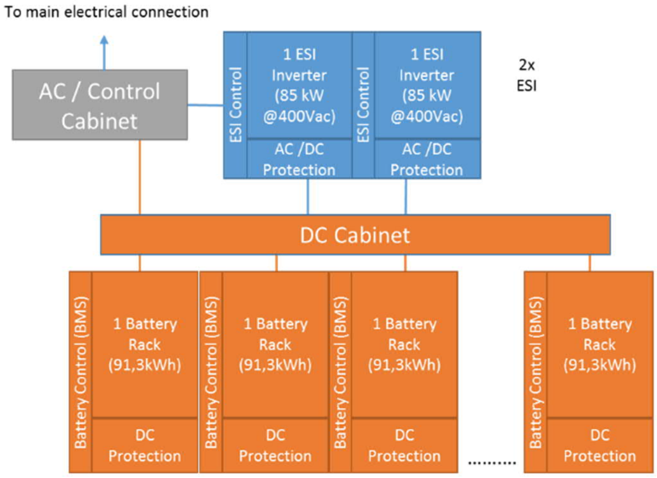

Figure 7-2- BESS System Overview

The salient features of the BESS are described in Table 7-3.

Table 7-3- BESS System salient features

System parameter	Value
Total Installed Power (kW)	170 kW @400 Vac
Power per ESI unit (kW)	85 kW @400 Vac
Range of Power Factor	Fully inductive to fully capacitive 100% P(kW) or Q(kvar)
Total Installed Energy (kWh)	552 kWh @ BoL – Beginning of life
Installed Energy per Rack (kWh)	91,3 KWh
Total Usable Energy BOL - 4wires	58% of Total Installed Energy @ BoL (discharge 1 C)
Inverter Parasitic Loads	2.5% of Losses @ Rated Power
Battery Parasitic Loads	2% of Losses @ Rated Energy
Auxiliaries Parasitic Loads (LV)	1.5% of Losses @ Rated Power / Energy
Typical round trip efficiency	>85% for 1 Full cycle at 1 CP
Max Temperature for Battery (°C)	25°C – Ambient Temperature
Max Temperature for PCS (°C)	40°C – Ambient Temperature
Max C Rate	1 CP Charge/discharge
Communication EMS/MCU	Via Modbus protocol**
Communication EMS/PCS	Via Modbus protocol
Communication EMS/BBMS	Via Modbus protocol

Storage demonstration follows a three-layer concept.

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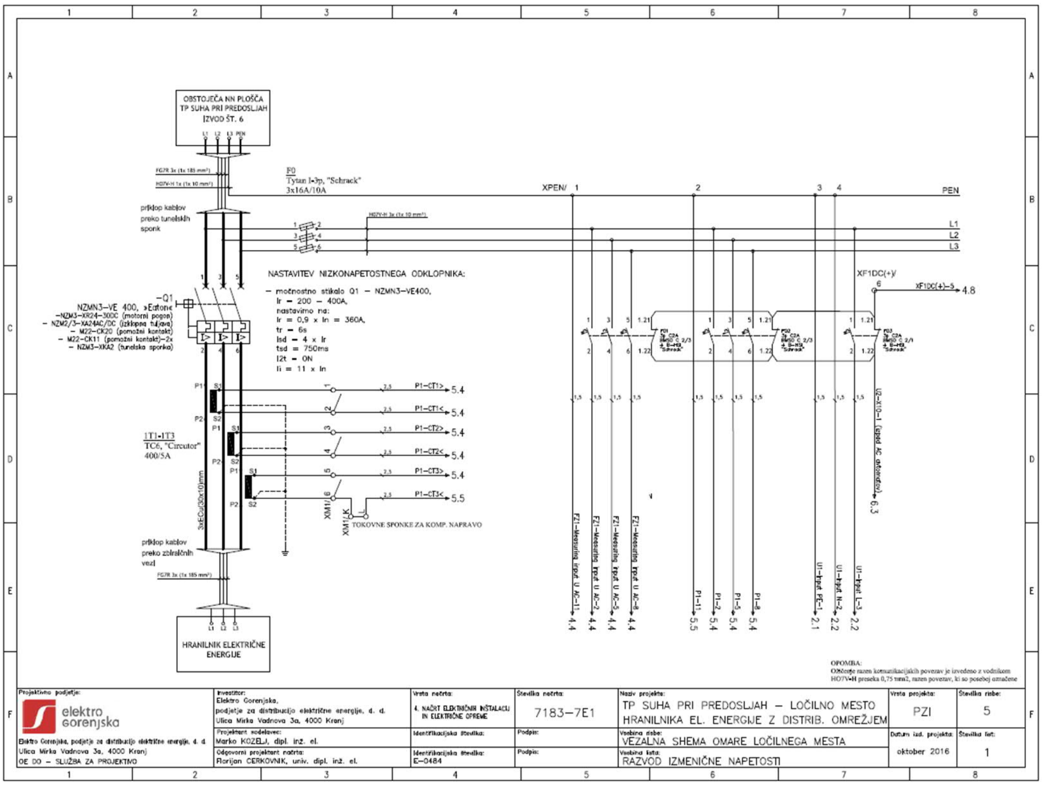

Figure 7-3-BESS Power connection

Primary, also refered a local layer, consist of a numerous device installed on site. Besides already mentioned BESS and PCC cabinet, different information and communication technologies, network monitoring and metering data systems and remote terminal units (RTUs) represent the vital and most utilized demo subsystems.

On the secondary level, remote demo system control and data acquisition (SCADA) system with remote main controller unit (MCU) provides a platform for complete system control and surveillance. MCU, as the front-end processor, executes the algorithm and controls BESS programmable logic controller (PLC) and is installed in PCC cabint in the transformer station itself. MCU and BESS PLC are directly connected with network cable in order to ensure maximum communication reliability. SCADA serves as a data collection and remote-control support. It collects and processes all demo signals for later analysis and enables complete remote control of MCU and BESS itself. Remote control with different levels of authorisation enables complete system insight.

Integration of a variety of EG technological subsystems and ABB storage as well, requires the utilization of three different standardised protocols. Modbus, enabling communication between MCU and BESS PLC, DNP3.0 for SCADA to MCU communication and OPC UA for data exchange between SCADA and servers on tertiary layer.

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EG private WiMAX and LTE broad band radio network provides two basic communication platforms, which enable communicaton among dispersed device locations.

Measurement system consists of the following devices:

- BESS (ABB power analyser), metering all storage parameters
- MV/LV transformer (MC power analyser), measuring all transformer parameters on low voltage side
- PV POWER PLANTS (MC power analysers) metering all individual PV power plant parameters

Power analyser measurement and storage resolution for all parameters is 1 minute.

7.3 Use cases evaluation (or performance evaluation)

Due to unstable BESS operation and a lot of unexpected shutdowns, not a single complete winter month period is available for equivalent operation analyses. Therefore, only one week of continuous winter operation had been chosen among the available data. Operation from 24. 1. – 30. 1. 2019, a typical winter period with low temperatures, lot of cloudiness and almost no sun is compared to a typical summer week period from June from 24. 6. – 30. 6. 2019, with high temperatures and a lot of sun radiation.

For additional comparison of storage operation and performance, results of small-scale simulations are presented as well. Analysis was performed on June 2017 dataset, which was used in development of the algorithms and in simulation activities of other work packages. In the results the Base case, which reflects situation before BESS implementation is compared to BESS implementation scenario. In addition of realistic demo scenario (Low RES) we simulated increased renewable penetration scenario (High RES), where additional 200 % PV installations were included.

7.3.1 Increased self-consumption

The aim of this use case is to increase self consumption/sufficiency. It is calculated for 24h, 7 days and 1 month.

7.3.1.1 Self-consumption level SCL

Self-consumption level SCL is defined as a ratio between self-consumption (local consumption) of locally produced energy and the total amount of locally produced energy, of which the surplus is injected into the main grid.

Calculation:

$$SCL(\%) = \frac{E_{Local,Consumed}(T)}{E_{Local,Produced}(T)} \cdot 100\%$$

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$SCL(\%)$	Self-consumption level
$E_{Local,Consumed}(T)$	Locally generated energy, consumed within the monitored sector in predefined time interval T in [kWh].
$E_{Local,Produced}(T)$	Total amount of locally produced energy [kWh] in predefined interval T.

7.3.1.2 Analysis of results

Weekly and monthly SCL data is presented inTable 7-4.

Table 7-4– Weekly and monthly SCL June 2019

Month June WEEK	KP1-SCL
Week 1	63,52%
Week 2	65,99%
Week 3	66,07%
Week 4	65,45%
June 2019	65,31%

Weekly SCL data for **seasonal comparison** is presented in Table 7-5.

Table 7-5– Weekly SCL data comparison

Seasonal comparison	SCL
Week 24. - 30. 1. 2019	97,97%
Week 24. - 30. 6. 2019	63,52%

June 2019 was one of the sunniest summer 2019 months, so high SCL and SSL levels are of no surprise. SCL is even higher on a cloudy days and majority of PV production being spent locally.

Table 7-6- Weekly and monthly SCL June 2017 – simulations data

Month June WEEK	KP1-SCL Low RES scenario		KP1-SCL High RES scenario	
	Base case	BESS case	Base case	BESS case
Week 1	25,13%	45,82%	15,38%	21,32%
Week 2	28,94%	53,88%	17,40%	25,24%
Week 3	44,02%	69,38%	31,38%	42,82%
Week 4	43,16%	65,93%	30,95%	38,42%
June 2017	34,63%	57,81%	23,24%	31,26%

With BESS implementation we observed at least 20% increase of SCL in Low RES and roughly 10% increase of SCL in High RES setting.

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7.3.1.3 Self-sufficiency level (SSL)

Self-sufficiency level is defined as a ratio between the consumption, covered by local production and the total consumption over a certain monitored interval.

$SSL(\%)$	Self-sufficiency level
$C_{\text{Locally covered}}(T)$	Network consumption in [kWh] in a predefined interval (24 hours), which is covered by localy production (PV sources)
$C_{\text{Total}}(T)$	Total network consumption in [kWh] in predefined interval T (24 hours).

7.3.1.4 Analysis of results

Weekly and monthly SSL data is presented in Table 7-7.

Table 7-7 -Weekly SSL June 2019

Month June	KP1-SSL
Week 1	38,39%
Week 2	40,50%
Week 3	35,91%
Week 4	38,69%
June 2019	38,94%

Weekly SSL data for **seasonal comparison** is presented in Table 7-8.

Table 7-8 -Weekly SSL data comparison

Seasonal comparison	SSL
Week 24. - 30. 1. 2019	10,96%
Week 24. - 30. 6. 2019	43,94%

Even the PV peak production power equals consumer load peak (both in a range of 180 kW), SSL level reaches less than 40 % on monthly level. If self sufficiency would be a goal for Suha village, that would require up to 500 kW of installed PV nominal power, based on more than average daily sun radiation prediction. Both indexes also significantly depend on transformer load profile, which is not so favourable due to low mid day consumption.

Weekly SCL and SSL comparison clearly shows the difference between winter and summer operation. Due to low PV production in January, winter SSL levels are considerably lower than summer ones. On the contrary, January SCL are much higher than in the summer, since almost all of winter produced energy is spent localy. As such, BESS operation does not bring any significant added value to SCL or SSL increase during winter period.

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Table 7-9: Weekly and monthly SSL June 2017 – simulations data

Month June WEEK	KP2-SSL Low RES scenario		KP2-SSL High RES scenario	
	Base case	BESS case	Base case	BESS case
Week 1	23,77%	43,17%	41,00%	53,92%
Week 2	24,44%	43,62%	40,80%	55,28%
Week 3	18,01%	31,83%	34,69%	47,35%
Week 4	21,96%	37,26%	36,49%	48,36%
June 2017	22,26%	39,34%	38,60%	51,59%

With BESS implementation we increase self-sufficiency of the network by more than 20% in Low RES and more than 10 % in High RES scenario.

7.3.1.5 Grid energy consumption change (GECC)

The grid energy consumption change KPI compares the grid-injected energy before and after storage implementation. The KPI evaluates the energy exchanged between the monitored region/section and the rest of the distribution grid and the increase of renewables share in local energy supply.

Calculation:

$$\Delta E_{\text{Grid}}(\%) = \frac{\Delta E_{\text{Grid,Use Case}} - \Delta E_{\text{Grid,Base Case}}}{\Delta E_{\text{Grid,Base Case}}} * 100\%$$

Where

$\Delta E_{\text{Grid}}(\%)$ Relative change of grid-supplied energy [%],

$\Delta E_{\text{Grid,Use Case}}$ Energy supplied from the main grid after the implementation of storage [kWh],

$\Delta E_{\text{Grid,Base Case}}$ Energy supplied from the grid before implementation [kWh].

Calculated time intervals: 24hours, 7 days, 1 month.

7.3.1.6 Analysis of results

Energy, delivered by the grid, is reduced on account of local PV production and the surplus of that energy being stored by BESS during production periods. On the contrary, grid energy infeed on a cloudly day can be even higher than normally, mostly due to the BESS grid night charging.

BC (Base Case) and CS (Case Study) results for Jun 2019 daily grid consumption change values are presented in Figure 7-4.

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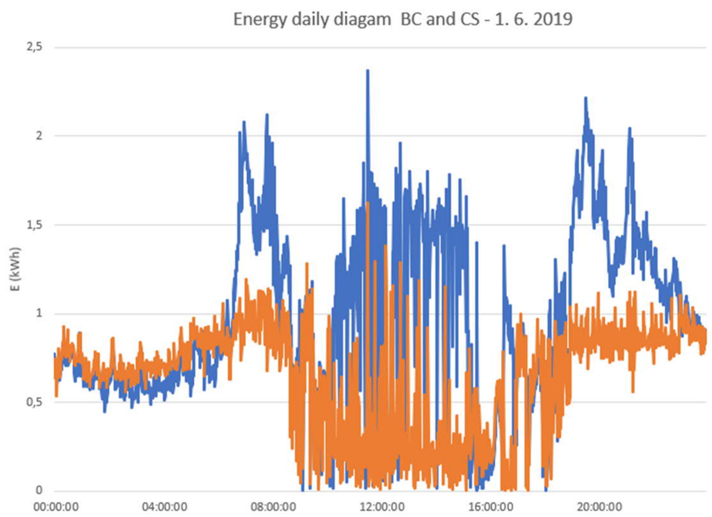

Figure 7-4-Transformer daily load diagram – BC (blue) and CS (orange)

June 2019 weekly and monthly consumption change values are presented in Table 7-10.

Table 7-10– June 2019 weekly grid consumption change data

	E BC (kWh)	E CS (kWh)	GECC
Week 1	9672,38	6603,55	**-31,73%**
Week 2	9345,68	6571,29	**-29,69%**
Week 3	8655,70	6835,79	**-21,03%**
Week 4	8586,91	6539,39	**-23,84%**
June	38798,55	28135,16	**-27,48%**

Weekly **seasonal** GECC data is presented in Table 7-11.

Table 7-11 –Weekly grid consumption change comparison

	E BC (kWh)	E CS (kWh)	GECC
Week 24. - 30. 1. 2019	13798,59	14538,00	5,36%
Week 24. - 30. 6. 2019	8849,93	5706,20	-35,52%

June daily grid energy consumption change is mostly negative, meaning less energy is consumed from the grid. As expected, mostly sunny June with high PV generation is the obvious reason for that. A great majority of locally produced energy is stored for effective morning and evening peak load shaving.

Grid energy consumption change ranges from more than -30% on a sunny day, while the grid consumption is higher for mostly cloudy days, change reaching up to almost 7%. The reason for that is the lack of PV production and consequently BESS night charging, in order to bring BESS state of charge high enough for predefined daily peak shaving.

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Winter daily grid energy consumption change is positive, meaning more energy is consumed from the grid. Low relative values at the same time mean unsignificant volumes change in kWh.

As expected, mostly sunny summer week with high PV generation results in negative grid consumption change, which is not only relatively higher but significant also in overall energy volume.

Table 7-12- Weekly and monthly GECC June 2017 – simulations data

Month June WEEK	GECC Low RES scenario			GECC High RES scenario		
	E Base case [kWh]	E BESS case [kWh]	GECC	E Base case [kWh]	E BESS case [kWh]	GECC
Week 1	5266,25	3982,50	-24,38%	4398,22	3434,00	-21,92%
Week 2	5483,26	4191,71	-23,55%	4578,27	3510,20	-23,33%
Week 3	6176,37	5337,98	-13,57%	5095,21	4209,37	-17,39%
Week 4	6489,61	5356,38	-17,46%	5590,76	4589,01	-17,92%
June 2017	24938,55	20009,85	-19,76%	20904,80	16696,52	-20,13%

The grid energy consumption change showed in simulation reduction of 20 % to 25 % in both simulated scenarios.

7.3.2 Transformer peak load control

Transformer active power peak control represents the main challenge and ultimate project goal. The distribution transformer is exposed to 3 daily load peaks. Besides two regular customer peak loads, represented by morning and evening peak reaching up to 160 kW, the operation of high number of photovoltaic power plants during sunny days results in a third, mid-day production load peak of up to 180 kW. All load peaks stress the operation of distribution transformer.

7.3.2.1 Peak to average demand ratio (PTADR)

Change of peak to average demand ratio is defined as the ratio between the peak value of the demand profile and its average value. Ratios before and after the implementation of storage are compared in order to provide the relative change of peak to average ratio. This KPI has been selected to evaluate the techno-economic benefits linked to an improvement of the grid capacity. Generally, grids and reinforcement plans are sized according to the peak power demand in the nodes. Therefore, most of the time the networks are underused since the energy demand is on average 2/3 of the peak power. An increased capacity factor leads to a rise in the use of the grid and a reduction of the energy cost.

Calculation:

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$$\Delta\mathrm{PAR}_{\mathrm{Demand}}(\%) = \frac{\left[\left(\frac{|\mathrm{P_p}|}{\underline{\mathrm{P}}}\right)_{\mathrm{BC}} - \left(\frac{|\mathrm{P_p}|}{\underline{\mathrm{P}}}\right)_{\mathrm{CS}}\right]}{\left(\frac{|\mathrm{P_p}|}{\underline{\mathrm{P}}}\right)_{\mathrm{BC}}} \cdot 100\%$$

$\Delta\mathrm{PAR}_{\mathrm{Demand}}(\%)$ — Change of the peak-to-average demand ratio relating to the case study and the base case [%],

$\left(\frac{|\mathrm{P_p}|}{|\underline{\mathrm{P}}|}\right)_{\mathrm{BC}}$ — Ratio of peak power (P) over base case average demand, where $|\mathrm{P_p}|$ represents peak power and $|\underline{\mathrm{P}}|$ represents average demand in selected time interval [unitless]

$\left(\frac{|\mathrm{P_p}|}{|\underline{\mathrm{P}}|}\right)_{\mathrm{CS}}$ — Case study average demand and peak power (P) ratio, where $|\mathrm{P_p}|$ represents peak power and $|\underline{\mathrm{P}}|$ represents average demand in selected time interval [unitless].

Calculated time intervals: 24hours, 7 days, 1 month.

7.3.2.2 Analysis of results

BC (Base Case) and CS (Case Study) load profiles for 1. 6. 2019 is depicted in Figure 7-5, clearly showing the peak power transformer load reduction. On that specific day, consumption PTDAR+ was higher than production PTDAR-, obviously due to highly intermitent daily PV production.

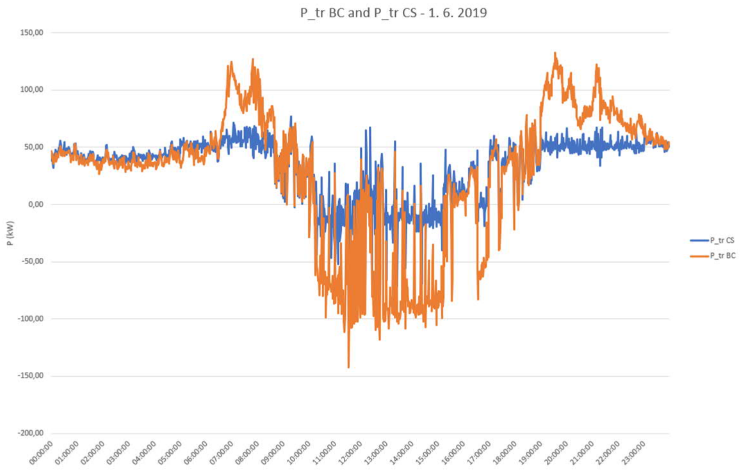

Figure 7-5-Transformer BC and CS daily profiles

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Due to two-way power fluctuation, relative peak change is calculated for positive (infeed) and negative (export) power flows.

Weekly and monthly PTDAR+ and PTDAR- are presented in Table 7-13.

Table 7-13 – June 2019 weekly PTADR+ and PTADR- data

June 2019	PTADR+	PTADR-
Week 1	45,08%	43,68%
Week 2	45,41%	49,92%
Week 3	43,97%	32,21%
Week 4	32,09%	53,50%
June	37,29%	44,80%

Weekly seasonal PTADR+ and PTADR- data is presented in Table 7-14.

Table 7-14- Weekly PTADR+ and PTADR- comparison

	PTADR+	PTADR-
Week 24. - 30. 1. 2019	8,01%	83,43%
Week 24. - 30. 6. 2019	54,81%	55,05%

June 2019 PTADR+ and PTADR- data show a very good peak to average load reduction. The PTADR+ values are higher for sunny days, obviously due to higher volumes of stored BESS energy, being later available for consumer load peak reduction. The cloudiness level shows no real impact on PTADR-, averages reaching very high values.

Winter to summer PTADR+ and PTADR- data comparison shows considerable differences in levels of both indicators. Indicators are significantly lower for winter period, revealing much lower peak to average demand ratio change compared to the summer. The obvious reason for that is almost negligible PV winter production, BESS night charging and consequently relatively low consumer peak reduction.

On the contrary, BESS operates much more efficiently in summer period, reaching much higher indicator levels and in that way fulfilling its role much better.

Table 7-15- Weekly and monthly PTDAR June 2017 – simulations data

Month June WEEK	Low RES scenario		High RES scenario	
	PTADR+	PTADR-	PTADR+	PTADR-
Week 1	51,09%	40,62%	39,26%	17,09%
Week 2	48,27%	48,12%	43,89%	29,89%
Week 3	39,00%	54,27%	40,64%	35,07%
Week 4	41,59%	52,13%	38,45%	30,40%

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June 2017	42,88%	46,81%	40,66%	24,93%

7.3.2.3 Peak power change (PPC)

Relative peak power change is defined as the change of peak power flows in the network, measured at the point of common coupling with MV network, before and after storage implementation, compared to peak power levels before the storage technology implementation.

Calculation:

$$\Delta RPP(\%) = \frac{P_{BC} - P_{CS}}{P_{BC}} \cdot 100\%$$

$\Delta RPP(\%)$ Relative peak power change

P_{CS} Grid peak power [kW] in the demo case (case study) and

P_{BC} Grid peak power [kW] in the base case.

Calculated time intervals: 24hours, 7 days, 1 month

7.3.2.4 Analysis of results

Due to two-way power fluctuation, relative peak change is calculated for positive (infeed) and negative (export) power flows.

Weekly and monthly data is presented in Table 7-16.

Table 7-16 – June 2019 weekly PPC+ and PPC- data

WEEK	PPC +	PPC -
Week 1	33,03%	31,32%
Week 2	30,88%	36,59%
Week 3	32,10%	17,84%
Week 4	13,47%	40,74%
June	21,98%	31,32%

Table 7-17 presents seasonal weekly indicators.

Table 7-17 – Weekly PPC+ and PPC- comparison

	PPC +	PPC -
Week 24. - 30. 1. 2019	2,66%	82,47%
Week 24. - 30. 6. 2019	40,43%	40,74%

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June 2019 PPC+ and PPC- data show a very good daily peak load reduction. The PPC+ values are again higher for sunny days, obviously due to higher volumes of stored BESS energy, being available for later consumer load peak reduction. Average PPC- value is high, meaning that energy storing during PV production is very efficient.

On the contrary, weekly and monthly indexes are lower due to the fact, that formula considers the monthly worst case values. As the number of readings is high (1 minute reading resolution), the result is of no surprise.

Summer PPC+ and PPC- indicators reveal a very good overall peak load reduction, due to high volumes of stored BESS energy, being available for consumer load peak reduction. Average PPC- value is also high, meaning energy storing during PV production is really very efficient.

Winter indexes are on the contrary much lower or even negative. On cloudy days, BESS is only charged during nights, reaching only low SOC in the mornings. With no stored energy available, daily morning and evening peaks are consequently not sufficiently reduced. Problem could be partially solved by introducing some changes in BESS control algorithm. Namely, BESS control algorithm limits night charging to max 100 kW transformer load. In case this limit is set higher, more energy could be stored for daily peak reduction.

7.3.3 Reactive power compensation

Reactive power, as being demanded by local load, contributes to distribution network unwanted energy losses and can potentially contribute to high voltages in HV network in case of undercompensated middle voltage networks. Despite being sometimes localy compenstated, a significant reactive power load flows can be experienced on distributions transformers. BESS reactive power compensation depends on the preset value and is constantly injected to network, in that way compensating transformer reactive load.

7.3.3.1 Distribution transformer losses (DTLC)

Change of grid losses is defined as deviation of losses in the network before and after implementation of storage. The BESS is directly connected to transformer low volatage busbars, so this KPI is calculated only for the transformer. Due to changed power flow through the transformer, the electricity losses will be different also on the complete middle voltage power infeed line, but this calculation is not being taken into account due to low middle voltage power line resistances.

Calculation:

$$\Delta P_{\text{loss}}(\%) = \frac{P_{\text{loss,BC}} - P_{\text{loss,CS}}}{P_{\text{loss,BC}}} \cdot 100\%$$

$\Delta P_{\text{loss}}(\%)$ Relative change of transformer losses in %

$P_{\text{loss,BC}}$ Losses through transformer prior to implementation of storage (base case)

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$P_{loss,CS}$ Losses in case study

Transformer losses calculation are based on transformer current measurements and distribution transformer specification (copper and transformer magnetization losses).

Calculated time intervals: 24hours, 7 days, 1 month.

7.3.3.2 Analysis of results

Figure 7-6 visualizes the transformer losses in the BC (in blue) and in the CS (in orange) for the 1.6.2020.

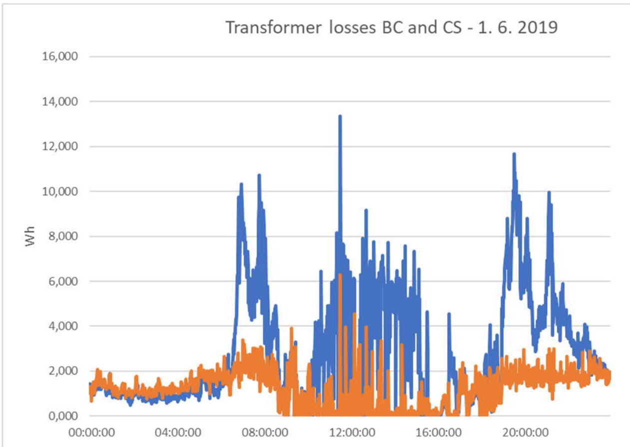

Figure 7-6- Transformer daily losses - BC and CS

Weekly and monthly KPIs are presented in Table 7-18.

Table 7-18 – June 2019 weekly DTL indicators

WEEK	E BC (kWh)	E CS (kWh)	DTLC
Week 1	26,76	13,06	**-51,20%**
Week 2	25,45	13,78	**-45,87%**
Week 3	22,33	13,81	**-38,16%**
Week 4	21,85	13,31	**-39,11%**
June	102,96	56,71	**-44,92%**

Weekly seasonal KPI is presented in Table 7-19.

Table 7-19 – weekly DTLC comparison

	E BC (kWh)	E CS (kWh)	DTLC
Week 24. - 30. 1. 2019	55,58	57,12	2,77%
Week 24. - 30. 6. 2019	22,89	10,05	-56,07%

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June 2019 distribution transformer losses change reveals relatively very good daily losses reduction. The reduction level corresponds to the amount of localy produced and stored energy, which replaces the energy, normally delivered by the transformer. On the contrary, transformer losses are higher on a cloudy day, when additional grid energy is injected to charge the storage for consumer daily peak consumption.

It is also important to notice, that even the reduction levels are relatively high, absolute losses reduction is not something that would significantly influence transformer operational cost. As for month June, with 46 kWh losses reduction, operational costs are only 2.3 Eur lower, considering 50 Eur as a market 1 MWh price. On a yearly scale, that would only mean up to 30 Eur savings in total.

Winter BESS operation obviously increases transformer losses due to BESS charging from grid. DTLC index is not significant.

Summer BESS operation decreases transformer losses by reducing transformer overall load. The reduction level corresponds to the amount of localy produced and stored energy, which replaces the energy, normally delivered by the transformer.

Table 7-20- Weekly and monthly Network Losses, June 2017 – simulations data

Month June WEEK	Change of grid losses (TR and network) [kWh], Low RES			Change of grid losses (TR and network) [kWh], High RES		
	E Base case [kWh]	E BESS case [kWh]	Relative reduction	E Base case [kWh]	E BESS case [kWh]	Relative reductio
Week 1	319,22	296,39	7,15	1232,98	960,89	22,07
Week 2	300,44	278,06	7,45	1101,40	879,12	20,18
Week 3	253,03	237,06	6,31	682,28	548,83	19,56
Week 4	304,83	284,67	6,61	959,06	760,86	20,67
June 2017	1266,90	1178,61	6,97	4293,54	3412,24	20,53

In addition to demo measurements of transformer losses, in simulations we analyse the losses in the MV/LV transformer and LV network as well. This way, we compare how much losses are reduced on transformer level, where BESS improved loss rate by 44 % on monthly level. With consideration of LV network, we see the energy losses are higher, and they are reduced only by 7 %. The reason behind this is the location of the BESS, next to the MV/LV transformer. So power flows through the transformer are reduced, but the power flows in the network are still at almost the same level. We observed reduction of 90 kWh on monthly level. The transformer model in simulations had slightly different loss rates due to static efficiency factors and voltage level as opposed to OLTC in Demo setting. In High RES scenario we see how BESS impact is increased on the reduction of the losses.

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7.3.4 Current harmonics compensation

Transformer currents distortion is normally related to non-linear customer load. In Suha network, transformer currents are additionally distorted due to operation of PV inverters during mid-day production period. Namely, high levels of current harmonics are contributed by PV inverters during intermittent production, when the sun radiation changes significantly. Current harmonics can reach extremely high values as depicted on Figure 7-7.

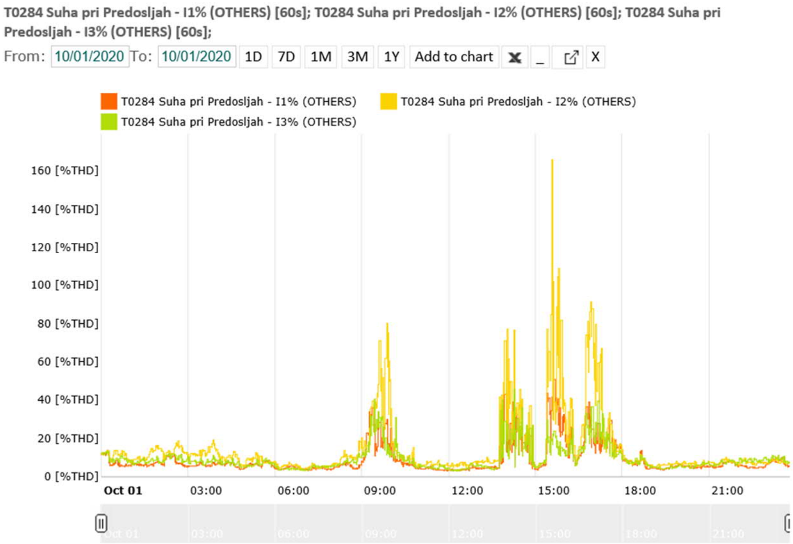

Figure 7-7- THD I daily diagram

BESS current distortion compensation is predefined as individual maximum distortion threshold value for individual current harmonic. Algorithm compares threshold set value with instant transformer currents harmonic distortions, and controls BESS active filter output in a way, that transformer current distortion does not violate selected threshold value. THD I set value for 3th, 5th, 7th and 9th harmonics were set to 0 Amperes, thus trying to compensate THD I as much as possible.

7.3.4.1 Current and voltage total harmonics change

$$\Delta \mathrm{THDI}(\%) = \frac{\mathrm{THDI}_{\mathrm{BC}} - \mathrm{THDI}_{\mathrm{CS}}}{\mathrm{THDI}_{\mathrm{BC}}} \cdot 100\%$$

$\Delta \mathrm{THDI}(\%)$ Relative current THD change

$\mathrm{THDI}_{\mathrm{CS}}$ Current THD in the demo case study and

$\mathrm{THDI}_{\mathrm{BC}}$ Current THD in the base case.

$$\Delta \mathrm{THDu}(\%) = \frac{\mathrm{THDU}_{\mathrm{BC}} - \mathrm{THDU}_{\mathrm{CS}}}{\mathrm{THDU}_{\mathrm{BC}}} \cdot 100\%$$

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ΔTHDU(%)	Relative voltage THD change
$THDU_{CS}$	Voltage THD in the demo case and
$THDU_{BC}$	Voltage THD in the base case.

7.3.4.2 Analysis of results

THD I compensation

THD I compensation was tested by switching the functionality on and off while observing THD I levels of individual phase.

Test results are presented in Table 7-21-THD I compensation results and in Figure 7-8-THD I test compensation diagram.

Table 7-21-THD I compensation results

Date: 15. 9. 2020				
Time	13:09	13:12	13:14	13:09
Comp. status	OFF	ON	OFF	ON
THD I1 (%)	24	13	19	12
THD I2 (%)	22	12	18	12
THD I3 (%)	22	11	19	14

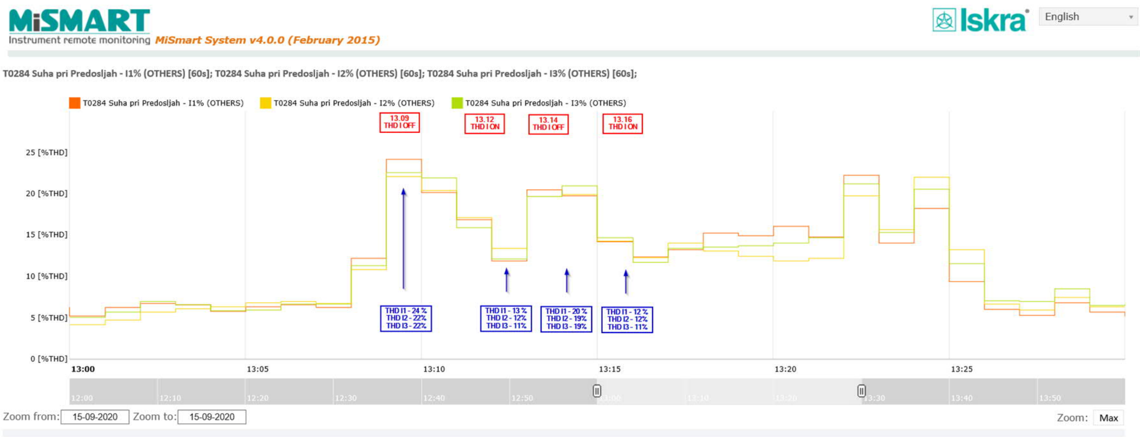

Figure 7-8-THD I test compensation diagram

Measurements clearly show the positive influence of THD I compensation by reducing it in average of 50%, but at the same time reveals, that THD I had not been compensated completely as requested. The reason might also be the fact, that THD I rate of change is very high and BESS compensating algorithm could not follow it properly.

THD U compensation

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THD U, besides the other important network paremeters, partly depends on the level of THD I and network impedance, the latest having the major influence. Even the THD I can reach relatively high values, it does not affect the THD U in case of low network impedance.

For THD I and THD U comparison, Figure 7-9-THD U daily diagram shows THD U levels for the same day as THD I on Figure 7-7- THD I daily diagram. Comparison clearly shows there is no THD I influence on voltage distortion, as can also be concluded from the Figure 7-10-THD U test compensation diagram.

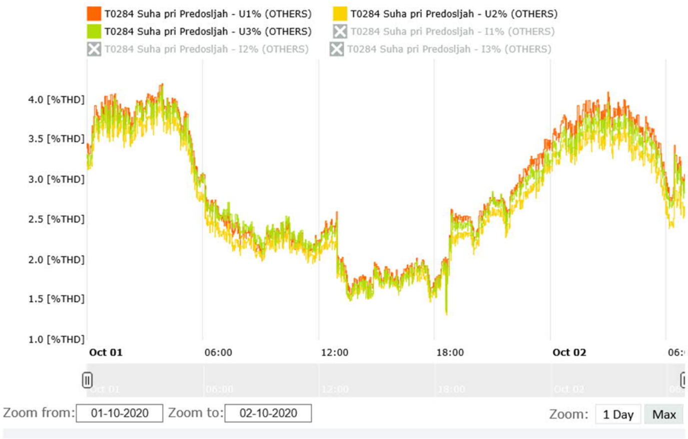

Figure 7-9-THD U daily diagram

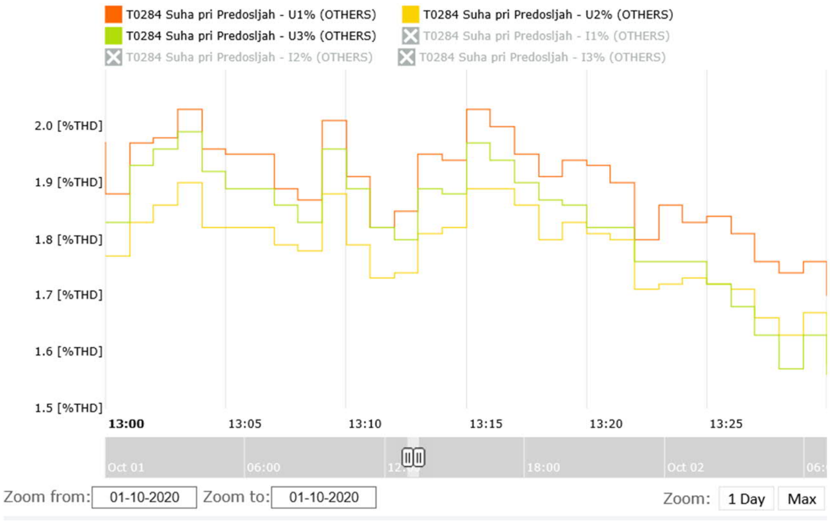

Figure 7-10-THD U test compensation diagram

The THD I test conclusions may indicate, that the THD I compensation functionality (by expectation should also improve voltage quality) might not be so important for the DSOs. By providing adequate low network impedance, as one of the most important network parameters, DSOs also sufficiently solve eventually high THD I occurrences.

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7.3.5 Zero load provision

Storage unit operates in island-like state of the network, with main goal to achieve minimal power flows on distributuion transformer. Storage unit, being located next to the transformer station, operates based on real time transformer power flow measurements. Unit is charged to predefined and high enough SoC level to be able to provide energy to the network. The algorithm checks and detects the need for the island mode operation, and if storage is available and sufficiently charged above predefined threshold SoC levels, storage is activated for zero load provision. Based on the transformers measurements of active and reactive power flows, storage charges and discharges at rates required for compensation of power flows and on the predefined boundaries for SoC level, dedicated for the island mode needs.

7.3.5.1 Performance evaluation

Zero load provision example is depicted in Figure 7-11- Zero load provision example. Zero load provision was activated on 29. 9. 2020 in a very interesting time interval from 9.00 h to 12.10 h. Within that period, the transformer load changes from consumer type (energy flowing towards consumers) to production profile, when surplus of energy is injected into MV level due to PV production.

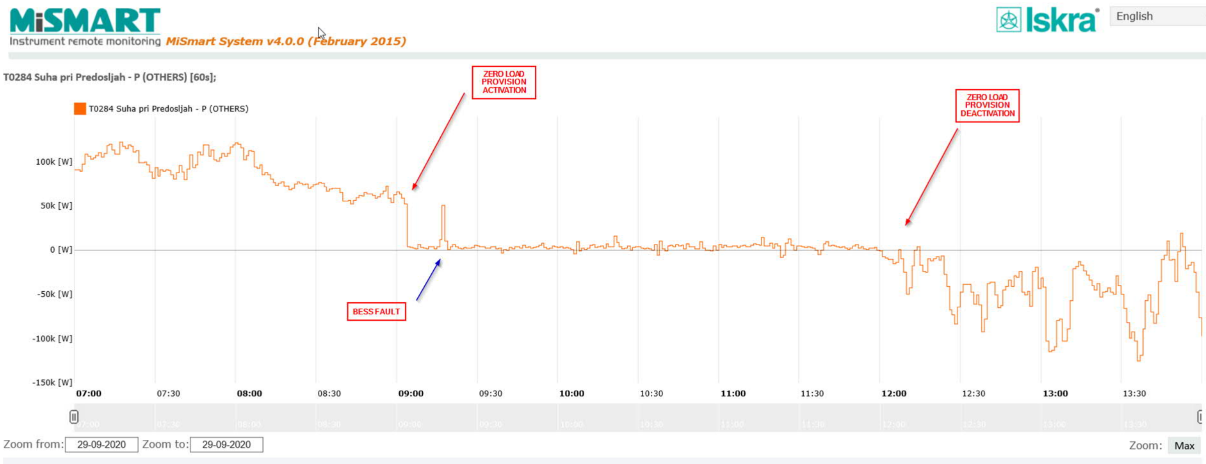

Figure 7-11- Zero load provision example

Diagram shows very efficient transformer load reduction, reaching an average value of only 3,4 kW. BESS active power visualises Figure 7-12- BESS active power during zero load provision. Diagram clearly shows BESS discharging during consumer period and BESS charging during high PV production period.

Zero load provision turned out to be a very efficient BESS functionality, simulating island operation of complete low voltage network almost up to 100%.

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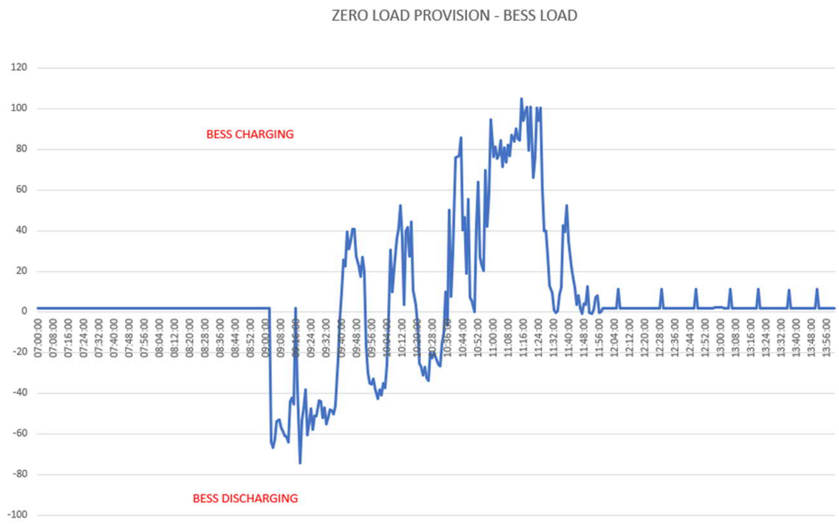

Figure 7-12- BESS active power during zero load provision

7.3.6 Tertiary reserve provision

Tertiary reserve provision of active power is rather common energy ancillary service, mostly required by transmission network operators. Tertiary reserve additionally supports TSO balancing efforts by injecting extra active power for predetermined time interval in cases of longer network frequency deviation, which usually follows different network supply failures. When the contract is in action, the amount of energy provided in the contract needs to be available for any possible activation. BESS minimum SoC must therefore be increased for the amount of contracted capacity, what normally reduces the normal BESS operation capacity boundaries. Serviceis activated on demand, and storage additionaly discharges reserved energy at agreed rate of power.

7.3.6.1 Performance evaluation

Tertiary reserve test was performed on 25. 9. 2020 from 9.00h to 9.35h with BESS 50 kW active power applied, as can be seen on Figure 7-13- Tertiary reserve provision example

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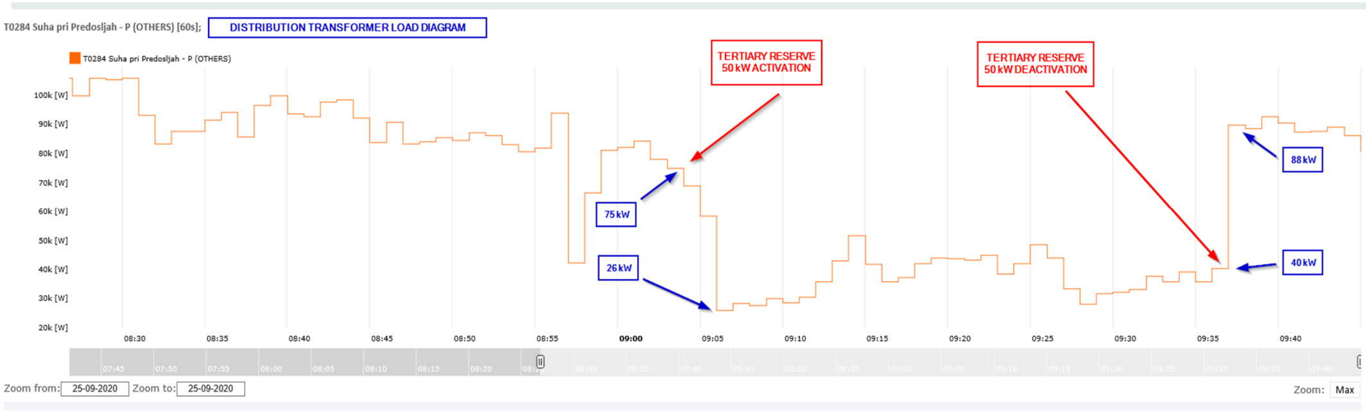

Figure 7-13- Tertiary reserve provision example

The level of applied power and the duration of tertiary reserve should be in accordance with daily BESS operation, due to the limited value of storage capacity.

Following TSO system services evolvement reasonably indicates that BESS tertiary reserve provision should be in the future upgraded also with secondary reseve provision, as it is becoming one of important additional services to TSO.

7.4 Energy storage systems performance evaluation

7.4.1 Full Cycle equivalent of storage

Full cycle equivalents of storage is the number of the full discharge cycles, which would storage perform if every cycle of operation would include full charge/discharge.

Calculation:

$$\mathrm{FCE} = \frac{E_{\mathrm{Out}}[\mathrm{kWh}]}{E_{\mathrm{Cap,nom}}[\mathrm{kWh}]}$$

$E_{\mathrm{Cap,nom}}[\mathrm{kWh}]$ The nominal storage capacity of the asset,

$E_{\mathrm{Out}}[\mathrm{kWh}]$ Total amount of energy that was extracted from the storage asset during the test period.

The energy EOut is the integral of the power output $P_{\mathrm{Out}}(t)$ [kW] at each time instance t, or directly measured at the device as $E_{\mathrm{Out}}[\mathrm{kWh}]$. Storage capacity $E_{\mathrm{Cap,nom}}[\mathrm{kWh}]$ is provided by the manufacturer and is given in documentation.

$$E_{\mathrm{Out}}[\mathrm{kWh}] = \int P_{\mathrm{Out}}(t)dt$$

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Alternatively, if the discharging energy is measured:

$$\mathrm{E_{Out}}[\mathrm{kWh}] = \sum_{k=1}^{n} E_{Out}(k)$$

Calculated time intervals: 24hours, 7 days, 1 month.

7.4.1.1 Performance evaluation

Full cycle equivalent depends on BESS discharged energy compared to the nominal storage capacity of 450 kWh.

June 2019 weekly and monthly full cycle equivalent values are presented in Table 7-22.

Table 7-22 – June 2019 weekly full cycle equivalent data

WEEK	BESS_discharge (kwh)	FCE
Week 1	1626,03	**51,62%**
Week 2	1675,85	**53,20%**
Week 3	1310,47	**41,60%**
Week 4	1292,51	**41,03%**
June	6345,68	**47,01%**

Seasonal weekly full cycle equivalent values are presented in Table 7-23.

Table 7-23 Seasonal weekly fullycycle equivalent data

	BESS_discharge (kwh)	FCE
Week 24. - 30. 1. 2019	1196,69	37,99%
Week 24. - 30. 6. 2019	1426,87	45,30%

Batteries are the most sensitive BESS element and operation must respect certain limitations. One of the most important requirements relates to battries state of charge (SOC) values. During normal operation, battery capacity should not fall bellow 20% and not exceed higher than 95 % of nominal value. That practically means only 75% of nominal 450 kWh capacity is available for daily operations. Being aware of above mentioned limitations, calculated full equivalent cycle values, averaging up to 50%, still seems quite reasonable. Values should possibly be (nonsignificantly) higher, but would require change of control algorithm parameters.

*The average winter to summer FCE difference is unexpectedly not so high as it is between cloudy day with no PV production compared to sunny or even a cloudy with at least some PV production**.*** ***It can be concluded that even the smallest BESS charge during PV production significantly contribute to the value of FCE indicator.***

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7.4.2 Storage capacity factor

Storage capacity factor SCF is defined as the ratio of maximum available capacity compared to the nominal storage capacity.

Calculation:

$$\mathrm{SCF}(\%) = \frac{E_{\mathrm{Cap,measured}}[\mathrm{kWh}]}{E_{\mathrm{Cap,nom}}[\mathrm{kWh}]} \cdot 100\%$$

$E_{\mathrm{cap,measured}}[\mathrm{kWh}]$	This refers to the measured value of maximum storage capacity and degradation over time. It is measured once in a specified time interval (e.g. 6 months), by initiating a full charging and discharging cycle if control allows it.
$E_{\mathrm{Cap,nom}}[\mathrm{kWh}]$	Storage nominal capacity is provided by the manufacturer and is given in documentation [kWh].

Calculated time intervals: 6 months, 1 year.

7.4.2.1 Performance evaluation

Storage capacity test was not performed due to the following reasons:

- Battery capacity has been reduced by 1/6 of the total capacity, due to Rack 6 disconnection.
- BESS nominal power has been reduced to half, due to one inverter failure.
- High level of transformer busbar voltage, disabling reaching BESS minimum SOC.

The only information, indicating the general state of the battery system is the State of the Health indicator, calculated by BESS itself. After two-year intermittent operation shows the value of **97,5 %.**

7.4.3 Storage efficiency

Storage efficiency is defined as the overall system efficiency, comparing the amount of injected and discharged from the device at the PCC back to the network.

$$\varepsilon_{\mathrm{Storage}} = \frac{W_{\mathrm{in}}}{W_{\mathrm{out}}} \cdot 100\%$$

$\varepsilon_{\mathrm{Storage}}[\%]$	Storage efficiency [%]
W_{in}	Energy stored in the device [kWh]
W_{out}	Energy extracted from the device [kWh]

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Calculated time intervals: 24hours, 7 days, 1 month.

Storage efficiency is extremely important system indicator, contributing a significant part to the operation costs. It consists of individual devices efficiencies like batteries, inverters, different power suppliers etc. and HVAC unit operation on the other hand, what represents high auxiliary load for system temperature conditioning. Efficiency, as presented in the following sub-chapter, is calculated on the real time measurements and represent storage overall efficiency, including all individual contributions.

7.4.3.1 Performance evaluation

June 2019 weekly and monthly efficiency values are depicted in Table 7-24.

Table 7-24 June weekly efficiency data

WEEK	BESS discharge (kwh)	BESS scharge (kwh)	SE
Week 1	1626,03	2621,07	**62,04%**
Week 2	1675,85	2878,60	**58,22%**
Week 3	1310,47	2329,79	**56,25%**
Week 4	1292,51	2467,39	**52,38%**

June 2019 weekly efficiency values are depicted in Table 7-25.

Table 7-25 Seasonal weekly efficiency data

	BESS discharge (kwh)	BESS charge (kwh)	SE
Week 24. - 30. 1. 2019	1196,69	1996,68	59,93%
Week 24. - 30. 6. 2019	1426,87	2491,06	57,28%

June 2019 daily efficiencies are within quite a broad range from 38 % to 78%, with average of 58 %. Operating efficiency is relatively low compared to the system beginning of life efficiency being 87%, measured during site acceptance test procedures.

As already mentioned, BESS efficiency is strongly related to the operating conditions influenced by BESS load level, storage capacity factor, environmental temperature and a consumption of auxiliary subsystems. BESS heating, ventilation and air conditioning (HVAC) unit with up to 13 kW consumption (cooling and ventilation) significantly contributes to relatively low overall system efficiency. Auxiliary daily load diagram is depicted in Figure 7-4 showing how frequent HVAC activation was during single summer day.

June 2019 losses total 4.67 MWh and at an average energy price of 50 Eur/MWh, that means 233 EUR of BESS operational costs for this period.

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Winter to summer comparison shows almost do difference in BESS efficiency. Both averages are unexpectedly low, compared to beginning of life test.

Both indicators are mostly influenced by HVAC unit operation, with constant 3 kW heating power during winter conditions and alternating operation of 13 kW for system cooling during summer.

7.4.4 BESS availability

The reliability of the devices operating and providing any kind of services also needs to be monitored. Device availability is defined as comparison of time, or number of availability checks, when device is available for operation and duration of monitored interval. The fallout duration is determined by measuring the time between the availability checks.

Calculation:

$$DA = (1 - \frac{\sum_{t=1}^{N} D_{NA}}{\sum_{t=1}^{N} D_{A}}) * 100\%$$

$$DA = (1 - \frac{\sum_{t=1}^{N} D_{NA}}{N}) * 100\%$$

DA Device availability (%)

D_{NA} Device not available check (integer/counter)

N Number of time instances / number of availability checks

Calculated time interval: 1 year (1. 10. 2018 – 1. 10. 2019).

7.4.4.1 Performance evaluation

The reliability of the devices operating and providing any kind of services also needs to be monitored. Device availability is defined as a comparison of time, or the number of availability checks when the device is available for operation and duration of the monitored interval. The outage duration is determined by measuring the time between the availability checks. BESS operating time totals 7113 hours, which means it was operating 81.2% time in one-year analysed period.

BESS should support distribution normal every day operations, but the device availability is not even close to the distribution reliability standards of supply. In order to support 24/7 operations, BESS would have to significantly improve its reliability, as e.g. the reliability of supply of 5h/year in Slovenia translates to 99,9999% reliability.

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7.5 Environmental analysis

More details on the LCA are provided in the STORY report “Environmental analysis of demo-scale storage implementation” as Additional Deliverable to WP6 as output of Subtask 6.2.8.

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8 Monitoring and evaluation of private industrial grid roll out (Belgium). Demo 5

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8.1 Introduction

Being a cheap alternative to electrical storage, thermal energy storage provides the added value of decoupling the production and demand of heat and thus enhancing 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 production can be increased during periods when electricity prices are high to gain an economic benefit.

In this report the results of the monitoring of this demonstrator site are reported. The installation was not always fully operational due to technical problems, which led to periods of downtime. The monitoring showed that the thermal demand on site is much lower than expected, so the added value of thermal storage for flexibility creation could not be clearly demonstrated. For this reason, a simulation tool has been developed that scales up the thermal energy demand in order to show the advantages of the thermal storage and its effect on the grid and the revenues. This simulation tool and its results are reported here, followed by the assessment of the installation using the KPIs. Conclusions are drawn at the end of the report.

8.1.1 Objectives

The goal of this particular demonstrator is to show the added value that thermal energy storage holds to increase the flexibility for an ORC installation and heat delivery while maximizing the profit. More specifically, the demonstrator focuses on:

- Efficiency enhancement and active control of ORC through use of thermal storage.
- Reduction of operational costs of energy consumption.
- Reduction of peak power demand.
- Potential optimization of thermal grid through alternate use of hot and warm water: short term hot water/medium temperature (90 ℃); short term warm water/low temeprature (45 ℃), with use of local small-scale storage.

To evaluate the achievement of these goals in the demonstrator, a number of technical, economical and environmental KPIs have been defined. A detailed description of the KPIs can be found in deliverable “Use cases and Key Performance Indicators (KPIs) of the STORY project”.

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8.2 The concept

Figure 8-1 illustrates the system architecture at the demonstrator site in Olen, Belgium. A wood-fired boiler of 1.6 MWth was installed, fueled by local waste wood from the company Beneens.

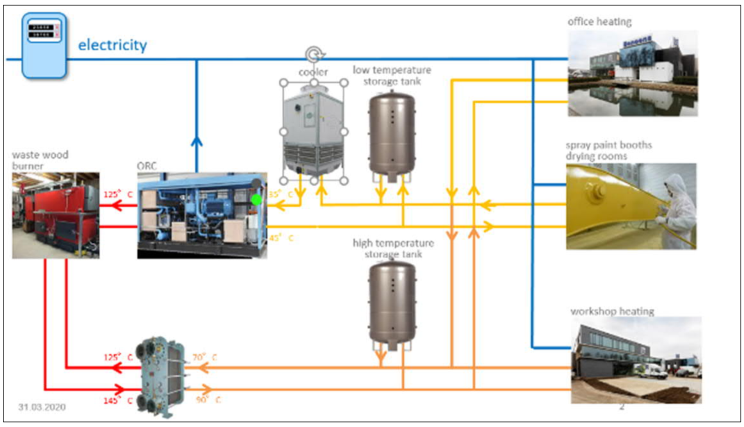

Figure 8-1-A representation of the system's architecture.

In case the amount of wood is insufficient to fulfill the heat demand, waste wood from other companies can also be used. The high-temperature heat (145 ℃) produced by this boiler is used in two ways: on the one hand to produce electricity using an ORC; and on the other hand, this high-temperature heat is transferred to the medium temperature circuit (90 ℃) via a heat exchanger and stored at a large storage vessel of 50 m^3 for further use for space heating (offices and the workshop) and for industrial processes in the painting and drying cabinets. Additionally, low-temperature (45 ℃) heat available from the ORC condenser can be further used on site for space heating. The electricity produced is either used directly on site or stored in batteries for later use. Any surplus is sold back to the grid. Moreover, excess low-temperature heat is stored in a second storage vessel of 20 m^3 or cooled off using a cooler.

The installation has been operational since June 2016. Monitoring of the thermal and electrical energy produced and consumed in the system has been active since September 2016.

8.3 Monitoring

Figure 8-2 shows the energy produced by the wood boiler and the total energy consumed (by the ORC and the medium 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.

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- Electricity 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 medium temperature circuit and how much by the ORC, Figure 8-3 can be examined. In that figure it is clear that the ORC was mainly operational in the year 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.

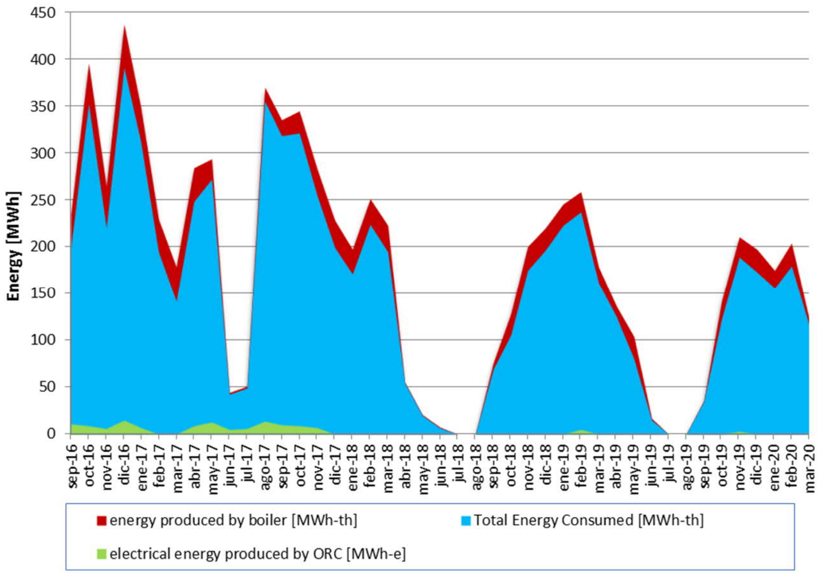

Figure 8-2- Energy produced by the boiler, total energy consumed by the medium temperature circuit and the ORC, and the electricity produced by the ORC on a monthly basis during the monitoring period from September 2016 until March 2020.

Regarding the heat consumption for the medium temperature circuit, the pattern was the same for the duration of the monitoring period: a high consumption during winter and autumn and a low consumption during spring and summer. It can be noticed that for the winter of 2019-2020 the thermal energy demand was lower than the previous years, which can be 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 in both installations. So, some components had to be changed due to damage and others had to be adapted, which led to periods of low efficiency and downtime.

In addition, it can be noticed that the electricity 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 and flow of the inlet water (source) as well as the temperature and flow of the cooling water: the smaller the difference between these temperatures, the lower is the Carnot efficiency of the ORC and therefore the lower is the electricity produced. For

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example, if we compare August 2017 and December 2016, the electricity production is almost the same but the heat input of the ORC in August 2017 is about 52% higher.

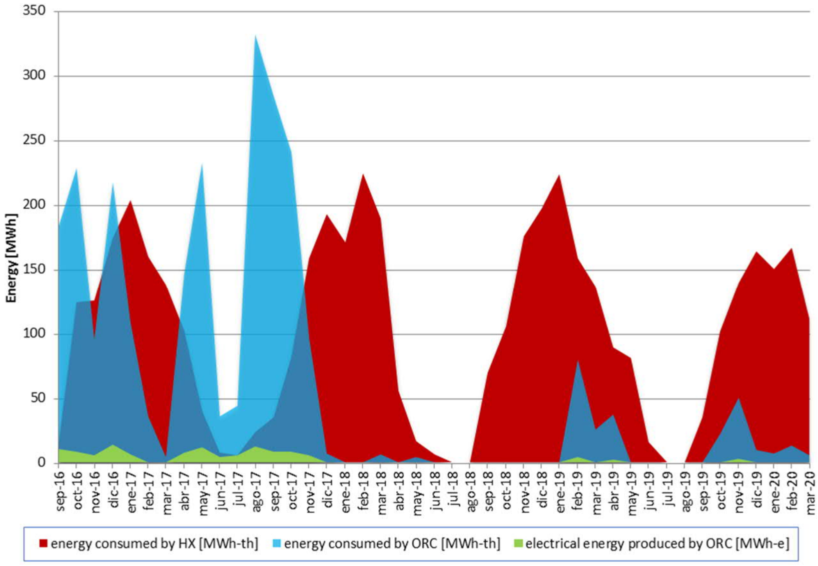

Figure 8-3- Energy consumed by the heat exchanger of the medium temperature circuit (HX), total energy consumed by ORC circuit, and the electricity produced by the ORC on a monthly basis during the monitoring period from September 2016 until March 2020.

8.4 Simulations

The main goal of the Beneens site use case is to evaluate the impact of the two additional thermal storages included in the CHP plant, from an economical and environmental prospective.

Given the low heat demand compared to the expected heat demand and the technical problems that occurred on the site, simulations were performed to assess the added value of the storage vessels on the thermal and electrical grid. Measurement data for thermal and electrical demand for the year 2017 were used as a basis to feed a linear system model developed in Python.

8.4.1 Model Description

A functional block diagram is shown in Figure 8-4.The maximum thermal power generation of the boiler is 1.6 MWth. There is no generation cost for the boiler.

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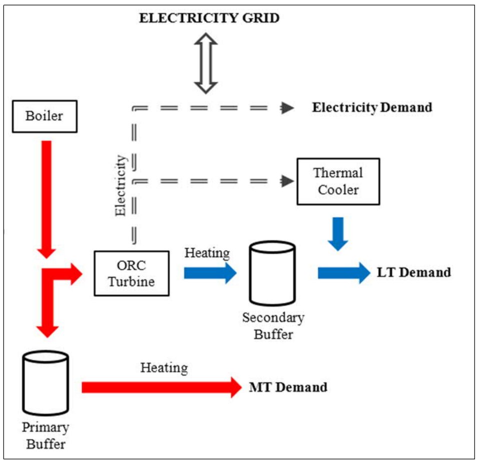

Figure 8-4- A functional block of the model implemented to represent the demonstrator's installation.

As aforementioned, the plant is divided in 2 sections. The first is the medium temperature circuit (MT) which includes the primary thermal storage (primary buffer) with a capacity of 1.163 MWhth (50 m^3), feeding the medium temperature demand. The second section is the low temperature circuit (LT) which includes the secondary thermal storage (secondary buffer) with a capacity of 0.24 MWhth (20 m^3), feeding the low temperature demand.

Both thermal storages are assumed to be perfectly insulated (no thermal losses).

The MT circuit is fed from the boiler through a heat exchanger. In the LT circuit, an ORC screw expander is included. Such a turbine converts part of the high temperature thermal energy from the boiler into electricity to feed the total electricity demand.

The LT circuit also includes an adiabatic cooler (thermal cooler) in order to cool down the excess heat output of the ORC turbine. The electricity consumption of that adiabatic cooler is also included in the simulation.

The electrical output of the ORC is used to cover the electricity demand on site including the adiabatic cooler. Batteries are not included in the framework.
The controlled variables of the simulation are:

- The boiler generation power;
- The energy loaded/unloaded by both thermal storages;
- The ORC electrical power generation.

The cost is defined here as the total cost for electricity bought from/sold to the grid through the full simulation period of 1 year.

For the energy costs, according to the plant energy bills, there was a difference of 15.32 Eur/MWh and of 10.76 Eur/MWh between peak and off-peak tariffs for energy offtake and energy injection, respectively.

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The goal of each simulation is to evaluate the economic cost of each scenario, assuming the plant is running under the optimal control conditions (i.e. the ones which minimize the running cost).

To find the optimal control sequence for each scenario, the linear mathematical model was used, which allows to perform linear programming optimization.

8.4.2 Simulation Results

Simulations have been performed using the electrical and thermal demands measured in the year 2017 and shown inFigure 8-5. The seasonal pattern is clear for the thermal energy demand, which is higher during winter and lower during summer. However, this is not the case for the electrical demand which is constant throughout the year with a dip in July due to the vacation period.

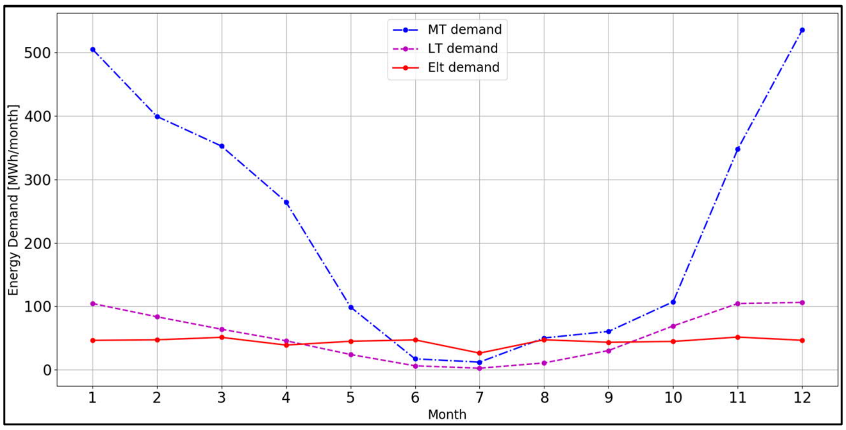

Figure 8-5-Monthly thermal and electrical energy demand measured at the demonstration site for the year 2017.

As mentioned in the last section, each simulation has been performed assuming the plant running under the optimal control conditions. Then, the corresponding running cost has been computed and compared to those resulting from other scenarios.

Two case-studies have been considered: (i) the base case: without thermal storages, and (ii) the demonstrator case: with thermal storages.

As mentioned earlier, the demonstrator showed that the heat demand is considerably lower than expected, especially that no connection to a thermal network has been made. For this reason, the heat demand in the simulations has been upscaled using a heat demand scale factor (SF). This factor increases the scale of the thermal demand but keeps the profile similar to what was measured in the demonstrator. On the contrary, the electricity demand was kept constant as it was not underestimated during the installation design. Figure 8-6 reports, for different thermal demand scale factors, the potential cost reduction (in Eur per year) for case (ii) compared to case (i). It should be noted that the SF increase is for both cases and not only for case (ii).

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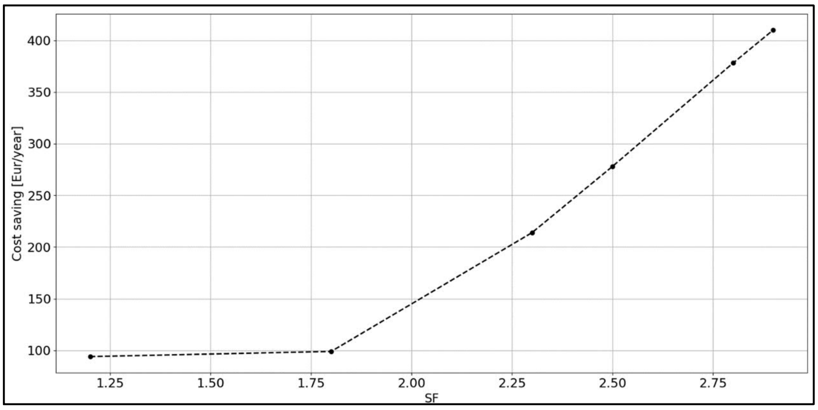

Figure 8-6- Cost saving [Eur/year], using thermal storages for increasing thermal demands.

The saving at the basic (measured) heat demand (SF=1) is 92 Euro per year. Those savings increase with SF, reaching 410 Euros per year for SF of 2.9. So, the higher the thermal demand, the higher are the savings. If the scale factor is higher than 2.9 the heat demand couldn't be delivered by the boiler for case (i). This is not the limit for case (ii) because of the presence of the thermal storage that can store heat if the thermal demand is lower than the thermal production, to be used later on.

These savings occur because as the heat demand increases the following happens: for case (i), more of the heat produced by the boiler has to be used for heating purposes instead of being used for the electricity production by the ORC. This means that less electricity is produced by the ORC especially during peak hours, leading to an increase in electricity use from the grid at a high cost. For case (ii), with an optimal system control, heat can be produced during off-peak when heat and electrical demands are low, and then stored in the thermal storage to be used during peak hours. Like that, more heat of the boiler can be directed to the ORC to produce electricity that is locally consumed, and high cost electricity imports can be avoided. As SF increases, the added value of the storage increases and hence the savings.

Figure 8-7 reports the reduced cost comparison between case (i) and case (ii) for values of SF larger than 2.9, corresponding to when the thermal demands exceed the boiler power capacity generation for case (i). As shown, for an SF increase between 3.0 and 4.0 the cost reduction for using the thermal storages becomes even more evident, achieving a maximum of 552 Euro per year for SF at 3.6. The maximum increasing factor of 4.0 corresponds to a total thermal demand beyond which it is not possible anymore to fully cover the demand even for case (ii).

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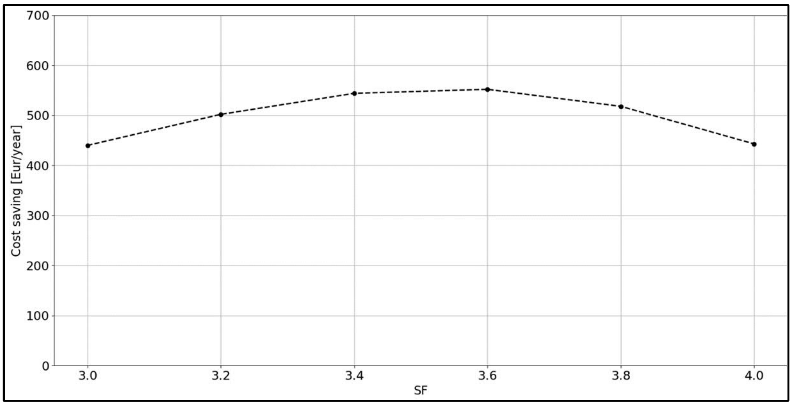

Figure 8-7- Cost saving [Euro/year], using thermal storages for increasing thermal demands exceeding the maximum generation capacity.

These results show that with the current installation, an extra thermal consumption up to three times the current consumption, with a similar profile, can be added without the need to upgrade the installation. This extra consumption can be for example a district heating network to nearby companies.

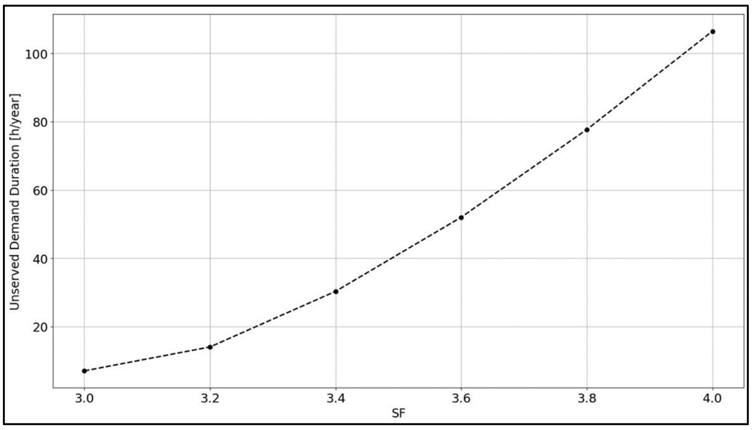

Figure 8-8-Number of hours (per year) where the thermal demand are not fully covered for case (i).

As mentioned, for the SF values shown in Figure 8-7, the heat demand is not always satisfied for case (i) because the thermal demand exceeds the maximum boiler capacity. This means that there is a number of hours during the year in which the thermal demand remains partially uncovered. Figure 8-8 shows, for case (i), this number of hours per year as a function of SF. The yearly unserved thermal demand hours increase from 7 hours at SF=3 to 106.5 hours at SF=4.

8.5 Performance Evaluation

To evaluate the performance and to assess the efficiency of the control strategies taken, an evaluation methodology based on KPIs was designed. The KPIs have been defined in deliverable “Use cases and Key Performance Indicators (KPIs) of the STORY project”.

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In the simulation for the industrial site, only one use-case was considered, which is the reduction of the operational/running costs of the installation. More specifically, the focus is on the case where SF=3.6, as it provides the highest operational cost savings.

The KPIs are divided into 3 categories: technical, economical and environmental. Some of the KPIs are general, for all the demo sites and other KPIs are demo specific. In what follows, the KPIs are calculated and the performance is discussed.

8.5.1 Technical performance evaluation

8.5.1.1 KPIs

The technical KPIs assess the thermal and the electrical performance of the installation and the added value of storage for the given control strategy. The KPIs are: increased RES use (K1), increased self-consumption (K2), relative peak power change (K4), ORC utilization rate (K29), storage ORC efficiency (K30), heat fulfilment share (K32), storage related coverage increase (K33), additional overall thermal storage losses (K34) and heat loss reduction of district heating network by multi-temperature network (K35).

8.5.1.2 Performance evaluation

The calculated KPIs are shown in the table Table 8-1.

Table 8-1- Technical KPI's

KPI	Value	Unit
K1	0.59	%
K2_SCL_NoStorage	66.27	%
K2-SCL_Storage	66.72	%
K2_SSL_NoStorage	81.48	%
K2_SSL_Storage	80.63	%
K4	1.79	%
K29_NoStorage	95.83	%
K29_Storage	96.29	%
K30	0.48	%
K32	100	%
K33	0.59	%
K34	32226	kWh/y
K35	24	%

The calculated KPI's show that the integration of thermal storage has in this case a limited improvement on most of the KPI's. The RES use increase, the increased self-consumption, the relative peak power change, the ORC utilization rate and the ORC storage efficiency improved by between 0.5 and 1.5 % on a yearly basis for the case with storage compared to the case without storage.

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Without storage, the installation is not able to provide the heat demand for 52 hours out of the 8760 hours of a full year. As the storage is integrated, the heat fulfillment share (K32) is 100%, meaning that all the heat demand is covered. The coverage increase due to the storage is therefore 0.59% (K33).

The additional thermal storage losses were calculated from the measurement data of the year 2017. The losses are the difference between the energy loaded in both storage vessels and the energy unloaded from the storage vessels, given that the state of charge of the vessels at the beginning and at the end of the year are identical. Those losses amount to 322 MWh/y which correspond to 23% of the energy loaded in the tanks. That's a considerable amount however this is not directly related to the performance of the insulation around the tank because in many cases the storage vessels were loaded but then left unused for longer period due to vacation period, technical problems and due to the low total heat demand, as mentioned earlier.

Part of the internal heating circuit can be supplied with either high or low temperature heat, depending on the demand. K35 calculates the percentage reduction in the heat losses in the distribution network (piping) due to the occasional use of low temperature instead of the medium temperature for heating. Measurements showed that the losses due to the alternating use of both temperature regimes is around 13 MWh per year. Low temperature heating was used for 2475 hours while high medium heating was used for 3974 hours during the year. If the heating would have been provided exclusively with medium temperature, the losses woud amount to 17.1 MWh/year. So, the use of low temperature heating led to a reduction of 24% (K35) in the distribution heat losses.

8.5.2 Economical performance

8.5.2.1 KPIs

The economical KPIs assess the economical improvements to the main actors due to the integration of storage. The two KPIs are: change of revenue for the main actors (**K13**) and average cost of energy consumption (**K14**).

8.5.2.2 Performance evaluation

The calculated KPI's are shown in the table below, Table 8-2.

Table 8-2-Economical KPI's

KPI	Value	Unit
K13	552	Eur/y
K14_NoStorage	0.00893	Eur/kWh
K14_Storage	0.00812	Eur/kWh

The KPI's show that by integrating storage in the system and using the control strategy aiming to maximize the electricity production, the owner saves 552 Eur/year on the electricity cost. Regarding the average cost of energy consumption, for the case with storage integrated, it is

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0.00812 Eur/kWh, a decrease of 9% compared to the base case. Important to note that this is a decrease in the electrical energy cost, as the thermal energy is considered to be free. This reduction occurs because with storage, the heat of the wood boiler can be used mainly for the ORC to produce electricity when the tarrifs are high, and it can be shifted to the high temperature circuit and the storage tank when the tarrifs are low.

8.5.3 Environmental analysis

8.5.3.1 KPIs

The calculation of the environmental KPI “Change of GHG emissions” is based on a LCA, including the environmental impacts throughout a product’s life cycle from raw material acquisition through production, use and end-of-life treatment.

The annual GHG emissions of the demo case are compared to the annual GHG emissions of two reference systems:

Reference system 1: heat is produced by natural gas boiler and the electricity is completely supplied by the power grid

Reference system 2: heat is produced by a waste wood boiler and the electricity is completely supplied by the power grid

For a valid comparison, both systems – demo case and reference - must include the same resources and provide the same amount of heat and electricity (Figure 8-9).

Therefore, the reference use of the wood waste was included. If the waste wood is not used in the demo case for heat and electricity production, it has to be deposed. The waste wood is transported to a waste CHP plant in Germany, where it is burnt together with other waste fractions. The additional heat and electricity, which is generated in the waste CHP plant in the reference system, also needs to be considered in the demo case. For the electricity, we assume it is supplied by the power grid and for the heat it is provided by a natural gas heating plant.

Input data for the assessment is mainly based on system simulations in combination with data from the LCI data base GEMIS.

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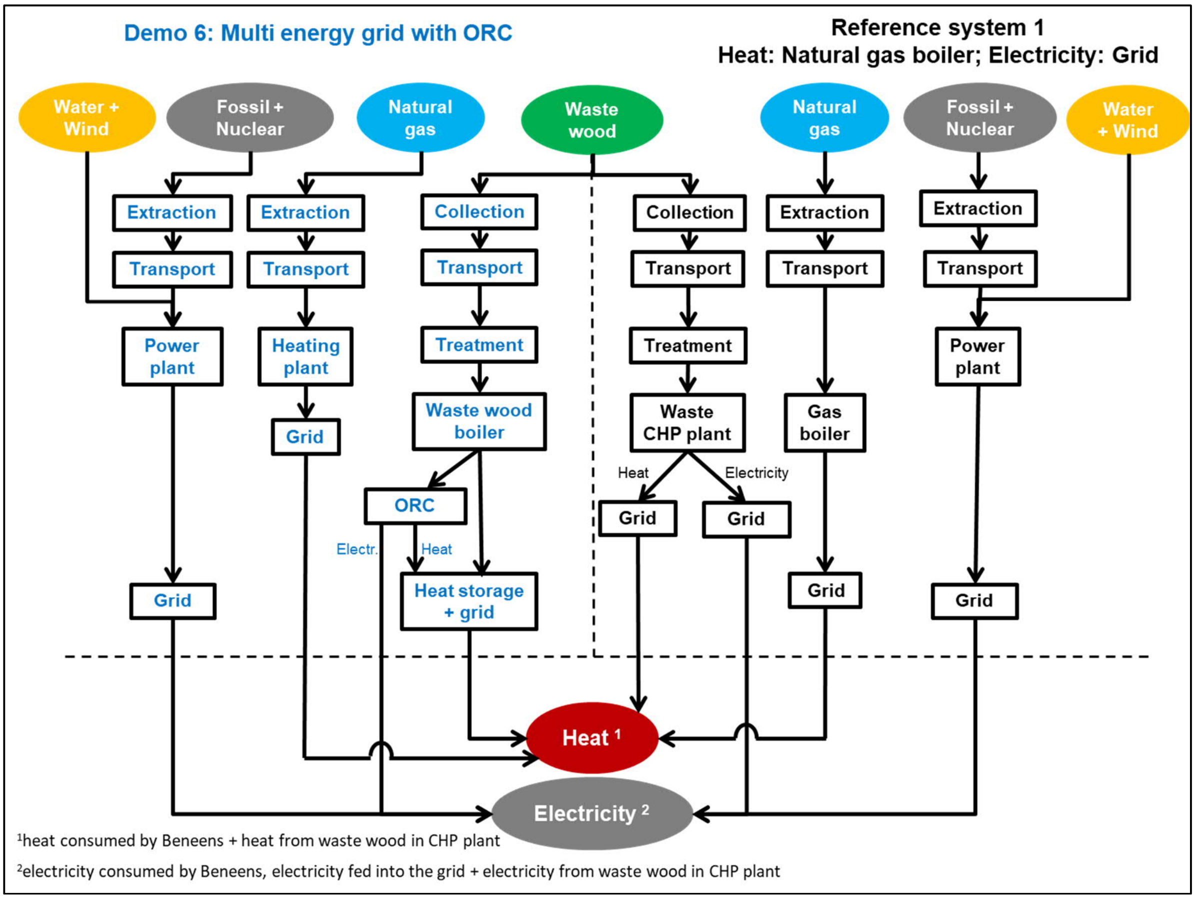

Figure 8-9- Comparison between demonstration case and reference system 1 with a natural gas boiler and total electricity supply from the grid

8.5.3.2 *Performance evaluation*

The LCA results show that the total annual GHG emissions are higher for the demo case compared to both reference systems (Table 8-3). Looking only at the energy supply of the demo site the GHG emissions seem to be lower for the demo case (120 t CO2-eq/yr compared to 510 t CO2-eq/yr with reference system 1 and 210 t CO2-eq/yr with reference system 2). However, for a complete system evaluation the reference use of the waste wood needs to be included. This leads to additional GHG emissions for the demonstration case of more than 1 kt CO2-eq/year.

The main reason for this result is the high amount of unused heat from the ORC process. Using more of this heat for low-temperature district heating in the future will improve the GHG performance of the demo case.

More details on the LCA are provided in the STORY report “Environmental analysis of demo-scale storage implementation” as Additional Deliverable to WP6 as output of Subtask 6.2.8.

Table 8-3: Annual GHG emissions of demonstration case in comparison to the reference systems

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Annual GHG emissions [t CO_2-eq/yr]	Demo case	Ref. 1: Natural gas boiler	Demo case	Ref. 2: Waste wood boiler
Energy supply demo site (new waste wood boiler + ORC)	120	-	120	0
Natural gas heating plant + grid electricity (reference use wood waste)[1]	1 410	-	1 220	0
Natural Gas Boiler	-	320	-	-
Old waste wood boiler	-	-	-	20
Grid electricity	-	190	-	190
Waste CHP (reference use wood waste)	-	540	-	450
Total	**1 530**	**1 050**	**1 340**	**670**
KPI - Change in annual GHG emissions	***+ 480***		***+ 670***	

[1] Amount of waste wood for reference use differ for reference system 1 and 2. This leads to two different results for the demo case.

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9 Conclusions and lessons learned

This report has collected in a unified way the main results obtained during the monitoring and evaluation of the proposed use cases, where energy storage added value is present in different degrees of improvement on most of the KPIs. The KPIs are divided into three main categories, technical (including demo specific), economical and environmental. In Table 9-1, the KPIs that have been monitored are coloured, and the ones that have been evaluated, calculated, and the performance is discussed are tagged with a check mark.

Table 9-1- Application of KPIs to the demos according to deliverable D6.2. Monitored and evaluated KPIs are check marked

KPI #	Type	KPIs	Demo 1, a): Oud – Heverlee Living Lab	Demo 1, b): Oud – Heverlee building level	Demo 2 : Oud – Heverlee neibour-hood	Demo 3: Spain	Demo 4: Beneens	Demo 5: Slovenia
K1	Tech. General	Increase RES use	▪	▪	▪	✓	▪	✓
K2		Increased Self consumption use	▪	▪	▪	✓	✓	✓
K3	Tech. Grid-related KPIs	Peak-to-average demand ratio				▪		✓
K4		Relative peak power change				▪	▪	✓
K5		Grid losses change				▪		▪
K6		Grid energy consumption change				▪		✓
K7		Current and voltage total harmonic distortion change				▪		✓
K8		Voltage deviation change				▪		
K9	Tech. Device level KPIs for performance monitoring	Full Cycle Equivalents of Storage				▪		✓
K10		Storage capacity factor				▪		✓
K11		Storage efficiency				▪		✓
K12		Device availability				▪		✓
K13	Economic KPIs	Change of revenue for the main actors					✓	
K14		Average cost of energy consumption					✓	
K15	Environmental KPIs	Change of emissions	✓	✓	✓	✓	✓	✓
K16		Avoided emission cost	✓	✓	✓	✓	✓	✓

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KPI #	Type	KPIs	Demo 1, a): Oud – Heverlee Living Lab	Demo 1, b): Oud – Heverlee building level	Demo 2 : Oud – Heverlee neibour-hood	Demo 3: Spain	Demo 4: Beneens	Demo 5: Slovenia
K17	Demo specific technical KPIs (demo 1)	Generation and consumption prediction accuracy	▪	▪				
K18		(In)voluntary imbalance	▪	▪				
K19		Available flexible power & energy	▪	▪				
K20		ICT gateway availability and volumes	▪	▪				
K21		Consumption change	▪	▪				
K28	Demo specific technical KPIs (demo 4)	Electrical performance of the ORC					▪	
K29		ORC Utilization Rate					✓	
K30		Storage ORC efficiency					✓	
K31		Share of covered thermal demand					▪	
K32		Heat fulfilment share					✓	
K33		Storage-related coverage increase					✓	
K34		Additional overall thermal storage losses					✓	
K35		Heat loss reduction of district heating network by multi-temperature network					✓	
K36	Demo specific technical KPIs (demo 5)	Reactive Power Compensation Efficiency						✓

In the following subsections, for all the demo sites conclusions from their KPIs results are summarized. As well, the usefulness of the lessons learned in potential future replications of similar applications of energy storage use has also been highlighted.

Monitoring and evaluation of residential building level demonstrations (Belgium). Demo 1, a)

The Living Lab's main focus is on technology cooperation, including interoperability, and limitation of grid exchange. The Living Lab is certainly unique in the world, from its design, the challenge of component selection, installation, and its operation. It comes as no surprise that many valuable lessons can be learned from this process.

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First, while it is easy to have everything custom build, use industrial automation solutions like SCADA systems, PLCs, cloud computing, expensive software licenses, etc., one should ask what a replicable solution is for a residential building, where cost is a very important factor.

Second, the abundance of innovative technologies and required use of components from different manufacturers to get the Living Lab built, make it difficult to achieve seamless operation. Interoperability is a huge challenge to overcome. There exists no blueprint, nor installation manual nor single manufacturer that can deliver all the necessary components. Standardization and regulation can help here but thorough testing remains crucial. There exists a tendency to look only at components and its performance, its power consumption, its optimization … In the end there is an optimal component which can never be used in a system.

It cannot be emphasized enough that, today, multidisciplinary profiles are needed more than ever. People who can apply system thinking across individual components, while still knowing enough about the limits and operation of each. People that can simplify enough to make high-level control algorithms computable, but also understand the need for an intermediate layer that deals with the complexity of the real-world.

Integrating a high-level control, like a Model Predictive Control (MPC) in a real-life residential system has proven a challenge.

The practical computation of the MPC requires that the real-life system be simplified to reduce computation time. From the MPC designers' point of view, having hundreds of parameters for optimization requires a lengthy and often impossible calculation. Thus, assumptions and simplifications are necessary to arrive at a viable algorithm.

Third, many manufacturers know too little of the actual limits of their products and while it is easy to be tempted by brochures, the performance in real life leaves much to be desired.

For example, the BESS in the Living Lab can inject energy into the grid. This is accomplished by programming the system with a current injection set-point and a time frame. The operation of this control is thus largely dependent on the BESS' ability to keep an accurate time. In practice the system does not support external time synchronization (confirmed by the manufacturer), so there is no way to automatically correct time drift. In practice, the system clock drifts several minutes per month making control and tracing events a nightmare.

More conclusions and lessons learned:

- Energy consumption and data transport should be considered when evaluating an algorithms' effectiveness.
- Insulation buildings towards zero energy is good for minimizing thermal losses, wireless sensor communication (4G, WiFi, Bluetooth, LoRa, etc.) becomes almost impossible without additional devices, increasing costs and energy consumption.
- The most economical way to store a large quantity of water is to install a pool. However, when used for cooling it becomes a perfect incubator for frogs that eventually clog the filters.
- During maintenance on the thermal system, the plastic inside of the VC flow meter melted. Suddenly clouds disappeared and temperature increased to 120°C in a matter of minutes.

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- EV charging, being the decisive load, is almost impossible to schedule since SoC data cannot be obtained from a residential charger.

Monitoring and evaluation of residential building level demonstrations (Belgium). Demo 1, b)

Performance evaluation of the demonstration 5.2. is focused on the control of three smart appliances in two houses of the same residential neighborhood. The control framework is a model predictive control setup which objective is to reduce the costs of the electricity consumption of the controlled appliances.

The performance of the control was evaluated using a comparative analysis on two comparable sets of days without (base case) and with external control (control case). Those sets are a subset of the measurement/control days that are similar in terms of qualitative (i.e. day of week) and quantitative criteria (i.e., outside temperature).

Those sets are defined separately for 5 different control periods, lasting 8 to 20 days, with temperatures ranging from 0°C to above 15°C, and taking place in the winter and autumn seasons.

The method is shown to be adapted for performance evaluation but tends to exclude extremes (i.e., <0°C) as extreme value observed during one of the days with external control could not always be found in the days during which no external control.

The first element of conclusion is that performances strongly depend on the ability of the appliance to immediately apply the control signals sent from the central optimisation. Direct control proved to be very effective with two of the three appliances: the water boiler in house 4 (control period 1,2) and space heating heat pump of house 3 (control period 5). The third appliance is a heat pump shows less responsiveness as control occurs via temperature set-points of an external thermostat connected to the heat pump. The existing (local) controllers of the heat pump take other parameters into account (internal pressure in the thermal cycle, etc.) that are not made available to the central optimisation. This setup leads to relatively good control performances but less pronounced than with the other appliances.

Appliances with good controllability proved to reach higher effective shifted energy and associated cost reduction (values from 4% to 10%).

Economic performance analysis showed a limited cost decrease potential (a small percentage). In the residential sector, appliances are of great diversity and user's preferences differ largely from one case to the other.

The ideal control setup must combine a simple and interoperable local controller with an adaptive and robust central control system, able to learn from the few parameters received from the local devices and to take user feedback into account in some way. The user feedback must be integrated, certainly to prevent permanent impact on user's comfort in case of poor controllability. This feedback integration limits the risk of users opt-out.

Cost effectiveness at larger scale is a real challenge, knowing all the above requirements. Therefore, there may be a need to increase the financial interest of the business case to make it more viable. Local considerations and neighborhood-level optimisation could be one of the most

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direct ways to increase the financial interest of the control framework. Indeed, the control could be adapted to take grid-level states into account (i.e. energy flows exchanged with upper level grid layers to avoid congestion), and the resulting benefits could be partially shared with the end user.

Table 9-2– Performances and Lessons Learned

	Description	Performance	Lessons learned
1	Impact of the control on Thermal Comfort of the end-user	1. Appliances with good controllability (direct control): Comfort levels have a high chance to be respected after introduction of the control. The optimisation leads the control temperatures to be more volatile around the desired level. This is linked to the larger use of the thermal storage (increased mileage). 2. Appliances with poor controllability (indirect control): Comfort levels will be respected <u>at the condition that user's feedback</u> is considered. 3. Note: Water boilers seems to have larger time flexibility than space heating.	In case the control infrastructure exploits load for which controllability is uncertain, thermal comfort will be maintained within acceptable levels under the condition that user feedback is considered. This requires the central control to adapt to and learn from the local appliance/the end-user. It is a challenge to scalability of the solution.
2	Impact of the control on Energy costs	Cost decrease is situated between 3 to 10% of the energy component of the bill of the appliance under control.	With current price spreads and taxation scheme in the belgian electricity system, the expected economic gains are insufficient to make a viable business case at the household level. Possible solutions are to perform optimisation of self consumption or at local and neighborhood level.
3	Impact of the control on CO2eq. emissions of the electricity consumption	The cost-based optimisation (dynamic pricing) tend to increase the share of the consumption at night/early morning which is negatively correlated with the hourly average emissions level of electricity generation in belgium. Consequently, emissions tend to slightly decrease.	CO2eq. emissions would drastically decrease in case of the business case at stake is to optimize the local use of energy. Yet, this would impact the external system as they could benefit less from cheap and clean source of power (PV).
4	Impact on local use of energy	Local use of energy (when applicable) is increased (both Self consumption and self sufficiency) even in the case of dynamic pricing. This is linked to a small correlation between low prices and PV injection and from the fact that consumption was not initially optimized to optimize self consumption of locally generated energy.	A dedicated optimisation would lead to much better use of locally generated energy. This could be evaluated in demonstration at household and neighborhood level.
5	Technical performance	The control chain is functional more than 95% of the time. This is achieved thanks to the robustness of the control framework to missing data. One of the explanations is that the Model predictive control framework is able to use past predictions of the model states as proxy of the current state of the actual system in case updated view is missing in real time (communication lost, etc.).	Data availability decreases mainly due to the nature of the data streams originating from a broad number of sources using multiple communication protocols. Robustness of missing data as well as data integration (interoperability) are two key elements of success for the control infrastructure.

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Monitoring and evaluation of neighborhood level demonstrations (Belgium). Demo 2

This demonstration focuses on the energy strategy to impact grid balancing and flexibility in the Oud-Heverlee neighbourhood demonstration. In this demo a neighbourhood battery energy storage system (BESS) is a way to scale up and ensure an adequate and well-orchestrated behaviour.

From monitoring and evaluation of this demo case, the main lessons learnt indicates firstly that improvement of power quality on the low distribution network can be done in a simple and cheaper way by low level control. This control is based on voltage measurements on central and on decentral devices. And, at the same time, it has to be focused on ensuring a fair distribution of impact, compensating for the normal deviations as a function of the connection location on the line.

Secondly, when focusing on local weaknesses and especially temporal situations and having multiple neighbourhood batteries acting in a coordinated manner, this can create benefits at medium and even high voltage level. and therefore an increase in the penetration of decentralized and centralized renewables can be achieved.

Finaly, when low voltage grids are well-sized and congestion is not an issue, there is little value for a neighbourhood battery. Together with the business case results, cable replacements are still a less expensive option to be taken.

Monitoring and evaluation of industrial building (Spain). Demo 3

In this demonstration, to evaluate the performance and to assess the efficiency of the control strategies taken, an evaluation methodology based on KPIs was designed. In this report, the KPIs are calculated and the performance is discussed.

A business case based on electricity bill savings was here analysed, in order to assess the system profitability. The main goal of the Spanish pilot plant was to demonstrate the added value of energy storage by reducing the demand charge of a factory, which in occasions rises up to 60% of the electricity bill.

One of the main issues that arouse during the operation of this use case was related to the integration of the different equipment present, especially with regard to the communication and control systems that should ensure smooth coordination.

The continuous errors made necessary numerous visits of the technical services of the equipment. At the same time, the errors caused the data finally recorded to be limited to shorter periods of time than desired, due to continuous interruptions.

It is clear that the integration of equipment from different manufacturers continues to be one of the main challenges for the successful deployment of this type of system, whether at a domestic, commercial or industrial level.

Ultimately, it becomes very difficult to obtain a return on investment, whether from an economic, environmental or operational point of view, if it is not possible to guarantee adequate availability values for the installed system.

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With regard to the behaviour of the plant during its effective operation time, the values obtained from the KPIs, allow for optimism about the suitability of these systems to reduce the costs of the electricity bill. Of course, the scale of the reduction would depend on the relative dimensioning of the PV system in relation with the experienced load demand, and also on the storage capacity of the ESS. Furthermore, the behaviour of the latter has been as expected and the results with regard to the peak-shaving and energy time-shift functions are proof of this.

The operation of the system was strongly influenced by the evolution throughout the project duration of the Spanish regulatory framework for self-consumption installations. At the beginning, surplus PV energy could not be fed into the grid, neither energy from the grid could be charged into the battery.

This regulatory framework limited the possibilities of the operation strategy. Subsequent amendments to the regulatory framework removed these restrictions on the operation and allowed for a wider scope of decision-making for the energy management strategy.

It is clear that the management strategy of a plant must be adapted to the objective sought, to the regulations in force in the country in which it operates, as well as to the conditions of the electricity market. Given the current developments in these sectors, it is likely that the strategy of a plant control system will need to be adapted during its lifetime for optimal operation.

Monitoring and evaluation of medium scale storage unit (Slovenia). Demo 4

The integration of a medium scale storage unit in a low voltage substation, connecting a residential area and photovoltaic production, is monitored and evaluated. Overall experience and major lessons learned are summarised as follows.

All BESS functionalities were successfully confirmed, resulting on a confident grid consumption reduction.

In relation with the transformer, a solid load peak shaving has been accomplished.

Reliable operation of EG broadband radio (WiMax) is achieved, even with unexpected high frequency noise generation encountered. Reliable operation of EG control and monitoring systems are developed within this high system complexity.

However, even if implementation of efficient BESS control algorithm is achieved, BESS system evidences low efficiency.

Moreover, the fact of having a high BESS investment costs, showing an unacceptably high number of different BESS failures and faults during the complete demonstration, added to maintenance and operational problems, means this solution has disadvantages.

Generally, all BESS predefined functionalities were successfully confirmed. The most important, load management functions, based on properly developed and optimized algorithm, proved to be efficient and well suited for future distribution network operations.

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Monitoring and evaluation of private industrial grid roll out (Belgium). Demo 5

The main goal of the Beneens site use case is to evaluate the impact of the two additional thermal storages included in the CHP plant, from an economical and environmental prospective.

The monitoring of the installation showed a seasonal pattern for the HT and LT heat demand and a relatively low heat demand for the 2019-2020 heating season due to a mild winter. It also showed 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. This reduction in operation is attributed to a series of technical problems which occurred on the ORC and the wood boiler and led to periods of downtime especially in certain periods in 2018, 2019 and 2020.

It was also shown by the monitoring that the heat demand for space heating and processes was considerably lower than expected and designed. For this reason, it was not possible to show in the demonstrator the flexibility potential that the thermal storage can provide. Therefore, a simulation model of the system representing the different components was developed in Python. In that model, the measured heat demand was scaled up to increase the usability of the thermal storage.

The heat demand upscaling demonstrated that, with the current installation, an extra thermal consumption up to three times the current consumption, with a similar profile, can be added without the need to upgrade the installation as designed. This extra heat can be delivered to for example a district heating network connecting extra nearby companies, providing additional revenue.

In the simulation for the industrial site, only one use-case was considered, which is the reduction of the operational/running costs of the installation. More specifically, the focus was on the case where heat demand was scaled up by a factor of 3.6.

The calculated KPI's show that the integration of storage has a limited improvement on most of the technical KPI's, between 0.5 and 1.5%. The heat losses due to the integration of storage, amount to 23% of what is injected in the storage, which is considerable. However, this is not only due to the performance of the vessels' insulation, but also due to low heat demand. Moreover, the use of low temperature heating occasionally during the year instead of high temperature heating led to a reduction of 24% in the heat distribution losses.

Regarding the economical KPI's, the simulations demonstrate that the average cost of energy decreases by 9% compared to the base case, so the owner saves 552 Euro on the electricity cost per year.

The environmental KPI's revealed an increase of GHG emissions for the demo case compared to the reference case. This is mainly due to the high amount of unused heat from the ORC process.

The GHG emissions of the demo case can be reduced compared to a reference case with a natural gas boiler, if the demo case uses more than 20% (1.4 GWh/a) of the currently unused heat (e.g. by extra (district) heat customers).

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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.

Moreover, given that the current installation is oversized for the wood joinery, the company Beneens can consider the possibility of connecting the installation to a network providing heat to nearby companies to improve the business case.

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10 Acronyms and terms

BC	Base case
BESS	Battery energy system storage
BTES	High-temperature borehole field
CHP	Combined heat and power
CS	Case study
DER	Distributed energy resources
DSO	Distribution system operator
ESS	Energy storage systems
EV	Electric vehicles
GECC	Grid energy consumption change
GHG	Greenhouse gas
HV	High voltage
KPI	Key performance indicator
LCA	Life cycle assessment
LT	Low temperature circuit
MILP	Mixed integer linear programming
MCU	Main controller unit
MPC	Model predictive control
MT	Medium temperature circuit
MV	Medium voltage
NZEB	Nearly Zero Energy Building
ORC	Organic Rankine cycle
PTADR	Peak to average demand ratio
PPC	Peak power change
PV	Photovoltaic
PVT	Solar hybrid panel
RP	Report
RTU	Remote terminal units
SCADA	system control and data cquisition
SF	Heat demand scale factor
SOC	State of charge
SCL	Self-consumption level
SSL	Self-sufficiency level
THD	Total harmonic distortion
VC	Vacuum collectors

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