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STORY

added value of STORage in distribution sYstems

Deliverable 5.1
Case study report: chapter on building integrated storage

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Authors:
Leen Peeters .... THNK
Andreas Tuerk ..... JR
Jan Diriken........... VITO
Arnout Aertgeerts. ACT

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Project STORY - H2020-LCE-2014-3

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1 Introduction

Each of the STORY demonstrations will be described as a chapter in a booklet. The monitoring and evaluation data will similarly be presented as one booklet.
The target audience for the booklet on the demonstrations, WP5, is a general public with no specific background in energy or technology. This audience might or might not be aware of the way European Innovation Actions are organized, i.e. in work packages with tasks and subtasks.
The chapters could be rewritten when all information on all demonstrations is available. A common lay out and writing style will then be guaranteed by the partners identified as the final editors.
In order to facilitate the review of this document as an integrated part in the demonstration, a cover sheet is added to each chapter indicating the objectives of that specific demonstration and the input from other work packages.

The aim of Demonstration 5.2 is to demonstrate the added value of thermal storage (short term small scale; shallow geothermal; inter-seasonal medium scale), electrical storage (Li-Ion, Lead Acid and Flow batteries), DMS in buildings with heat pumps, PV and fuel cells.
Schort and long term thermal storage is added to the Living Lab, as well as two types of batteries (NiFe and Lead-acid), a heat pup and hybrid PV. 2 electrical cars are added to complete the set-up. Of the 4 other houses, 1 is equipped with a fuel cell, 3 are provided smart remotely operable control for their heat pump and one additionaly received a small scale thermal storage while 2 have batteries (1 lead acid and 1 Li Ion).

The Living Lab is presented as a separate chapter, because of the different approaches and the complexity. In this chapter the different technologies are presented and a first insight in the complexity with regards to interoperability is given. The second chapter provides insight in the demonstrations in the other buidlings: standard buildings with conventional devices for which teh flexibility is exploited.

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2 Demonstration 5.2 – Part A

2.1 Publishable executive summary

The living lab brings together different technologies as depicted in the below scheme (Figure 1).

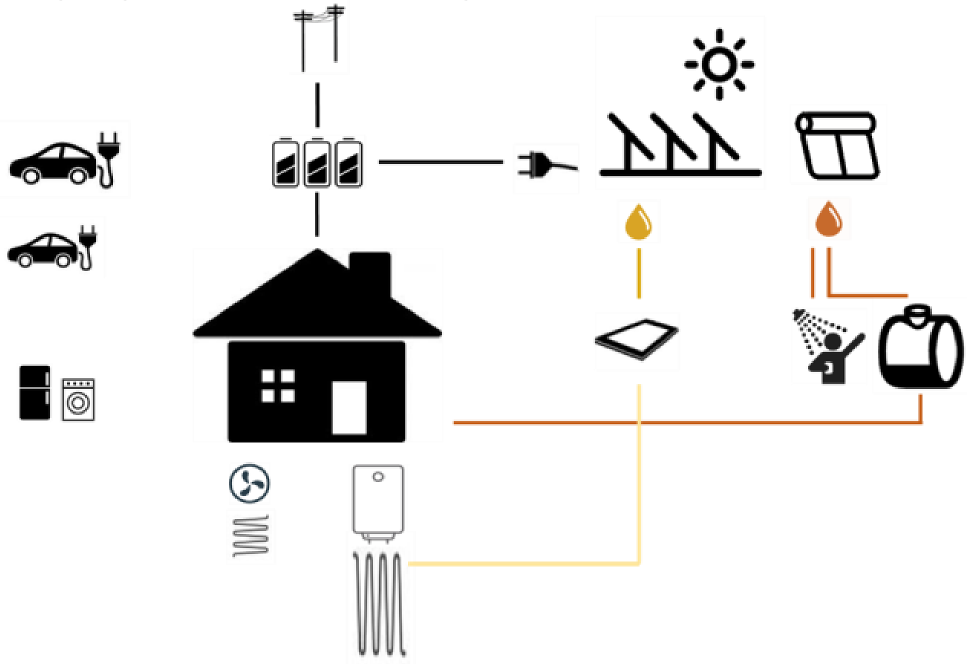

Figure 1: Schematic overview of Living Lab

In this demonstration, they will all cooperate to show the added value of storage in minimizing the impact on the grid and exchange with the grid. Included storage technologies are 2 types of batteries, underground seasonal storage tanks, short term thermal storage and a shallow geothermal system. The building itself meets standards beyond those of passive houses. The 350m^2 is heated using a 1 kW electrical heat pump, shower heat exchangers are added to reduce the demand for sanitary hot water, a mechanical ventilation system with possibility to operate in zones ensures good air quality in all 14 zones, smart home appliances with best available energy performance were added, all lights are LED, 33 PV panels were rebuilt as hybrid PV panels (PVT) and finally 2 electrical vehicles complete the set-up.

The storage technologies are added to further ensure an optimal day-night and seasonal flexibility. The underground storage needs to shift heat from summer to winter to reduce the use of the heat pump. The PVT circuit will, after cooling down in the open reservoirs, regenerate the geothermal system to maximize the performance of the heat pump as the seasonal storage will not be sufficient. Cooling down the PVT panels increases their electrical efficiency. The produced electricity is either directly used or stored in the batteries or cars. The batteries are large enough to cover several cloudy days.

A major outcome has been the effective off-grid operation for 35 successive days.

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2.2 Living Lab

2.2.1 Introduction

The Living Lab is presented as a separate chapter, because of the different approaches and the complexity. In this chapter the different technologies are presented and a first insight in the complexity with regards to interoperability is given.

2.2.2 Objectives

The objective of the Living Lab is to show the potential of different energy storage technologies and how they interlink. Furthermore, the Living Lab will contribute to demonstrating interoperability challenges.

The demonstration further shows the cooperation between different devices, each with its own communication protocol and signal frequency. All of them interlink through a self-developed SCADA system.

Th!nk E has designed and developed the Living Lab on its own. And, although the demonstration has delivered the objectives, it will be further developed to show the impact of advanced model Predictive Controls as designed and developed by VTT. The Living Lab will play an important role in the microgrid, part of demonstration 5.3.

The demonstration set-up was fully operational spring 2017. Soon after that, the Living Lab went completely off-grid for 35 successive days. During these days, the full building including thermal and electrical demands as well as the two electrical vehicles where supplied by thermal and electrical energy which was generated and stored on-site. Additionally, the period resulted in a storage of over 450 kWh of heat for use in winter.

2.2.3 Interlinkages

The hardware and software design are allocated to tasks on hardware and software integration (WP4). Th!nk E was responsible for these tasks with regards to this building. Measurement and communication hardware has been installed by Th!nk E. University College Leuven Limburg (UCL) assisted in some of the monitoring device selection.

2.2.4 Partners engaged

Th!nk E delivered the Living Lab with the current control. Vlaams Instituut voor Technologisch Onderzoek (VITO) has installed its State Of Charge (SOC) measurements in the seasonal storage tanks as well as a 400 litre sanitary hot water tank. Enersys delivered lead acid batteries. BaseN stores the data and calculates the Key Performance Indicators (KPIs) (as part of WP6). UCL assisted in some of the monitoring device selections.

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2.3 Booklet chapter

The chapter is added as annex 1.

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3 Demonstration 5.2 – Part B

3.1 Publishable executive summary

The exploitation of flexibility in conventional houses is challenging. In this demonstration, 4 conventional buildings were the starting point and add smartness and flexibility to them in order to show the added value this can bring to the building. In a further step, these buildings will be used as part of a microgrid where cooperation between them is key.

The 4 houses are all different:

- 1 house has 2 heat pumps and a heat pump boiler
- 1 house has a heat pump, an electrical car and PV
- 1 house has a gas boiler and a hybrid car
- 1 has 2 heat pumps and direct electrical heating

Each of them is transformed in a more future oriented version. The heat pumps and heat pump boiler are remotely controlled to exploit the flexibility of the device and the building. The gas boiler is replaced by a fuel cell.

The interoperability challenges were mostly overcome as part of the preparatory work on ICT as supporting service (WP4).

Flexibility is one of the key aspects to enable end-consumers to take up a more active role in the energy system. In this demonstration, different business models are tested to understand and demonstrated the flexibility that can be achieved and hence relate to part of the role the end-consumer could play.

The demonstration has shown the potential of the fuel cell as local generator, but less as a flexible device due to the complexity of the chemical cycle. The new version of the device will already provide more shifting potential.

The demonstrated operation of the smartened boiler with advanced SOC control has shown a good performance. It has been triggered based on wholesale energy market prices and delivered the expected performance. The operation of the smartened heat pumps has been demonstrated in the same building. It has confirmed that the developed control works well and has shown the potential of shifting the load based on wholesale energy market prices.

3.2 Flexibility at building level

3.2.1 Introduction

Compared to the Living Lab, the neighbouring buildings are more conventional buildings. It is important to understand how existing buildings can be integrated in a smart energy infrastructure and what they can provide with regards to flexibility.

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The communication technologies are different compared to the Living Lab, with resulting deviating challenges on interoperability. Furthermore, the interlinkages with other Work Packages is more intense.

Four buildings are considered for this part of the demonstration. One has a fuel cell; all others have heat pumps.

3.2.2 Objectives

This demonstrations site's aim is twofold: first what interoperability challenges are typically encountered onsite and second the demonstration of the different technologies (storage, ICT, DSM, …) and what they could bring on building level.

The impact of adding storage building per building and not controlling the use of it is demonstrated.

The fuel cell has performed well, with over 4500 kWh of electricity produced so far. It turned out to be a much less flexible device due to its complexity. The current version, B, allows one Proton Membrane Exchange Fuel Cell (PEMFC) cycle per day. The maximum cycle duration is 21.5 hours as a starting cycle of 1 hour and a cooling down of 1.5 hours are needed connected to each cycle. Further versions, as the upcoming version C, will allow for more cycles. In combination with the recently added electrical car, the self-provided electricity covers the demand of the building, but using the grid as a battery. This will be solved by installing a power quality improving battery set-up, as the low power quality in the neighbourhood already caused two outages of the fuel cell (due to over-voltages of above 264 Volts causing minor damage).

The implementation of the metering and communication devices that Actility needs for its tasks, has faced several delays. The LoRa signal needed local additional gateways, the electricity meters posed some challenges with regards to reliability and availability of data. A first selection of a remotely controllable thermostat showed a major problem with regards to the quality and stability of the indoor temperature measurement. A second and more common remotely operable thermostat was installed August/September 2017 and data are hence only available for a short period for one building.

The SOC control works well. Communication has had minor issues only.

3.2.3 Interlinkages

The installation of temperature sensors (WP3) and the development of the controls (WP3) deliver parts of direct relevance to the demonstration. Actility is in charge of the temperature sensors in the houses and the development of the building control. VITO is in charge of the State of Charge (SOC) methodology that will be used to control the heat pump boiler in one of the buildings.

The part of ICT as supporting services, work done as preparation of the demonstrations (WP4), supports the demonstration even more clearly. The first important input is delivered by setting up the ICT architecture (Figure 2).

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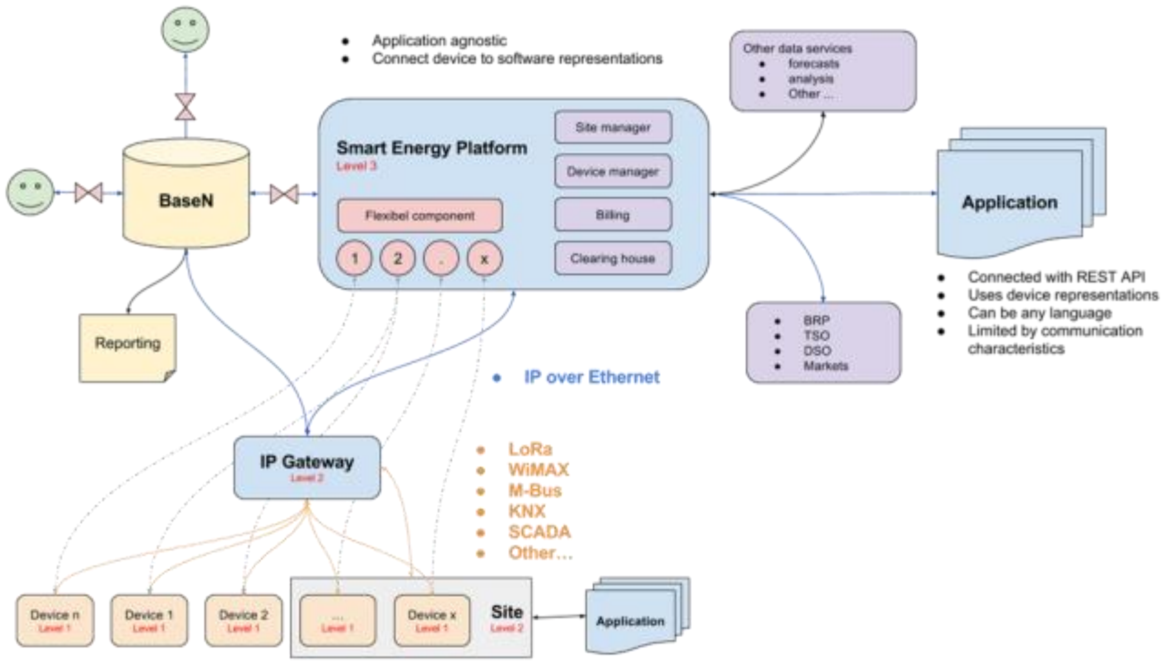

Figure 2: Data communication and exchange scheme for the 4 buildings

Second, the integration of the control algorithms in prepared, which includes hardware selection and software integration. Tasks that result in the effective implemented hardware in the demonstration.

Finally, the smartification of 3 flexible devices is prepared (WP4) for demonstration in one of the 4 buildings. Actility has prepared the heat pump boiler, with VITO's SOC methodology. The schematic for that is given below (Figure 3).

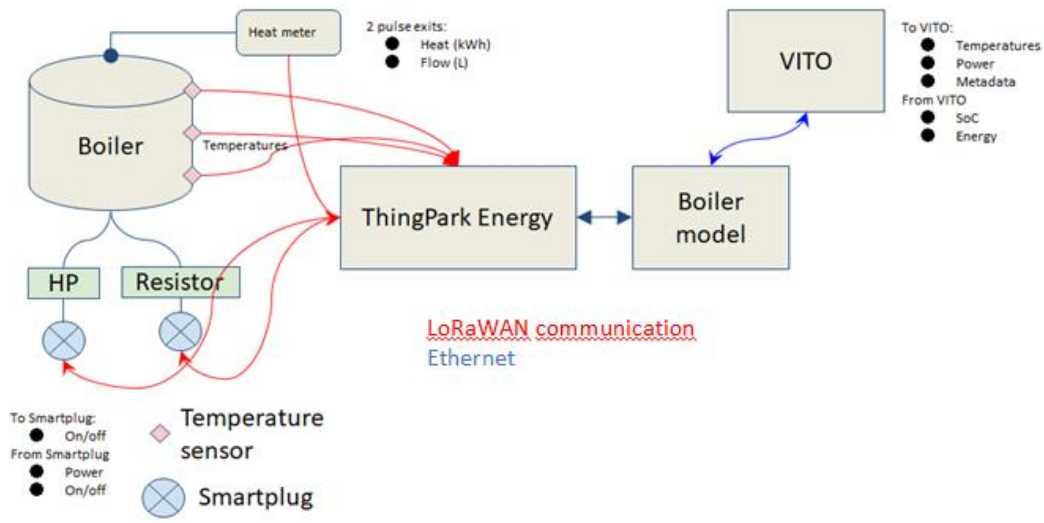

Figure 3: Boiler control schematic for the heat pump boiler in one of the houses.

Actility also prepared the communication and smartification of the Danfoss heat pump, installed in one of the demonstration buildings.

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Th!nk E prepared the communication (request for charging and discharging on 3rd party demand) for the batteries. It has been demonstrated in the Living Lab.

3.2.4 Partners engaged

Viessmann installed and monitors the fuel cell. VITO, as part of WP3, assisted in the design of the SOC metering and developed the SOC methodology in WP3 that is now used in the demonstration in one of the houses.

Actility is in charge of installing its metering solution (electricity meters as part of WP5, temperature sensors as part of WP3), and control the flexible devices that were prepared for smart remote control in WP4. Actility is further in charge of demonstrating demand side management and ICT.

3.3 Booklet chapter

The chapter is added as annex 2.

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4 Acronyms and terms

DSM	Demand Side Management
ICT	Information Communications Technology
KPI	Key Performance Indicator
SCADA	Supervisory Control and Data Acquisition
SOC	State Of Charge
WP	Work Package

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5 Appendices

- Annex 1: The added value of storage for residential buildings – Part A: Consumers, Prosumers and Prostormers
- Annex 2: The added value of storage for residential buildings – Part B: Flexibility exploitation of conventional buildings

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The added value of storage for residential buildings

Part A: Consumers, Prosumers and Prostormers

Author: Leen Peeters (Th!nk E)
Edited by Andreas Tuerk (Joanneum Reserach)

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1 Introduction

The role of residential energy consumers has changed in the last decade. Nearly 20% of Europe's photovoltaic (PV) power has been installed on residential roofs end of 2016, i.e. 19 GWp. This distributed generation of energy brings both challenges and opportunities. Many of the challenges relate to using our energy infrastructure for something it was not designed for: bi-directional flows, i.e. both from and to prosumers. Distributed generation also opens opportunities to give the end-consumer a more active and more central role in the energy system by enabling new cooperation models, developing new products and introducing new business models.

The Living Lab is designed to demonstrate the potential and the impact a residential building can have in 2030 and beyond.

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.

The building has been subject to deep retrofitting before the project started, delivering building performances beyond passive house standards. The normal electrical consumption is minimized by selecting the most efficient appliances and LED lighting throughout the building. Two shower heat exchangers are added in series to minimize the demand for sanitary hot water. A mechanical ventilation with brine heat exchanger and heat recuperation from the exhaust provides continuous preconditioned fresh air. The remaining heat demand for house heating is delivered using a heat pump connected to a shallow geothermal system. Two electrical vehicles ensure that not only the full energy consumption of the building, but also the majority of the energy consumption for mobility are taken into account. A set of hybrid PV panels provides both electrical and thermal energy.

Within STORY, the system is further leveraged to provide more self-consumption and more flexibility. An over-sized solar collector feeds two underground thermal storage tanks for use in winter. A short term storage tank for sanitary hot water and one for house heating are added to optimise the use of solar thermal energy. A battery set-up is added to store a maximum of on-site produced electricity and reduce the energy exchange with the public grid, i.e. reduce both consumption and injection. A smart model predictive control (MPC), i.e. a specifically designed control program, automatically manages the operation of valves and pumps and the charging of the cars and the static battery.

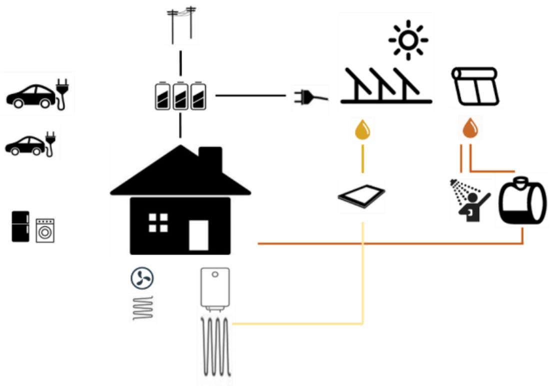

Figure 1: Schematic of the Living Lab energy concept. Local production is provided by solar thermal and hybrid PV. Storage is realized in hot water tanks and in electrical batteries, and by regenerating the geothermal system that feeds the heat pump. Electrical vehicles and all normal household electricity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

In a later stage and when regulation would allow, a building like this could provide a range of services to balance the local grid or be part of an overall aggregated load or production that delivers flexibility at the transmission level. Within STORY, the goal is to build, test, optimise and evaluate the concept.

3 The making off

The storage concepts that were selected for the Living Lab are not commercially available as an integrated package or set-up. The engineering work, the search for all relevant components on the market and the installation and integration are as interesting and eye-opening as the actual demonstration part. Without going through all aspects, the below provides a glimpse of the adventure.

3.1 The seasonal underground thermal storage

The seasonal storage stores thermal energy in water over a longer period, i.e. typically from summer to winter. It would be charged and discharged gradually and therefore working with stratification, i.e. with consecutive layers of a nearly constant temperature, is key to ensure a maximum use of the quality of the stored thermal energy. The concept of quality of thermal energy is linked to the temperature: the higher the temperature, the more use can be made of the same amount of energy. Important to consider is that for stratification to work optimally, the width and height of the storage should be similar. There is no such thing on the market as a ready made highly insulated thermal storage tank of 24 000 liter that is manageable to install and matches the criterium of height equalling width. The closest to this ideal, and providing additional testing opportunities, is two identical tanks of 12 000 liter meant for storing oil for house heating. These tanks are placed in a large bag made of water impermeable rubber and surrounded by a large amount of high temperature resistant insulation (Figure 2).

Figure 2: Putting the seasonal underground storage tanks in place. The tanks are installed in a large rubber bag filled with insulation. On the picture, the first tank is put in position.

On top of the tanks, an access is created that allows maintenance on the installed temperature sensors and the water inlet and outlet. It is a small zone that is filled with removable blocks of insulation. In each of the tanks, VITO installed 10 thermal sensors reaching different depths, spanning the entire height of the tank (Figure 3) . They provide information on the energy content in the tank at any moment, expressed as State Of Charge (SOC).

Figure 3: The picture shows the top of the tank, inside the small chamber before insulation is added. The stainless-steel heads with green wires connect the thermal sensors in the tank to a central management system. The tank is 2.5 m deep which equals the length at the top.

3.1.1 Hybrid PV to connect electrical and thermal energy production

The photovoltaic thermal (PVT) panels connect the thermal and electrical parts. The hybrid PV panels are made of standard PV panels to which a cooling panel is attached (Figure 4). Hence, they produce both electricity and thermal energy.

Figure 4: Pile of PVT panels ready for installation. An aluminium radiator of the type of the back of a fridge is glued to the back of a standard PV panel. Consequently, an insulation panel that can resist high temperatures is put on top of it and a closing aluminium shield is attached to finish. The part around the junction box is left open, to allow maintenance and free cooling.

33 of these panels are installed (Figure 5), providing 11.05 kWp of solar electrical power. The cooling of a PV panel leads to increased electrical yield, but there are no field data on the effective impact. The thermal outcome is much more dependent on outside weather conditions compared to a standard solar thermal collector, but still perfectly suited to provide low temperature heat to inject heat into the shallow geothermal system to restore its annual heat balance.

Figure 5: View on roof with vacuum solar thermal (upper roof) and PVT (lower roof) panels.

As the injection has to be done at a maximum of 25 ˚C in order to ensure a long lifetime of the geothermal system, the heat extracted from the PVT circuit is cooled down in two open reservoirs. The first one is made of full epoxy vinyl ester resin with an armoured core of high performance fibres and can resist temperatures over 40 ˚C. It is insulated to the ground to limit the impact on the surrounding soil (Figure 6). The second is more integrated in the natural environment: the idea is to use plants to improve the water quality. It’s temperature should therefore remain below 35 ˚C.

Figure 6: First cooling reservoir made of full epoxy vinyl ester resin with an armoured core of high performance fibres equipped with sensors before it is installed in the ground.

3.1.2 The thermal connections

All different parts, PVT panels, vacuum solar thermal set-up, cooling reservoirs, different thermal storage tanks, heat pump in the main building, ..., need to cooperate in an orchestered manner. The thermal connections and heat exchanges need to facilitate this. Developing a research set-up requires thinking about all potential future scenarios and the collection of as much data as possible. Hence, the thermal connections are set up as a lab: all potentially interesting operating modes are considered. The below schematic (Figure 7) provides an overview.

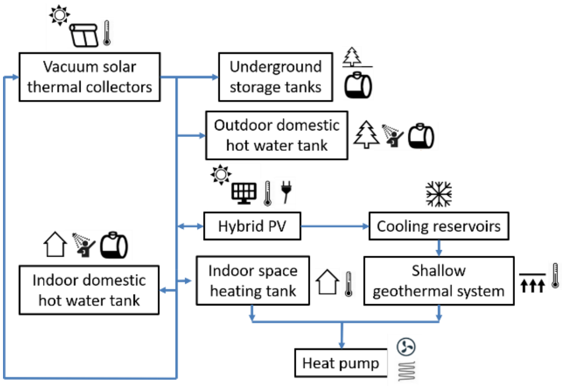

Figure 7: Schematic overview of the circuits and exchanges that can be delivered with the thermal lab set up.

The integration of that scheme into a real-life set-up in an existing building is challenging. Several connections to the outdoor are integrated, such as the underground tanks, the cooling reservoirs, the thermal part of the PVT, the vacuum solar collectors as well as the underground connection to the main building. 10 different pumps, 62 temperature sensors, 7 flow meters and 24 different automated valves are connected to the control system (Figure 8). These are all controlled and monitored via a local SCADA installation.

Figure 8: View on the 2 identical circuits connecting the heat exchangers with the vacuum boiler circuit with the two underground storage tanks. On the right is the exit to the underground tanks, on the left is the connection to the vacuum solar collector circuit.

The energy consumption of all pumps operating leads to an additional power consumption in excess of 1500 Watts. But operating all of them together never happens. The most energy consuming pumps only operate when there is an intense solar radiation. In winter, on cold and cloudy days, energy consumption drops below 100 Watts and is mainly due to transporting the hot water from the underground tanks to the main building.

3.1.3 The battery set-up

The lead-acid battery (Figure 9) is a key element to enhance self-consumption and thus reduce the exchange with the grid: it stores the electricity produced during the day to be used in the evening and at night. In this set-up, the battery is the heart of the electrical set-up. 48 batteries with a total capacity of 46.3 kWh. The available capacity, the SOC, is more difficult to estimate as previous cycles, external conditions and the power to discharge all have an influence. In general, about 28 kWh, or around 60% of the total capacity is available for energy exchange. Because the SOC is not a very accurate indicator, the batteries are therefore managed using their voltage as main indicator, with values varying between 45 Volt and 54 Volt. In case of dark and cold weather, this is sufficient to provide energy for just over 2 days. Lead-acid is used in this set-up because it provides a cost-effective and reliable energy storage solution.

Figure 9: Lead-Acid batteries, 28 in total, providing 46.3 kWh full capacity, around 28 kWh of useful capacity. A large switchboard manages the smooth transition between off-grid and on-grid mode.

The battery is integrated in order to allow for off-grid operation (Figure 10). A dwelling is obliged to be connected to the DSO network, but the connection does not come with a consumption obligation. One is thus allowed to turn off the connection for a couple of days, a longer period or even permanently. As shown in the schematic below, it is situated in between between the grid and the building itself. The PVT panels inject directly into the batteries. In fact, this set-up is very similar to a standard UPS, an Uninterrupted Power Supply.

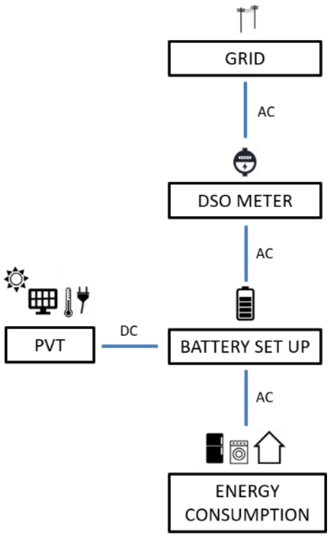

Figure 10: Schematic of battery set-up and the connection between the building and the main grid.

On-grid operation is possible in cases when the batteries are empty, the power demand is too high, the grid would demand for higher consumption, or in case of maintenance on the battery storage set-up. Injection in the grid is possible on demand, where both the amount and the time can be programmed. With on-demand injection and consumption, the battery system can thus deliver different services to an aggregator or grid operator.

On sunny days, the 10 kWp electrical power of the PVT provides more energy than needed for the electricity demand of the building including the pumps and valves in the thermal lab, the charging of the two electrical vehicles and the charging of the battery. Instead of overloading the grid, when all other PV set-ups are producing energy too, the production of electricity in the Living Lab can be stopped.

3.1.4 The UPS battery set-up after the UPS

A second battery set-up (Figure 11) safeguards the operation of the thermal lab in case of a black-out in the main grid, followed by an empty lead-acid battery. This set-up is smaller and uses Nickel-Iron (Ni-Fe) batteries. Roughly 3.5 kW and 2.5 kWh can be delivered.

Figure 11: NiFe UPS system providing additional safety in case of a black out. Mainly relevant for preventing damage in very cold or relatively warm and/or sunny days. This battery system provides back-up power for pumps, valves and control in case the grid and the main battery system fail.

On warm and/or sunny days as well as on very cold days, the operation of several of the pumps should not be interrupted to prevent damage. The idea for the Living Lab in STORY is to use different kinds of batteries in a single set-up. Mixing batteries this way in one energy storage unit would merit extensive research by itself. Combining two different types in a larger system however, provides the safety needed here.

Why NiFe? Because it is a very robust battery which is tolerant of abuse, (overcharge, overdischarge, and short-circuiting) and can have a very long life even if treated suboptimally. It is often used in backup situations for example in the telecommunications sector, where it can be continuously charged and can last for more than two decades. The batteries have a low specific energy, i.e. they have a small amount of energy storage capacity for the volume they take, and high cost of manufacture. NiFe batteries require regular follow-up, i.e. they are rather maintenance intensive if seldom used. Therefore, besides for UPS operation, they will be subject to regular cycles of non-critical loads.

4 Interoperability challenges

Setting up a project with parts either designed and developed from scratch or provided by different manufacturers, brings interoperability challenges . Interoperability is the ability of different systems (hardware and software) to operate in conjunction with each other. Hardware-wise this is often less complicated because connectors are widely available: interconnection pieces for different pipe diameters, converters for AC/DC, ... Software-wise this is more complex given the wide range of communication protocols (like Modbus, KNX, bacnet and many more) but also the different measurement frequency and how to deal with this in a control system. To get to the point of all devices communicating and cooperating in a harmonized way is no easy task.

In this demonstration, the original renovated building used KNX mainly. Monitoring devices and actuators for the thermal lab are mainly on modbus, the electrical lab uses the proprietary Studer SCOM protocol. The measurement frequency of monitoring devices differs per brand and type. Within protocols, a kind of slang may exist, therefore e.g. one KNX device does not automatically communicate well with another KNX device. Next, all this information needs to be integrated in a database and be read in by a program that can consequently evaluate, calculate and take decisions on the charging or discharging of batteries, activation of valves, pumps, ...

As such, that leveraging of a database to provide input for a program to perform calculations, seems reasonable. Now, the programs are not all running in the same place. Hence withing the code layer, application program interfaces (API's) are needed. That implies that, as was previewed at the start of the project, besides hardware implementation, a large amount of resources is further needed for overcoming interoperability challenges to deliver a smooth and coordinated operation of all devices (Figure 12).

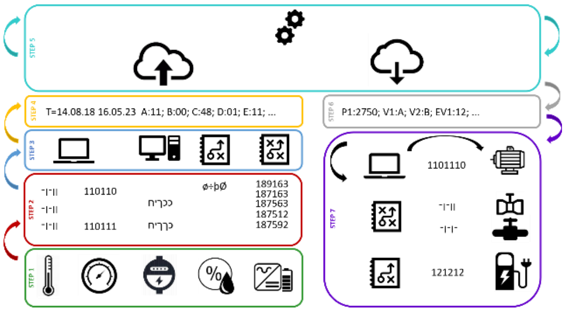

Figure 12: Interoperability from device sensors (left green box) with variation in language and frequency (red) over different methods of reading and conversion (blue) to a single line readable by one code (yellow). Uploaded to perform calculations in the control layer (turquoise) and send it back as one line (grey box) to be redistributed and sent in each own language to pumps, valves, ... (purple box).

5 Conclusions and experiences

Some activities had been done prior to the acceptance of STORY, e.g. the building's energy efficiency envelope, installation of technologies such as shower heat exchangers, mechanical ventilation with heat recovery and ground loop and smart home appliances. Further leveraging all of these however as part of an innovation action was a learning experience.

A Living Lab is a concept in which by definition the inhabitants are part of the lab-aspect. That means, there are weeks when they have to show a certain behaviour and every step is even more closely monitored. First of all, knowing that in advance, the monitoring aspect is not experienced as intervening with the privacy. All the data are more of an interesting part, where the inhabitants gain understanding in every aspect related to energy supply and demand.

Janne, 14 years old: "Living in a kind of a Lab is OK. Due to the graphs, we get to know how much energy normal activities require. Trying to drive as energy efficient as possible, makes us aware of the energy demand for transport. What I like most, though, are the insane conversations that I think no other families have. When I make cookies, the question is not how unhealthy they are but how much energy is required to prepare them. Dinner options are sometimes defined by the battery content. Making fun and fighting with each other is afterwards visible in the CO_2-measurements. I think we are much more into energy and sustainability compared to most teenagers."

Being self-sufficient is easy on sunny days. The system is fully automated and the only thing to consider is to avoid charging the car at night as it would drain the batteries. But when a sequence of cold, rainy and grey days occurs, remaining off-grid is less obvious. However this challenge is something to be taken on and therefore ... the lessons learned:

- Normal household energy use is mostly non-flexible and if by design all appliances and lighting has been selected based on the lowest consumption profile on the market, there is little to gain.

- Electrical cars are the main disturbers, but the good thing is that they do not ask for a step-function, i.e. their load profile shows a smooth increase in power demand. This increase is essential for an off-grid installation to have enough time (about 5 seconds) to synchronise with the main grid and avoid a drop out of one or more phases.

- Cooking is very energy and power demanding. Although a steamer is one of the most efficient ways to prepare food, it does ask for nearly 4 kW. Going off-grid means watching both energy and power.

So far, 35 days completely off-grid were easily achieved. During these days, the underground storage tanks were further loaded leading to an average temperature increase of over 18 ˚C. The cooling of the PVT panels increased the temperature of the first cooling reservoir to 37 ˚C and the second one to above 25 ˚C.

STORY

STORY D5.1 – part B| Nov 2017

The added value of storage for residential buildings

Part B: Flexibility exploitation of conventional buildings

Authors: Arnout Aertgeerts (Actility), Jan Diriken (VITO)

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1 Introduction

This demonstrations site's aim is twofold: first what interoperability challenges are typically encountered on site and second the demonstration of the different technologies (storage, ICT, Demand Side Management (DSM), …), what they could bring on building level as well as demonstrating the potential and the impact a residential building with a high degree of self-sufficiency can have in 2030 and beyond. This includes the added value storage can bring in load shifting and peak shaving at building level. Furthermore, the impact on the grid of adding storage building per building and not coordinate the use of it, will be shown. Also the link to energy market as an additional source of revenues will be explored.

This part of the demonstration focusses on the 4 houses in the same neighbourhood as the Living lab. These 4 houses have storage possibilities which exist in most residential buildings such as thermal mass or a domestic hot water boiler. In some cases, these possibilities are extended by adding a battery. While the focus of the Living Lab in on the medium to long term, the 4 houses will show the added value of storage on a short term. Therefore, it is important to take into account the potential different buildings could offer with regards to flexibility and impact on the grid usage. All the buildings in this demo will be part of a microgrid in a subsequent demo case in which the diversity of technologies of all 5 houses will be used.

2 The reference case

In the neighbourhood which consists in total of 13 houses, 4 are chosen to be equipped with detailed measurements, control hardware and additional energy storage or production devices. The houses are rather large and well insulated compared to the Belgian standard.

The following table (Table 1) gives an overview of these four houses before the start of the project and the added controllable energy consumption or energy generation devices. This demonstration is in first instance only interested in electrical devices such as a heat pump or a fuel cell as only these devices can change the status of the electric energy flow or the electric grid (in contrast with for example a gas-fired burner). If during the demonstration **a device was added, it is shown in green**. If **a device was replaced, it is shown in orange.**

House	Space heating	Domestic hot water	Electricity Production
2	2 Heat pumps	Heat pump Heat pump	/
3	Fuel cell		
4	Heat pump		10 kWp PV
5	2 Heat pumps		/

Table 1: Overview of the technologies in this demonstration.

House 2 is a large recent building (<5 years) and reasonably well insulated. It is occupied by a couple with 2 teenagers. It is a massive wooden construction with concrete flooring. It is equipped with 4 heat pumps with a clear function for each heat pump. The two heavier, water-water HPs are used for space heating while the two air-to-water HPs are used to heat the internal separate boiler tank. House 3 is a recent building (11 years) and reasonably well insulated. It is a massive wooden construction with concrete flooring and was initially heated by a gas boiler which was replaced by a fuel cell in the frame of this project. House 4 is a recent building with a flat roof and almost no windows on three of its facades while the back façade is a huge window. It shows an interesting combination of a building heated by a heat pump while producing its own electricity with PV, creating room to optimize the consumption of the HP with respect to the energy produced by the PV. Finally, house 5 is heated by two heat pumps.

Measurements have been collected on the energy consumption of these houses without any changes made. These measurements give a reference case to compare the STORY project developed algorithms with.

3 Overview of the deployed technologies

3.1 Storage technologies

To optimize an electricity consumption of a house based on energy prices, PV production or other objectives, the consumption or production of electricity must be able to be shifted in time. The figure below (Figure 1) shows this principle in a simplified way:

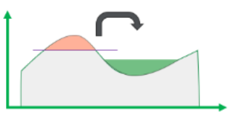

Figure 1: Demand side management principle.

For Actility, any system that can do this is a possibility to optimize the electricity consumption. Therefore, we define a storage technology as a system which can shift its energy consumption or production in time, extending the possibilities in the demonstration beyond batteries. The following paragraphs explain several systems and how they are used to change the energy consumption of the house.

3.2 Thermal mass with heat pumps

When a house is heated, the heat is stored inside the building structure such as the walls and floors. This effect is called the *thermal inertia* and is especially pronounced for buildings heated by floor heating which is the case for the houses studied here. Due to the thermal inertia, a house can be preheated to ensure the thermal comfort of a resident at a later period, thus shifting the electricity consumption. Furthermore, when the heating of a building is stopped, the inside temperature in the house does not drop immediately but takes time. This effect is shown for House 3 in Figure 2.

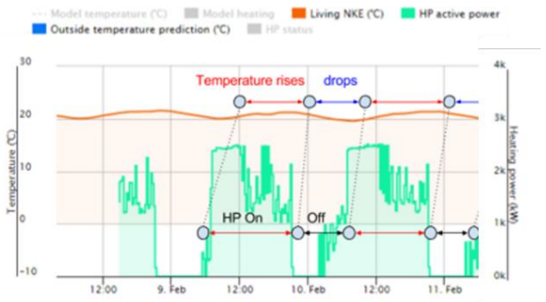

Figure 2: Thermal inertia of the building.

It takes time to see the temperature rise in the building after the HP is started and the heat can be stored in the building for several hours. The conventional control ensures the comfort of the resident is never violated by employing a simple temperature boundary (hysteresis) control. Actility overwrites this control to consider the electricity system and optimizes the heating periods and thus the HP consumption.

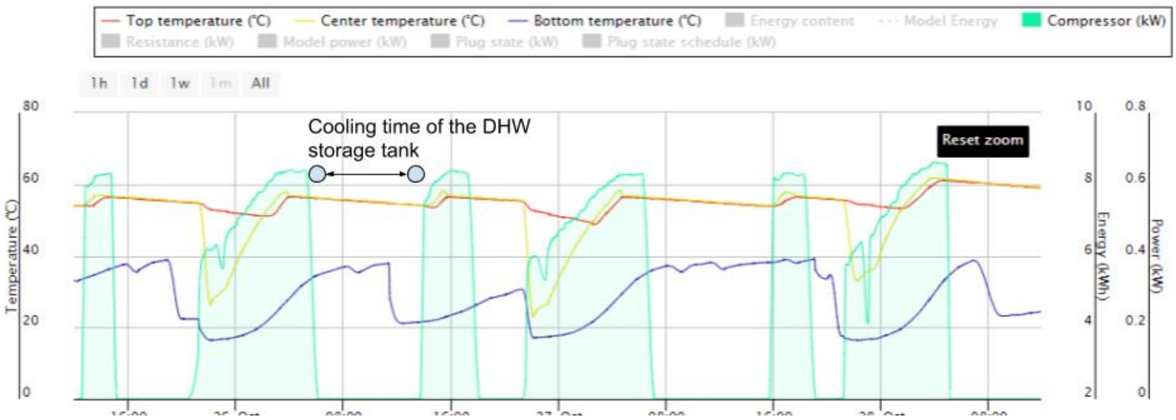

Figure 3: Thermal inertia and cooling constant of hot water tanks

Houses 2, 4 and 5 are heated by heat pumps and are able to shift their electricity consumption in time by using the thermal inertia of the building structure. Heat pumps are believed to play a very important role in the future energy system by adapting their energy consumption to the system needs without compromising the user's comfort.

3.2.1 Heat pump boiler

The same principle as for the building structure holds for domestic hot water storage tanks. When domestic hot water is stored in a tank, the ideal moments to heat the water can be found by using advanced control algorithms.

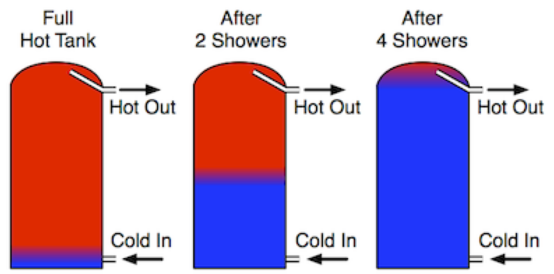

Figure 4: Stratified storage tank and top temperature dependence of the energy content[1]

The above figure (Figure 4) clearly shows the **top temperature is not a good indicator of the amount of heat stored in the tank** as this temperature will continue to be high just until the tank is out of hot water. Actility equipped one of the two boilers in house 2 with 3 temperature sensors as part of the preparatory work in STORY (WP4). This way, VITO could use its advanced State of Charge algorithm they developed as part of STORY (WP3) to calculate the energy content in the tank.

With the increased complexity of energy systems, it is becoming vital to monitor the State of Charge (SOC) of thermal storage systems in order to optimally operate them and integrate them into the energy management systems while generating flexibility options. VITO has developed methods to determine the state of charge of different thermal energy storage techniques. Those techniques include small water storage tanks, large thermal storage tanks, thermal storage in Phase Change Materials (PCM) and thermal storage in concrete for Concrete Core Activation (CCA) in buildings. In this case, VITO concentrated on a further improvement of its SOC for small water boilers.

The methods are able to determine the SOC with the lowest number of sensors.

1 http://www.apricus.com/html/solar_hot_water_basics.htm#.WfdY2mjWyUk

This reduces investment costs in monitoring equipment while keeping the accuracy high. In order to do that, we first develop a model of the system then monitor it by placing sensors in different locations within this system and perform a series of tests to characterize the storage type. The outcome is an algorithm that is able to predict the state of charge of the system with the lowest number of sensors.

In the case of SOC determination of domestic hot water cylinders, the method is a combination of a model and estimation algorithm that can automatically characterize a broad range of domestic hot water cylinders and hot water storage buffers. A model takes into account the heat losses, internal heat exchange, convection and mixing dynamics associated with water storage systems. The algorithm is able to adequately reconstruct the temperature variations inside the storage vessels (errors are smaller than about 10 %). This algorithm is suited for predicting the state-of-charge of thermal energy storage vessels in model based control applications and this is how it is used here: as input to the control of Actility.

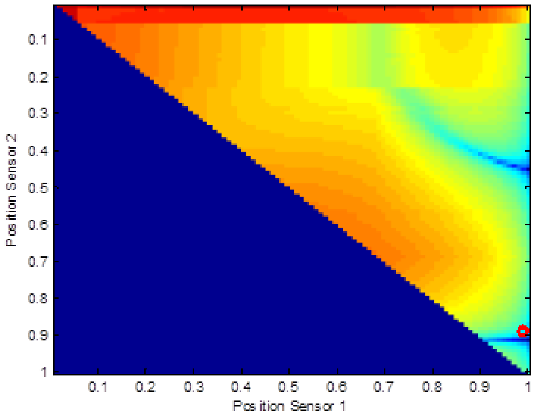

Figure 5: Sensor position optimisation.

One application is to find the position of sensors inside such a buffer system. Figure 5 shows the information content as a function of the position of sensors inside a buffer. This enables us to gain the maximum amount of information from a system with the minimum amount of sensors. Figure 6 illustrates on the upper part the measured temperatures inside the buffer. One needs 10 sensors to measure the temperature evolution with such a precision. On the bottom of the figure, a reconstruction of these temperature profiles is shown, where the reconstruction in based on only two sensors. The model has been used to identify the best position for both sensors and is used to interpolate the temperature profile, where sensors have been removed.

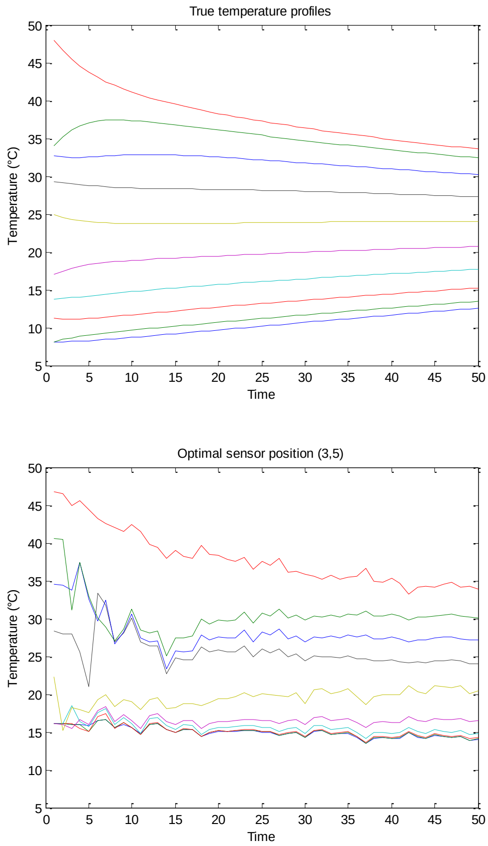

Figure 6: Measured and modelled temperature profiles.

The advantage of hot water boilers is the limited number of disturbances that can impact the energy storage, making it easier to predict for control algorithms. The only disturbance that really matters is the hot water offtake compared to multiple important disturbances for space heating such as occupancy, outside temperature, solar radiation, opening windows, ...

3.2.2 Fuel cell

The fuel cell (Figure 7) installed produces heat and electricity using natural gas as energy source. The Viessmann Vitovalor produces 750 Watt electrical power and 1 kW thermal power and combines the fuel cell part with a conventional gas condensing boiler of 19 kW. Priority is always given to the fuel cell part, ensuring a maximum of on-site produced electricity. In summer, the average production of 10 kWh sanitary hot water can therefore typically provide 7.5 kWh electrical production. The high demand for heat in winter, leverages the daily electrical production to 16 kWh.

Figure 7: Inside of the device: left part is the fuel cell itself, right hand is the gas condensing boiler on the top and a thermal storage on the bottom.

The device is mainly a local energy producer rather than a flexible device. The Proton Exchange Membrane fuel cell runs a chemical cycle that is to be managed carefully. The start-up of the device takes about 1 hour, cooling down and including the automated cleaning of the device take another 90 minutes. 1 cycle a day is allowed, i.e. a maximum of 21.5 hours of fuel cell electricity production. 2 storage tanks are added to ensure the operation can deliver a maximum contribution to the occupants' heat demand.

The device runs stable and smoothly. The needed interventions where related to poor quality of the grid-supplied electricity: voltage swings with drops down to 188 Volt and rises to 264.5 Volt. This exceptional situation caused damage on several appliances and electronics in the dwelling including a failure in the fuel cell's current counter, that was easily replaced.

The fuel cell is a device that provides less flexibility compared to heat pumps or electrical boilers. The complexity of the cycle prevents frequent cycling. Maximizing the operating hours is the best available strategy, also when leveraging up to a microgrid scale in a further stage of the project.

3.2.3 Batteries

The batteries that were previewed where single phase set ups. Due to safety, single phase batteries should not be installed in a 3-phase building. Early 2018, the battery set-ups will be upgraded to a 3-phase set up. A similar operational set-up is described in the part of the Living Lab.

3.3 Communication technologies & interoperability

To monitor and control the installed storage technologies, a multitude of sensors and actuators had to be installed in the houses. The smart grid is a combination of the IOT and energy fields. Furthermore, several communication technologies have been used such as Wi-Fi, Ethernet, 3G and LoRa to ensure the reporting of all variables and cope with legacy or popular technology. Finally, to setup the smart energy platform for the demonstration, several integrations with 3rd parties had to be implemented. This demonstration in a residential environment clearly shows the challenge of adapting the required solution to each house as already experienced by the Linear project.

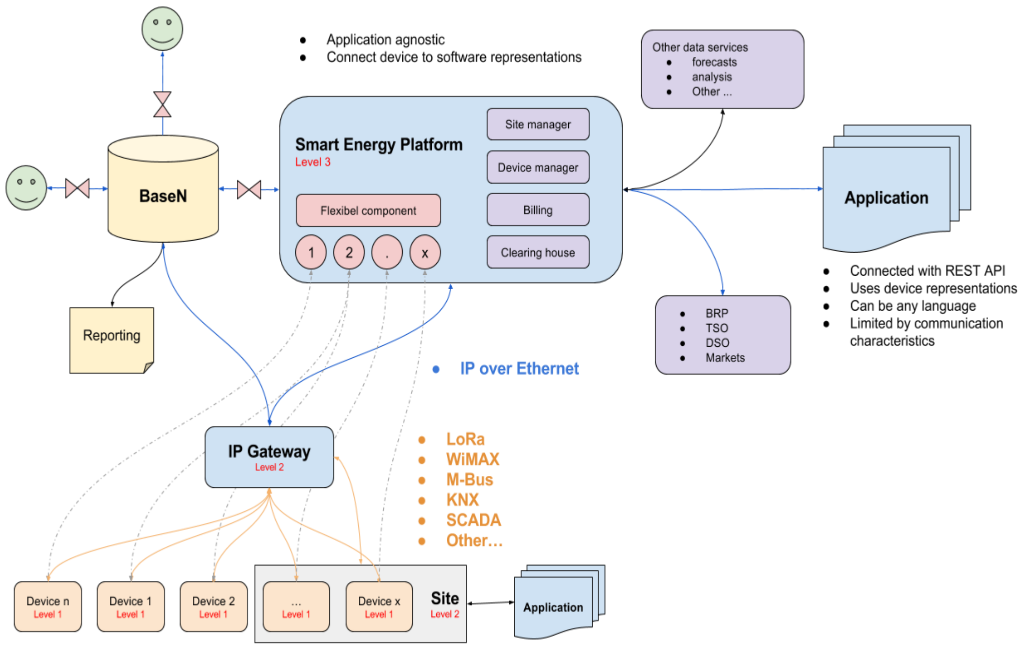

Figure 8: Smart Energy platform framework from WP4.

The Smart Energy platform presented in Figure 8 (WP4), can only do its job when it can rely on solid field data from sensors and when it can access and control actuators. Multiple data sources have been identified together with specific in-use requirements. In the residential context, requirements can be quite different and sometimes conflicting, some sensors need wireless communication and very long autonomy (battery) because of the ease of installation and because of the aesthetical impact while for other sensors the accuracy is far more important.

Examples of sensors that are used in the project are sensors for temperature & humidity (WP3), electrical power, voltage, current and heat. For Actility, the high-level structure of its smart energy platform called ThingPark is seen in Figure 9.

On top of the ThingPark Platform, Actility deploys ThingPark Energy containing the energy related applications and developments to reach the objective of the demonstration. Within STORY, the main challenge for Actility is to apply the industrial algorithms to the residential context.

ThingPark Energy not only takes input from the STORY community, but it also must deliver output under the form of process optimizations and control signals to the flexible devices. The outputs of ThingPark Energy are linked to actuators that can control elements in the houses. For example, smart plugs control the heating of domestic hot water boilers; they may interact with electrical storage cells, fuel cells, heating systems (heat pumps, …) Interacting with these elements poses the problem of interoperability (WP4). Indeed, as these elements are consumer grade commercially available products they may or may not have any option for remote control, may or may not be connected to the internet, and may or may not use proprietary communication protocols.

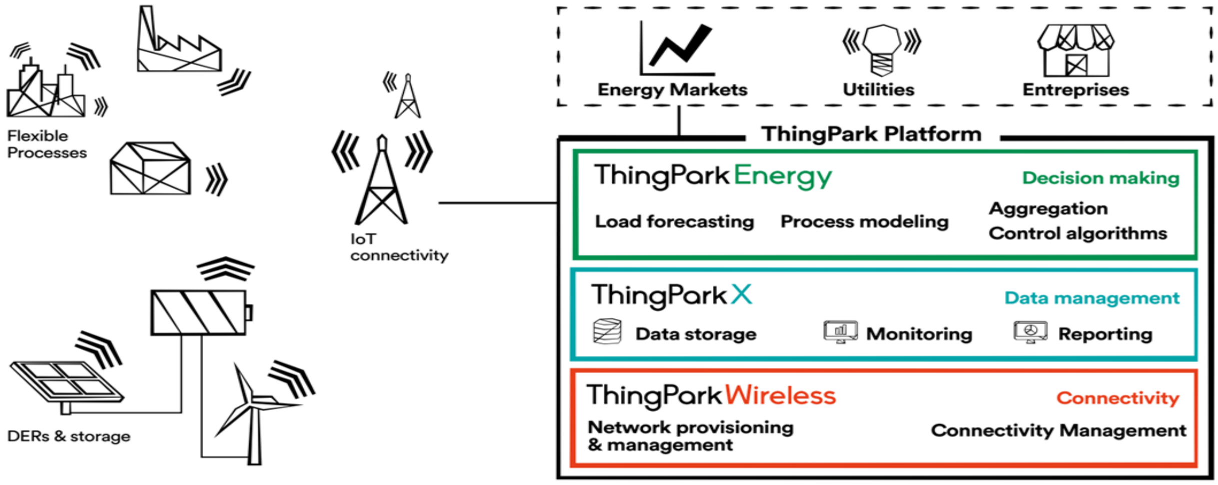

Figure 9: Actility implementation of the SEP.

On the sensors side, because of the ease of installation and very long battery power requirements we have opted in some cases for LoRaWan devices (Figure 10) that are registered on a public network. The temperatyure sensors, as part of WP3, are examples of that. For other sensors such as the electric power consumption, Actility opted for dedicated measurement devices which communicate at frequencies around 1 minute to the Actility platform.

Figure 10: Example installation of a LoRaWAN temperature sensor (WP3). The installation consisted of placing the sensor in the house away from direct sunlight. These sensors are used to identify the thermal inertia of the building

For all means of communication, the necessary care and attention needs to be applied to the protection of the data (network security).

3.3.1 LoRaWan gateway and sensors

The LoRaWan sensors are registered devices in the public network of Proximus, a Belgian telecom operator. The devices send their data via wireless communication to Gateways (antenna stations) which are typically property of a national telecom operator. The LoRaWan standard foresees a very advanced 2-layer security mechanism that protects the data at 2 levels: the packets are encrypted at Network level such that the Operator can route the packets while a second application level encryption is used. That way the data can be protected towards the operator.

In case the devices are not able to reach the antennas of the operator, it is necessary to add so called LoRaWan gateways. These gateways act as a collector of the wireless signals and forwards the packets to the Operator via Internet. Besides the antenna, such a LoRaWan gateway typically has as interfaces: a power plug connector, an ethernet connector and sometimes a mobile internet connection as backup. They are security hardened; it is not possible as an outsider to get access to the devices.

Figure 11: Gateway antenna installed in the neighbourhood, as part of WP3

Within the context of STORY (WP3 and WP4), it was indeed necessary to add a few LoRaWan Gateways because the closest Proximus antenna was quite far in distance and because we had a number of devices that are placed in the house basements (the soil prevents so called 'line of sight' for the radio waves towards the antenna).

In one installation we managed to circumvent the interoperability problem by using a Modbus to LoRaWan converter device (WP4). That specific installation was based on a Danfoss heat pump for central heating (floor) and domestic hot water heating (boiler). A Modbus interface was available on the heat pump which allows us to read out the internal parameters of the installation and it also allows us to modify the maximum powered used by the heat pump for heating.

3.3.2 Thermostats

The smart thermostat (Honeywell Lyric) is a nice example of a device that resolved the problem of interoperability. The Honeywell thermostat is linked to the internet via the end-user's Wi-Fi and there is a smartphone app for the end users available to monitor their installation remotely.

We are also capable to connect to the Honeywell platform and readout and control the thermostats of the Story end users.

From a security point of view, a complex authentication and encryption protocol is necessary - based on trust relationships - such that the end users grant access to Actility to get access to the data of their thermostat.

3.3.3 WAGO communication

Measuring the power consumption in all its parameters and communicating the results to the Smart Energy Platform is done using a WAGO PLC (Programmable Logic Controller). The PLC captures the electromagnetic fields from the current conducting conductors via so called current transformers. The current transformer signals are processed and transformed into the digital domain and successively sent to the Smart Energy Platform.

To protect the data, a special device 'Secomea SiteManager' is used to encrypt the data. The Secomea SiteManager is a commercially available security certified and hardened device.

3.3.4 Service layer

In IoT terminology the above-mentioned communication means are typically part of what is often called the Network Layer. The devolpment work for this part was done in WP3 and WP4. At least 2 different Network Layers have been described: one using the Proximus LoRaWan network and another one using the Internet. Actility aggregates multiple Network Layers into a so-called Service Layer in compliance to the ETSI M2M standard. It's the job of the Service Layer to make abstraction of the multiple kinds of Network Layers and to offer the data to the (multiple) applications that are to be found in the Application Layer. The ETSI M2M Service Layer on itself is quite complex because of the multiple functions it must implement (security and authentication, make devices able to publish their data, make users able to subscribe to the data, provide caching and timestamping, …).

Within the context of Story, all Actility managed devices report to this Service Layer whereas the optimization algorithms and business logic of the Smart Energy Platform are subscribers to this Service Layer. Besides Actility, other partners also subscribe to this Service Layer.

3.4 Measurement Technologies

Actility installed all necessary monitoring sensors to report the required variables for the control algorithms and the KPI calculations.

As mentioned before, the LoRa temperature sensors were installed as part of WP3. Table 2 gives an overview of the different installed devices as part of all WP3, 4 and 5:

Device	Communi-cation	Variable	Unit
Tempe-rature sensor	LoRa	Temperature	°C
		Humidity	%
Electricity meter	Ethernet or 3G	Total Active Power	W
		Total Reactive Power	W
		Total Apparent Power	W
		Total Power Factor PF	/
		Total Active Energy	J
		Total Reactive Energy	J
		Total Apparent Energy	J
		Current per Phase	A
		Voltage per Phase	V
		Cos Phi per Phase	/
		Maximum Voltage	
		Frequency per Phase	Hz
		Harmonic per Phase	
NKE pulse sensor	LoRa	Pulse count	/
Smart plug	LoRa	Power consumption	W
		Energy consumption	Wh
		Smart plug state	On/off
Honeywell Thermostat	Honeywell API	Indoor Temperature	
		Outdoor Temperature	
		Minimal heat set point	
		Maximum heat set point	
		Heat set point	

Table 2: Overview of the different sensors and actuators installed in WP3, WP4 and WP5.

As indicated, the LoRa sensors are easily installed. For the electricity measurements, Actility opted for a sophisticated meter that reports a large amount of data. For technical reasons linked to the electric switch board in each house, 2 kinds of clamps have been used. There are the 64 A clamps with Class 1 accuracy, and the 32 A clamps with Class 0,5 accuracy. Both have a very good accuracy to provide the data needed for the Story project.

3.5 Flexible device communication

As mentioned, control of Consumer grade installations is typically an interoperability challenge. More and more of the consumer grade installations will become smart and connected which will help the challenge, but this is still an ongoing process. In WP4, considerable attention has been paid on overcoming interoperability challenges. As part of those tasks, the communication with the flexible devices was developed.

In 2 installation cases we work with the Honeywell Lyric smart thermostat. As the authentication process is quite difficult and as we needed to depend on SW development support from Honeywell (in US Westcoast time zone) we originally opted for a Dutch supplier of smart thermostats. Although that Dutch supplier was initially very helpful on the SW implementation, the devices did not fulfil in their most basic requirement: measuring the environment temperature accurately.

For the Danfoss based heat pump installation we managed to resolve the interoperability problem using a Modbus to LoRaWan converter (WP4).

In one case we used LoRaWan smart plugs to control the heat production of a domestic hot water boiler (as a last resort: just switch the whole system on and off) as rpepared in WP4.

Note that at level of the Service Layer all the interoperability concerns are resolved.

4 Controlling the technologies to show the added value of storage

Actility's ThingPark Energy Platform is a cloud-based, end-to-end solution for capacity and energy management. It is design for both energy intensive industrial units and distributed, low power units. It allows end-users to connect, monitor and operate flexible processes to capture energy market opportunities, and benefits from the multiple services offered by Actility and other actors plugged to the platform.

By connecting flexible units, the platform is capable of interfacing with both these units and the market, making use of conventional as well as innovative communication technologies. The flexibility operator monitors his processes while Actility algorithms identify opportunities for value creation. Finally, these opportunities are translated in real-time actions to monetize these opportunities by providing services with the flexible processes.

This platform offers a large set of applications for Automated Demand Response, capacity and energy management, automation of processes, as well as monitoring and management tools and interfaces. Actility's main usage of its ThingPark Energy Platform is to valorize flexibility of sites connected to it through various programs that can be combined to maximize the value creation.

Within STORY, Actility is expanding its platform capabilities by adding support for residential appliances such as low power batteries, heat pumps, solar panels and more. Furthermore, several additional algorithms are incorporated to ensure an effective control of a high amount of distributed resources and to valorize new business opportunities arising in the distribution grid (WP4).

4.1 Model Predictive Control

Actility developed the model predictive control described below (WP3). It is implemented (WP4) prior to its testing and demonstrated (WP5).

Actility has developed a dynamic model for the applicable storage technologies such as the buildings heated by an electric source (e.g. a heat pump). Furthermore, a battery model and a domestic hot water (DHW) storage model in corporation with VITO are added.

A dynamic model of a storage system enables Actility to completely automate the management and remote control of a site which have been modeled. Using the model of the sites and processes, the application schedules an optimal profile of consumption based on the chosen market opportunities, plan and operate a Demand Response program and remotely operate a global industrial process according to the computed profile and opportunities on the flexibility markets.

The application optimizes the energy process models while taking the **market opportunities** and all relevant metering data to calculate the best consumption profile of the sites into account to minimize the energy price for the consumer, without violating any current or future operational constraints.

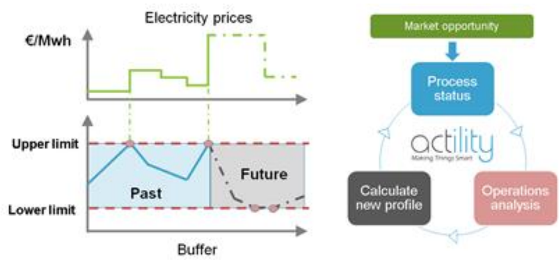

Figure 12: Model Predictive Control schematic

Consumption is scheduled for the next 24 to 36 hours. It is then updated every 15 minutes to adjust real consumption to the resources level and availability (status of controllable devices) and the real-time electricity prices.

First, ThingPark Energy computes an optimal consumption profile that would maximize the objective, based on the current weather forecast and the available process models. Then, based on a constant update of the weather forecast and PV production, Actility can use the models of the storage systems to evaluate the opportunity to deviate from the current consumption profile. By using the dynamic models, it ensures that a deviation will not violate any current or future operational constraints of the flexible units, nor any contractual or local grid constraints.

The above described control (WP3) is thus applied in the demonstrations of all 3 houses with a heat pump (WP5). Results will be discussed in WP6.

4.2 Business cases

Actility develops the control (WP3) for testing two different business cases within the STORY context to show the added value of storage in a neighbourhood.

4.2.1 Dynamic prices

Dynamic pricing is characterized by time-varying tariff structures which can be based upon short-time wholesale prices. In case of day-ahead time-of-use pricing, each day is divided into different time blocks to which different electricity prices apply. These prices are fixed for a specific period. An example of the price fluctuations is given in the figure below for a week in the fall of 2017 for day ahead prices.

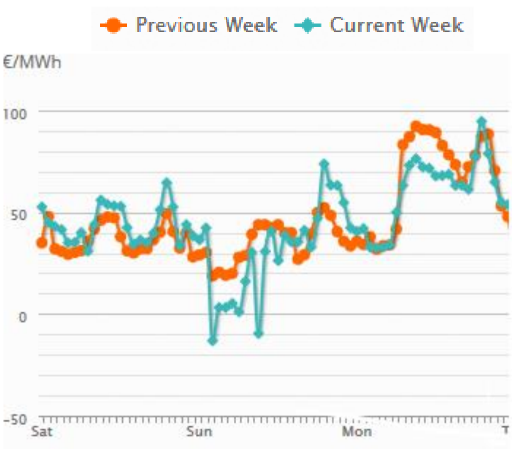

Figure 13: Belpex hourly prices fall 2017.

As currently, activated volumes cannot be monitored via the DSO validated meter. The installed electricity meter will be used as a substitute for the smart meter. Furthermore, the hourly prices remain a *virtual price signal* for the residents as in Belgium residential consumers do not have access to these markets.

4.2.2 Maximize self-consumption

Actility will try to minimize the residents invoice by minimizing the power/energy exchanges with the grid. Exchanges with the grid are being charged by important grid tariffs. By limiting those, the final invoice of the grid user is optimized.

For current meters, the benefit is limited as they do not register gross injected and off taken energy volumes. Only the net volume is registered and charged. However, this is expected to change and only the power rating could become more important in the future due to the introduction of a grid connection based capacity ratification. Within STORY, Actility will try to minimize the energy exchange with the grid on a 15-minute basis. This business case is only suitable for houses with generation.

4.2.3 Overview of business cases for the houses

The following table gives the overview of the business cases applied individually for each house. The dynamic pricing objective will be tested in each house while the self-consumption business case will be only tested in house 4 where local generation is present in the form of PV.

N°	Storage technology	Dynamic pricing	Maximize self-consumption
2	2 Heat pumps for SH 2 Heat pumps for DHW	Yes	No
3	Fuel cell	Yes	No
4	Heat pump PV installation	Yes	Yes
5	2 Heat pumps	Yes	NO

Table 3: overview of business cases per house.

4.3 Controlling the storage technologies

The control of the storage technologies is done by applying the WP3 model predictive control (MPC) as explained above while the chosen business case is plugged into the control as **market opportunities.**

4.3.1 Dynamic pricing with the boilers

As part of WP4, a heat pump boiler has been adjusted to become a smart and flexible device. The control has been jointly developed by VITO and ACT as part of WP3. The testing and demonstration is done in one of the houses.

The set up consists of 2 boilers in series. These are controlled based on the dynamic pricing business case. The objective is to keep the boiler warm between predefined boundaries while ensuring it is heated at a minimal energy price. Therefore, the model tries to find the cheapest hours on the day-ahead market and schedule the heat pump energy consumption during these hours.

As soon as the energy level in the boiler drops too low, the resident might encounter comfort issues which we want to avoid always. These moments can occur when multiple large hot water offtakes arrive in short succession such as multiple showers or baths.

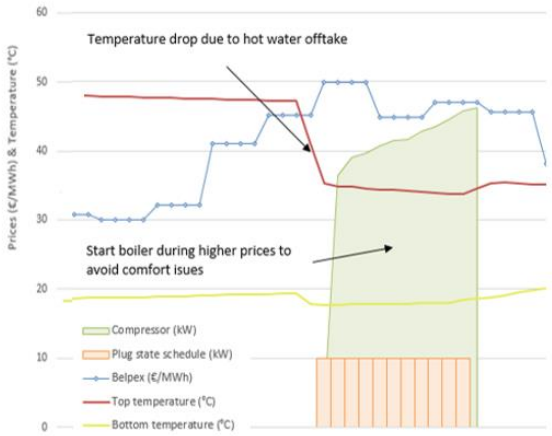

Figure 14: Dynamic pricing business case applied in an MPC to a boiler

When the energy level is between the minimum and maximum level, we schedule the boiler to heat during the cheapest hours. This control is shown in Figure 14..

The smart plugs are easily controlled over LoRa by ThingPark Energy and the boiler shows very large time constants which can result in a significant reduction of energy cost based on the virtual day-ahead prices. Based on the three temperature measurements installed in the boiler, VITO can provide Actility with a good estimation of the energy contained in the boiler. The overall structure of this setup is shown in Figure 15.

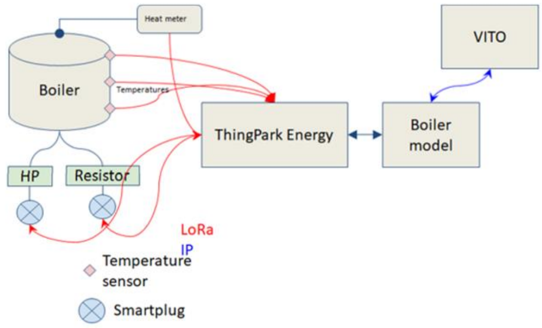

Figure 15: "Smartification" of a commercially available boiler (WP4).

Figure 16 gives an example of the MPC control where a prediction of the energy levels of the boilers is made and the consumption scheduled in the future based on the future energy prices.

During this day, the cheapest hour were observed during the night leading to an optimal scheduled consumption during the off-peak hours. Note that the black dotted line is a **prediction of the energy content of the boiler** based on the dynamic model simulated by ThingPark Energy.

4.3.2 Dynamic pricing with heat pumps for space heating

Similarly, the smartification of the heat pumps was done in WP4 , control developed in WP3 while WP5 delivers the testing and demonstration environment. The below explains this with a focus on the demonstration and insight in the results of the house it has been applied in.

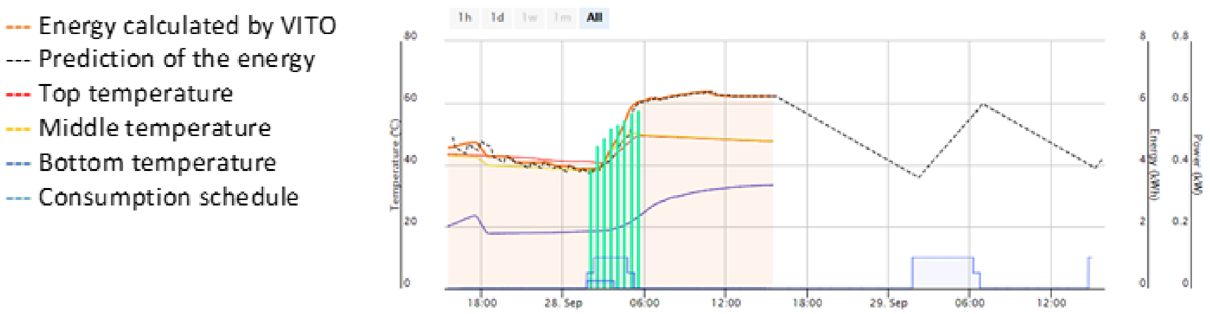

Figure 16: Boiler energy prediction example.

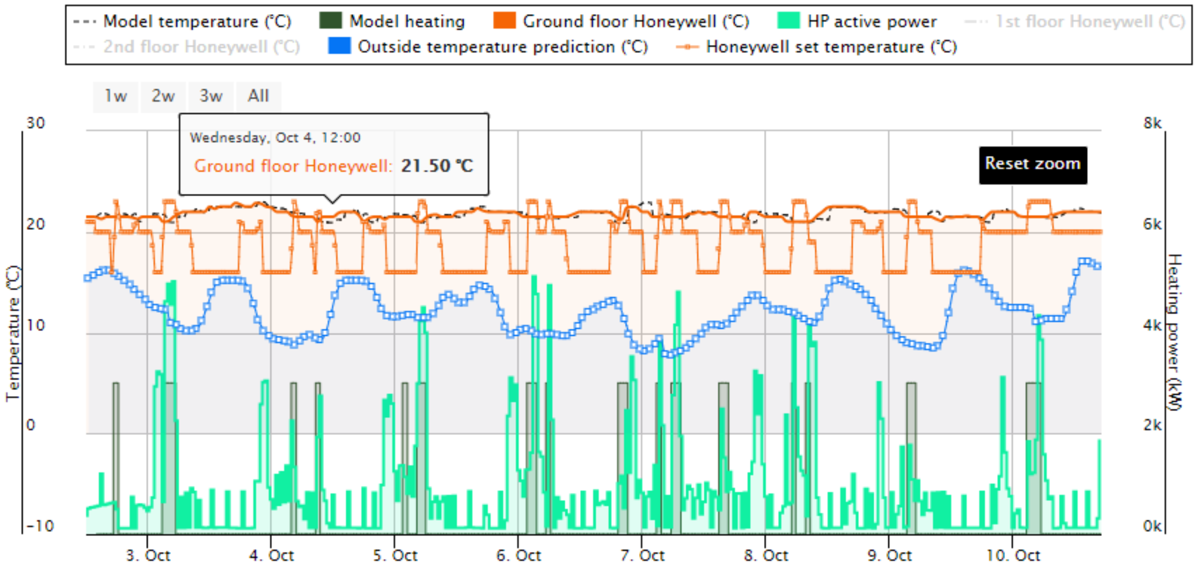

Figure 17: Thermal inertia of a building and indirect control of the heat pumps using smart thermostats

The same methodology as with the boiler is thus used for the control of the heat pumps which are used for space heating. ThingPark Energy communicates the control signal to the smart thermostat installed in the building. The main disadvantage compared to the boiler control is the indirect control which is required, ThingPark Energy can control the scheduled temperature of the thermostat but not **the direct consumption of the heat pump.**

The indirect control consists of two schedule temperatures which are set and are meant to start and stop the heat pump when required. To ensure the comfort of the residents are never violated, the house is controlled in an extremely narrow band of 1°C between 21°C & 22°C while the used setpoint temperatures are 19°C and 23°C. This is shown in Figure 17.

5 Conclusion

Testing and demonstrating the different parts developed in the previous work packages is the start of the work in this part of the demonstration task. The preparation of the different parts has been intensive and less self-evident compared to previewed.

The coming months will be used to deliver the demonstration of the different business models, with tuned settings for metering and control devices. An update of this document will then be delivered.