STORY highlight Nr.2

State of charge determination for thermal energy storage

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1 Introduction

The ambition to increase the share of renewable energy sources in the energy system inherently leads to several challenges. One of those challenges is the temporal mismatch between the energy demand and the renewable energy production which has an intermittent nature. Energy storage offers the possibility to decouple demand and supply and to add flexibility to the system.

Thermal energy represents the largest share of the final energy consumption in the residential sector in the EU with more than 75% for space heating and domestic hot water production combined (Commission, n.d.). Thermal storage can play a supporting role for the local electricity grid, if electrically driven. This includes heat pumps, CHPs (combined heat and power) and electrical boilers, which, in the presence of storage, can be used in a more flexible way. Different kinds of technologies are available for thermal storage like sensible, latent and thermochemical options. Sensible thermal energy storage is the most commonly known and wide-spread technology in the form of hot water storage units. Additionally, it is the cheapest way to store thermal energy.

To optimally control the energy system where thermal storage is present, accurate knowledge on the state of charge (SOC) of the storage unit(s) is required and can be a good basis for new business models. The state of charge is a metric to quantify the amount of energy that is stored in a given unit at a given time. The value is usually quoted as a percentage.

The demonstrators in the H2020 STORY project provide an excellent opportunity to develop methods that can estimate the SOC of thermal storage units. These methods rely on a combination of temperature measurements and (physical) models. The methodology is outlined in section 2 with a focus on presenting the output of the methodology in terms of temperature evolution in time at different heights of the storage tanks. In total, a number of different storage tanks have been used to develop and test the SOC methods: two seasonal storage tanks of 12 m³ each as well as a solar boiler (domestic hot water storage tank heated by thermal solar collectors) are used in the Belgian residential demo site (Oud-Heverlee) that serves as a Living Lab for storage solutions. A heat pump boiler is used in the neighbourhood of the Living Lab. Furthermore two large scale industrial storage units (20 and 50 m³ respectively) are used in another Belgian STORY demo site at the Beneens construction company.

It should be noted that adding energy to a thermal energy storage device does not automatically lead to an increase of the SOC. For this to happen, at least a portion of the storage volume should already be above the minimum temperature (see also below). In case this condition is not met, the SOC will be 0%. When heat is added using an internal heat exchanger, the temperature in certain parts of the storage tank will increase gradually, but the SOC will remain 0% if there is no water present with a temperature above the predefined minimum temperature.

In a similar fashion it is also possible for the SOC to change when no heat is added or removed, due to standing losses or loss of stratification.

2 Methodology

All storage tanks are modeled as n layers of water $(i = 1, \dots n)$. Each layer has a uniform temperature and a known volume calculated from the total volume and the number of layers.

If the storage tank has *m* temperature sensors installed, the method to calculate the state of charge (SOC) can be derived from the *m* temperature measurements, where n is not necessarily equal to m. To do so, a reference point defining when the storage tank is fully charged is needed. A fully-charged tank means that all water stored has a temperature of at least T_{max}. Accordingly, the reference energy content of the buffer is equal to the energy content of the buffer when all water is uniformly at T_{max}. The state of charge of the buffer can therefore be calculated as described in [1], [2] and using equations (1) - (3).

$$SOC = 100\left[1 - \frac{3600(E_{max} - E_{min})}{4.186(T_{max} - T_{min})V_t}\right] \quad (1)$$

, where

$$E_{max} = \sum_{i=0}^{n} \frac{4.186Vi(T_{max} - T_i)}{3600} \quad (2)$$

$$E_{min} = \forall j\big(j: 0 \rightarrow n, T_j < T_{min}\big) \rightarrow \sum_j \left[\frac{4.186V_j\big(T_{min} - T_j\big)}{3600}\right] \quad (3)$$

Table 1: definition of symbols used for SOC calculations

Symbol	**Meaning**
SOC	State of charge (in %)
T_{max}	Maximum temperature of the storage tank
T_{min}	Minimum outlet temperature
T_j	Temperature of layer j $\big(j: 0 \rightarrow n, T_j < T_{min}\big)$
V_i	The volume of layer i
V_t	The total volume of the tank, i.e., $V_t = \sum V_i$
E_{max}	Energy required to fully charge the tank, i.e., $\forall i: T_i = T_{max}$
E_{min}	Energy required to get all water at minimal T_{min}

The definition of reference points is not strictly necessary. In case no reference points are defined, the temperature distribution along the height of the storage tanks can provide some insights concerning the status of the tank, instead of a percentage indication of the SOC.

Two methodologies can be used to obtain the temperature evolution in time at different heights of the storage tanks: methodology 1 described in [1], [3]. Both methodologies consider thermal losses, conduction and mixing effects.

For methodology 1 there is no need to have historical data to calibrate the model. The required data are: the initial conditions (temperatures at different heights of the buffer); information about the flow rate and temperature of the water being injected or withdrawn from the storage tank in each time step, the amount of heat injected or withdrawn from the storage tank in each time step and other tank specifications (such as the heat loss coefficient and dimensions of the storage tank).

Methodology 2 can take advantage of the existence of historical data to estimate some of the models' parameters.

The temperature distribution can be calculated using equation (4).

Knowledge about the shape, dimensions and type of insulation of the storage tanks is needed for both methodologies.

$$T_{t+1,i} = T_{t,i} + \left(\alpha \frac{T_{t,i+1} + T_{t,i-1} - 2T_{t,i}}{\Delta z_i^2} + \frac{P_i k}{\rho c_p A_i}\big(T_a - T_{t,i}\big) + \frac{1}{\rho c_p A_i \Delta z_i}\dot{Q}_{t,i} + \frac{1}{\rho A_i \Delta z_i}\dot{m}_{t,i}\big(T_{t,i}^{in} - T_{t,i}\big)\right)\Delta t\ [K] \quad (4)$$

Table 2: Definition of parameters and variables used for calculating the temperature distribution along the storage tank

Symbol	Meaning
$T_{t+1,i}$	Temperature of layer i at time step t+1 $(i: 0 \rightarrow n-1)$ $[K]$
$T_{t,i}$	Temperature of layer i at time step t $[K]$
$T_{t,i-1}$	Temperature of layer i-1 at time step t $[K]$
T_a	Ambient temperature [K]

α	Thermal diffusivity $[m^2/s]$
Δz_i	Thickness of layer I $[m]$
P_i	Perimeter of layer i $[m]$
k	Thermal conductance of the isolation wall $\left[{}^{W}/_{(m^2K)}\right]$
ρ	Water density $[kg/m^3]$
c_p	Heat capacity of water $\left[{}^{J}/_{(kgK)}\right]$
A_i	Cross-sectional area of layer i $[m^2]$
$\dot{Q}_{t,i}$	Amount of heat injected or withdrawn from the storage tank $[J]$
$\dot{m}_{t,i}$	Water flow rate $[m^3/s]$
Δt	Integration timestep

3 Preliminary Results

A schematic representation of the 50 m^3 storage tank at Beneens is depicted in Fig. 1. In the steady state, the water in the bottom layers is colder than the water in the upper layers. However, when charging the buffer, hot water enters the tank between layer 9 and 10, while colder water leaves the tank from the outlet located between layers 1 and 2. When discharging the tank, the flow reverses and hot water leaves the tank between layer 9 and 10, while colder water enters the tank between layers 1 and 2. The layers interact thermally through conduction and mixing. Each water layer also loses heat to the environment. Original measurements and simulation results are represented in Fig. 2 and Fig. 3.

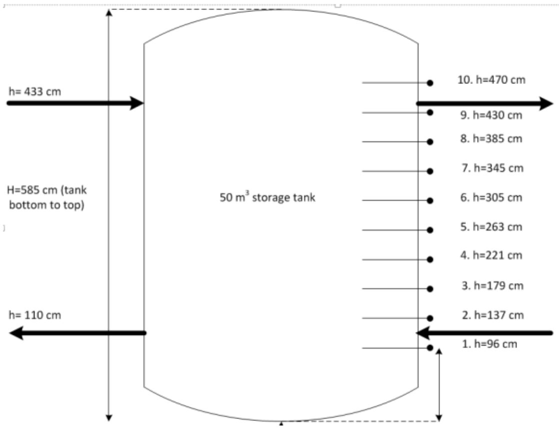

Fig. 1: 50 m^3 storage tank at Beneens – the location of the 10 temperature sensors and of inlet/outlet pipes is depicted

Measurements **Results of the simulation**

Discharging situation

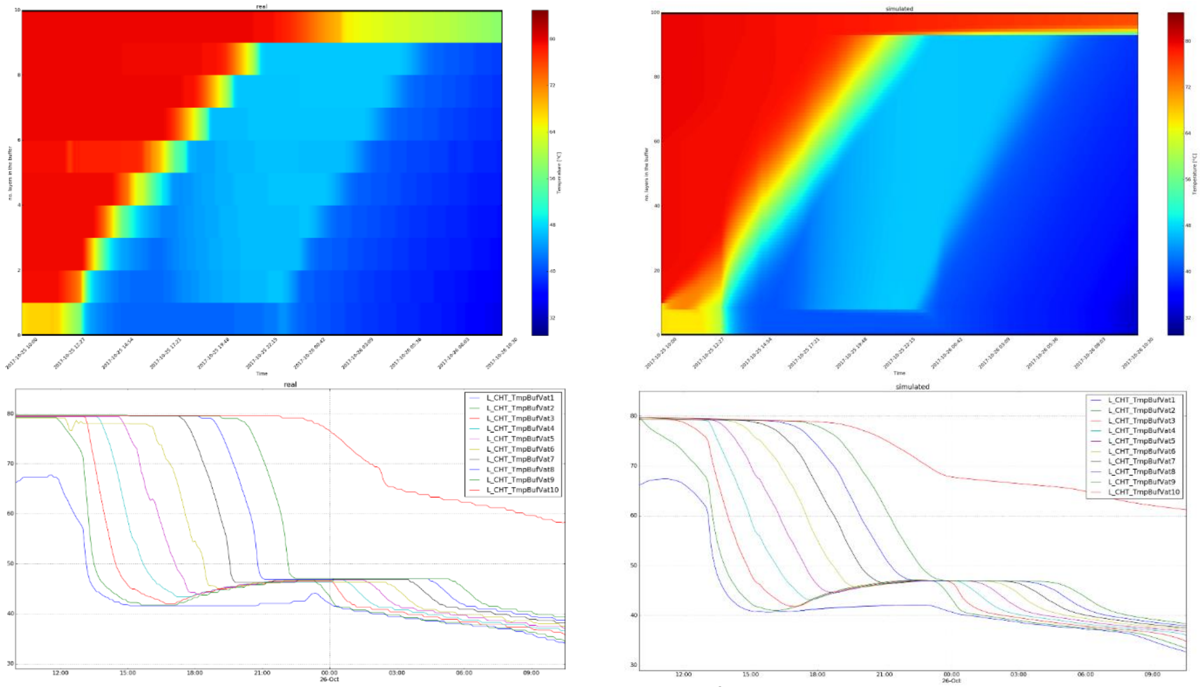

Fig. 2: Measurement data and simulation results for the 50 m^3 storage tank at Beneens - discharging

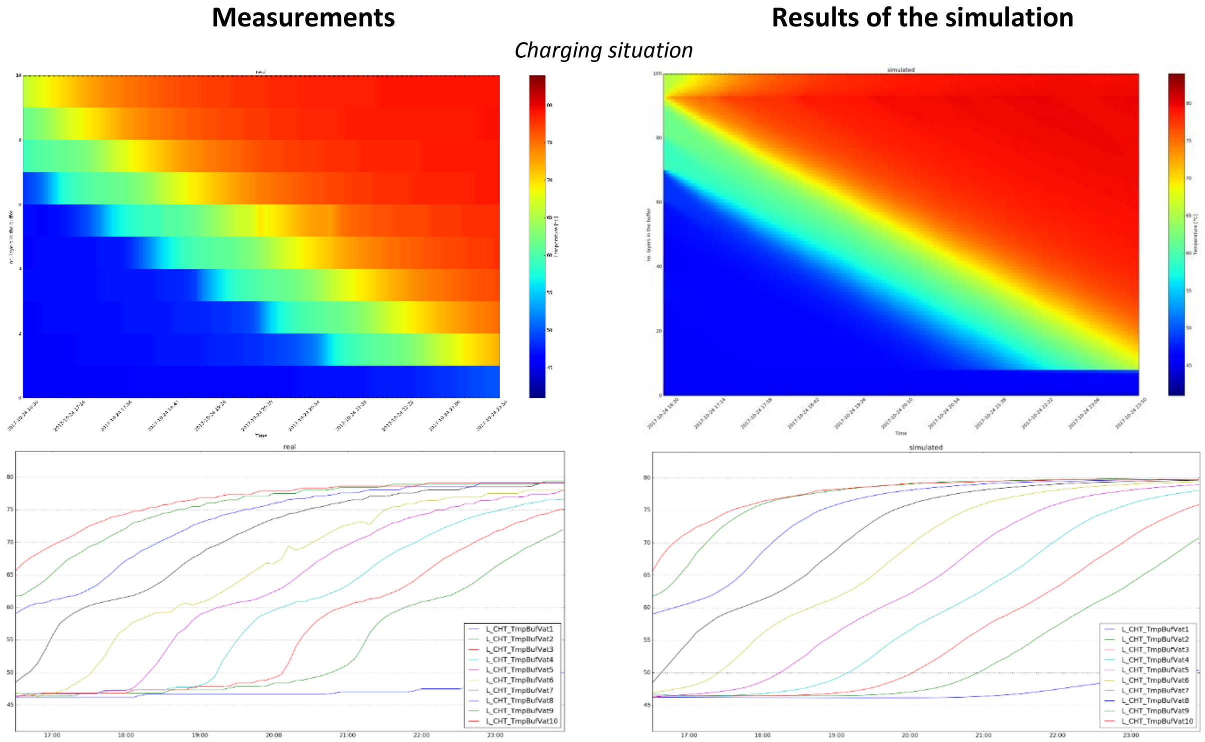

Fig. 3: Measurement data and simulation results for the 50 m^3 storage tank at Beneens - charging

The two seasonal storage tanks of 12 m^3 in the Oud-Heverlee residential demo site have different dimensions, insulation and shape when compared to the 50 m^3 tank at Beneens. Also, the usage profiles are different. For the storage tanks at Beneens, there is a large temperature difference (20 K) between the inlet and outlet of the tank combined with a high flow rate. In case of the seasonal storage at Oud-Heverlee, the flow is lower and the temperature difference is lower (10 K). Hence, different dynamics are present in both cases.

The evolution of the temperature for the measurement data and simulation results for these two tanks is illustrated in Fig. 4 and Fig. 5. Additionally, a domestic hot water tank with a volume of 400 litre is present in the Oud-Heverlee residential demo site. This storage unit is equipped with an internal heat exchanger, in contrast with the storage units discussed before. Measurement data and preliminary simulation results are shown in Fig 6. For this site, charging and discharging situations during day to day usage have not yet been explored.

4 Application example: dynamic pricing with a heat-pump boiler

Within the STORY project, a heat pump boiler has been adjusted to become a smart and flexible device. The control has been jointly developed by VITO and the aggregator Actility. The testing and demonstration is done in one of the houses which are part of the Oud-Heverlee neighborhood demonstrator.

The set up consists of 2 boilers in series. These are controlled based on the dynamic pricing business case. The communication with the boilers is done via a “Long Range Wide Area Network” (LoRaWAN). 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 (or SOC) in the boiler drops too low, the resident might encounter comfort issues which should be avoided at all times. These moments can occur when multiple large hot water offtakes take place in short succession such as multiple showers or baths.

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 in Fig. 7.

The overall structure of this setup is shown in Fig. 8. The smart plugs are controlled over LoRaWAN by Actility's ThingPark Energy Platform. The boiler shows very large time constants which can result in a significant reduction of energy cost based on 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, based on the methodology described previously.

Fig. 9 gives an example of the Model Predictive control (MPC) where a prediction of the energy levels of the boilers is made and the future consumption is scheduled based on the future energy prices.

During this day, the cheapest hours 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 Thing Park Energy.

5 Conclusions

Both methodologies explored so far provided good preliminary results. The maximum difference between simulated temperature and measurements occurred for the storage tank at Beneens for a specific sensor in the discharging situation. In that specific situation, during 3% of the simulated time, the observed temperatures had an error larger than 10°C. For comparison, on average the typical error is below 5°C.

Both methodologies can provide the temperature distribution along the height of the storage tanks in case of no reference points being defined. This temperature provides useful information concerning the status of the storage tanks, although not providing a percentage indication of the SOC.

Situations explored so far included:

1. A tank which is directly discharged by means of hot water leaving the tank;
2. A tank which is directly charged by means of hot water entering the tank;
3. A tank initially charged and without any charging or discharging for a certain period of time;
4. A tank initially at medium temperature $(\sim 40°C)$ and without any charging or discharging for a certain period of time.

Results so far are satisfactory, but additional situations still need to be tested. Those situations include for example tanks with indirect charging and discharging (tanks with coil inside).

References:

[1] K. Vanthournout, R. D'Hulst, D. Geysen, and G. Jacobs, "A smart domestic hot water buffer," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2121–2127, 2012.

[2] K. Vanthournouth, J. Van Bael, B. Claessens, and R. D'Hulst, "EP 11 168 672.1, PCT/EP2012/060527 - Method and system for buffering thermal energy and thermal energy buffer system."

[3] J. Lago, F. De Ridder, W. Mazairac, and B. De Schutter, "A 1-dimensional continuous and smooth model for thermally stratified storage tanks including mixing and buoyancy effects," *submitted*, 2018.

Measurements **Results of the simulation**

Steady state

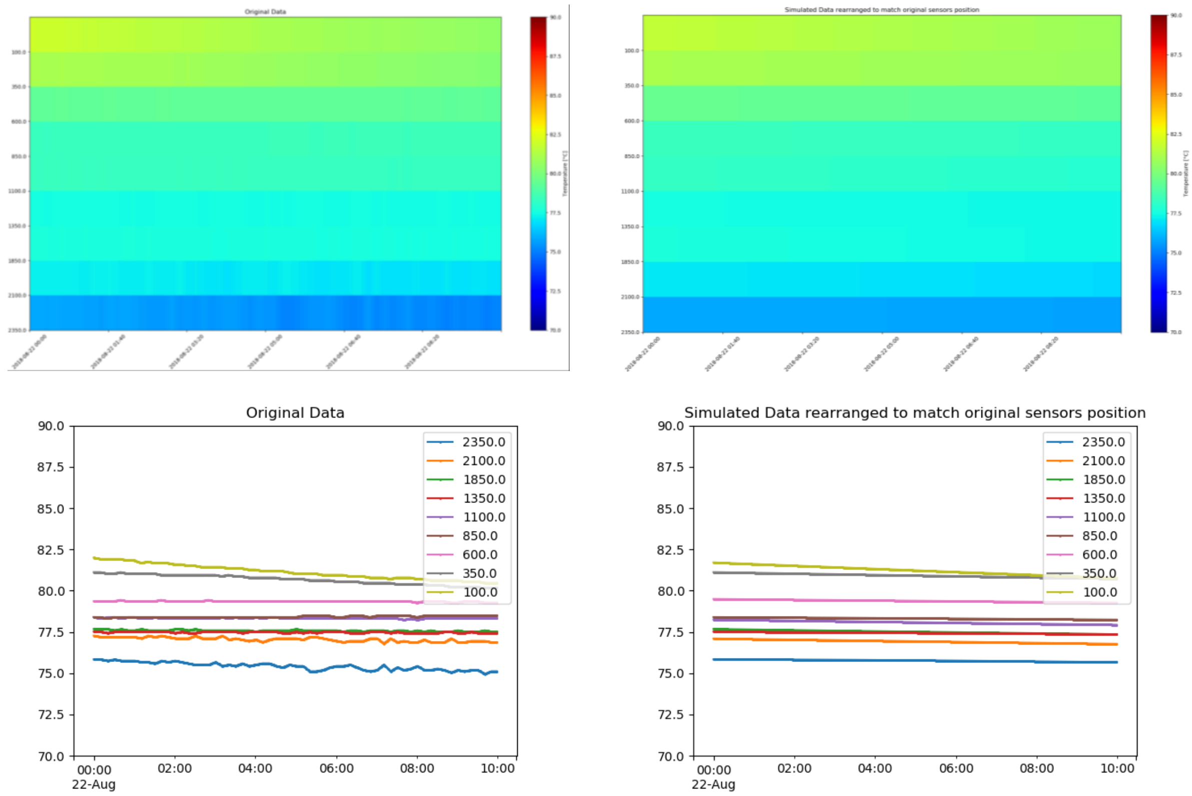

Fig. 4: Measurement data and simulation results for the 12 m³ seasonal storage tank 1 at the Oud-Heverlee residential demo site

Measurements **Results of the simulation**

Steady state

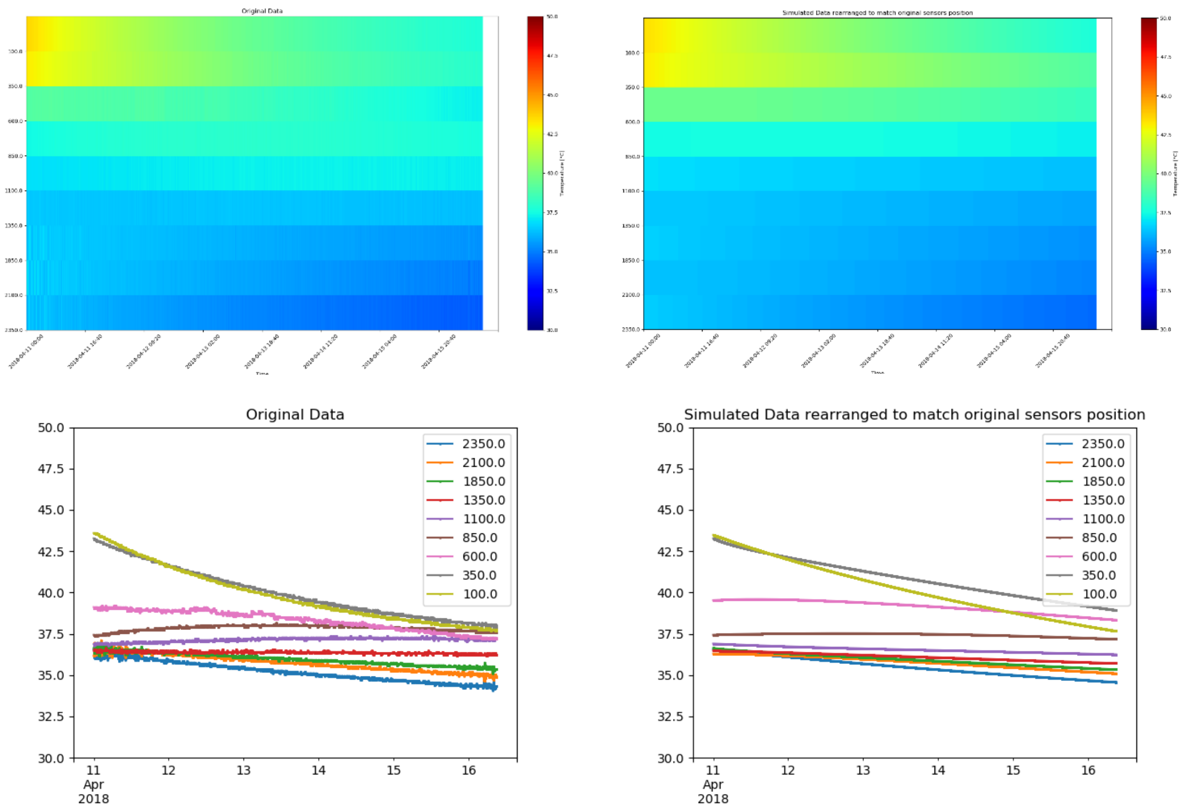

Fig. 5: Measurement data and simulation results for the 12 m³ seasonal storage tank 2 at the Oud-Heverlee residential demo sites

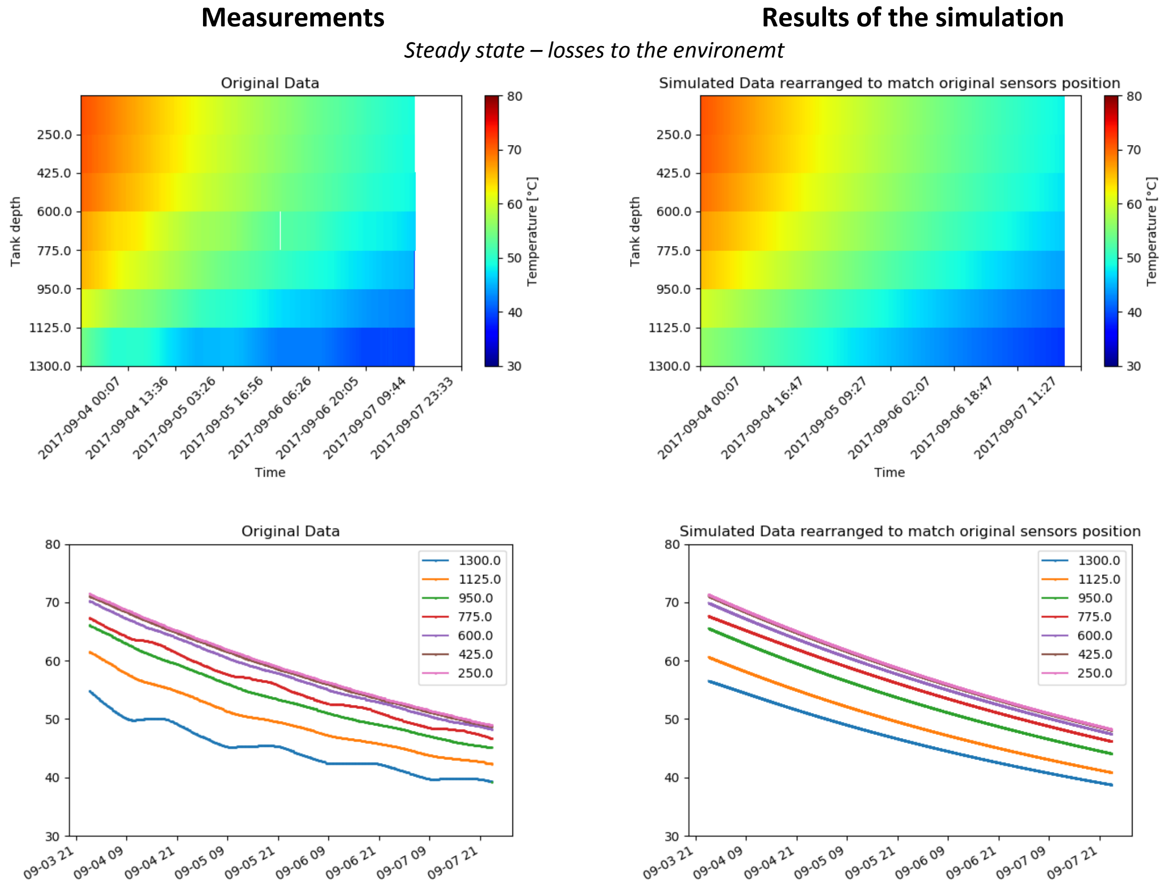

Fig. 6: Measurement data and simulation results for the 400 L domestic hot water tank at the Oud-Heverlee residential demo sites

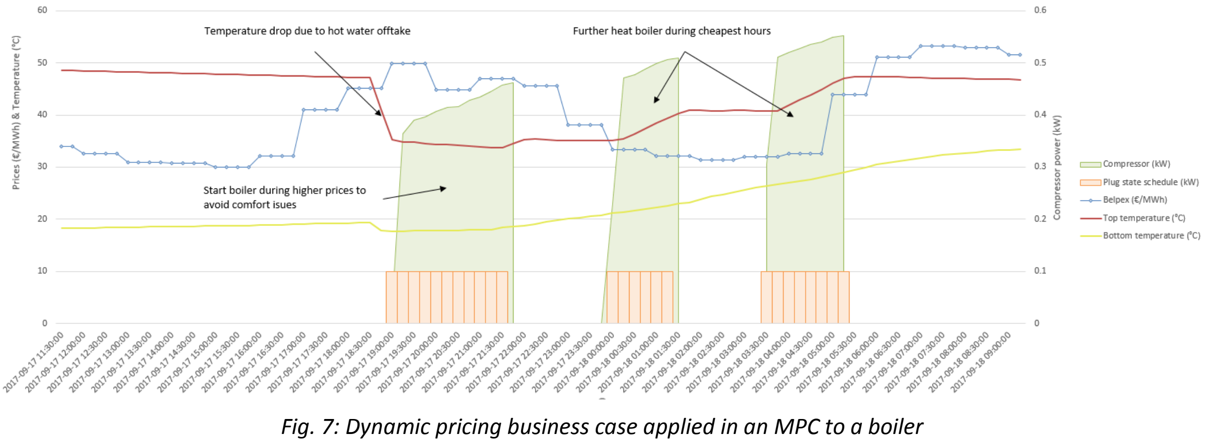

Fig. 7: Dynamic pricing business case applied in an MPC to a boiler

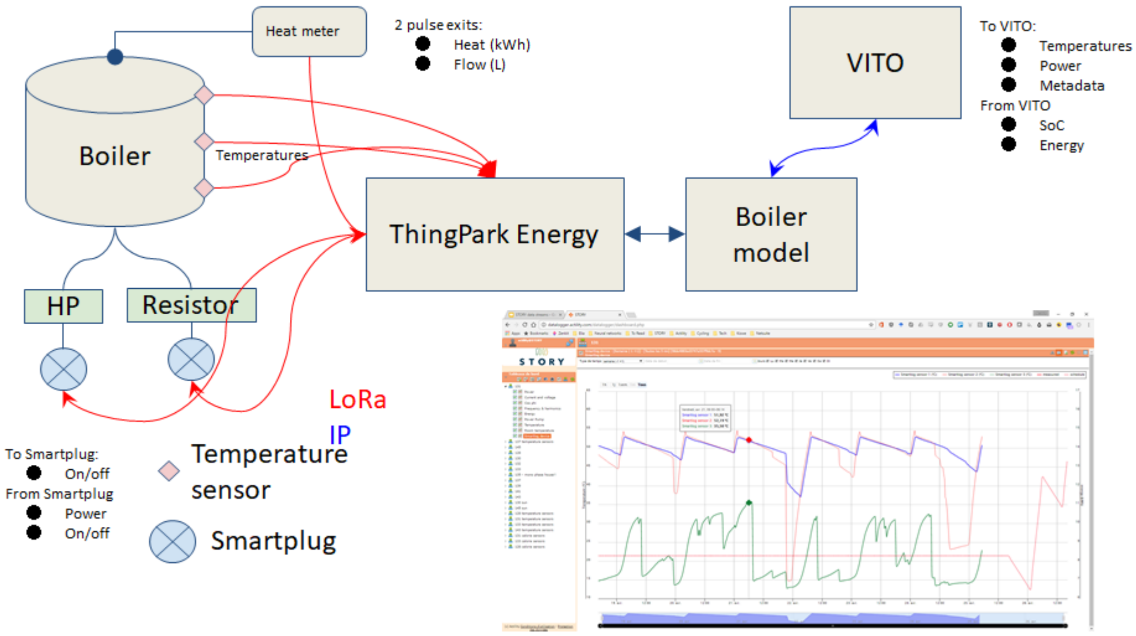

Fig. 8: "Smartification" of a commercially available boiler

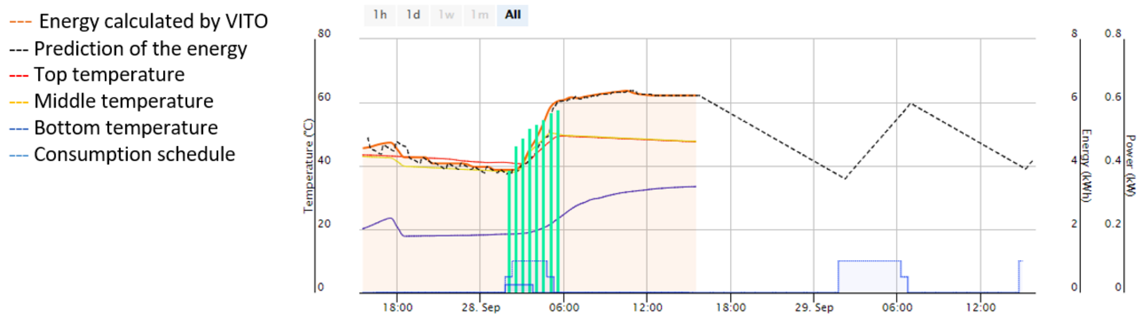

Fig. 9: Boiler energy prediction example