Interreg North-West Europe

EUROPEAN UNION

DGE-ROLLOUT

EFFICIENT HEAT DEMAND MANAGEMENT

Evaluation of the impact of innovative demand side management on the Balmatt site

Somil Miglani, Koen Allaerts, Matsen Broothaers (VITO)

13.01.2021

Contents

List of Figures

Executive summary

As DH system move towards the use of renewable energy sources, their production side is becoming less controllable due to the inherent unpredictability of renewable sources. To address this challenge, efficient and innovative heat demand management techniques are gaining attention. The unpredictability of the sources can be dampened by the flexibility of the demand side. Until now, demand side management (DSM) in DH networks has been a complex problem to solve. However, with the availability of new technologies such as big data, artificial intelligence, advanced algorithms, IoT and cloud computing, the solutions to the DSM problems are within reach. One such solution is an innovative technology called the STORM controller co-developed by VITO.

This report evaluates the potential of efficient and innovative DSM for the Balmatt DH network located in Mol, Belgium. The fundamental principle of using the buildings' thermal mass source of thermal flexibility in a DH network is employed by the STORM controller, is also used as the underlying basis for the evaluation conducted in this report. The Balmatt site consists of 42 buildings in total, connected to a 3rd generation DH network, which is served by geothermal energy source and natural gas. Out of the 42, the 5 largest consumers (buildings) are responsible for 50% of the total heat consumption in the network. This is a great opportunity for DSM using STORM as it limits the number of connections to STORM thereby limiting the complexity (and costs), and at the same time maximizes the flexibility potential.

A simulation model that replicates the real time behavior and performance of the STORM controller is developed and presented. The results of the model indicate that DSM can save the network around 610MWh of natural gas consumption annually, which translates to 18kEUR in cost savings. This is a highly promising result that should encourage decision makers and relevant stakeholders to pursue DSM solutions on this network.

CHAPTER 1: Introduction

District heating (DH) systems are predominantly demand driven. Traditionally these systems are controlled in such a way that the heat production is controlled to match the heat consumption at any given time. A large part of DH systems especially the relatively older ones still work on this operating principle. Often, not a lot of emphasis is laid on controlling the demand in such a way that it can benefit production. The main reason for this is the highly distributed nature of the heat demand making it very difficult to control. Another major reason is that each building connected to the DH network is unique in its heat demand requirements, energy management system, occupants and their behavior. A large effort is required to steer the demand of such unique distributed buildings, which is not trivial.

Renewable energy sources answer the climate change problem very well, however, they bring new challenges along. As DH systems adopt renewable energy sources, which are inherently less predictable and thereby less controllable, it is imperative to have control over the demand side. This is important to ensure the service of heat delivery is not interrupted or reduced in quality at any given time. With the help of latest technologies such as big data, Artificial intelligence, distributed optimization and control algorithms, the non-trivial problem of active demand side management (DSM) is within reach today.

CHAPTER 2: Efficient demand side management (DSM)

2.1 The STORM controller

STORM is an acronym which stands for Smart Thermal Operational Resource Management. STORM is an artificial intelligence based controller for district heating networks, which achieves operational optimization through active demand side management. It brings together the latest tools, techniques and technology from three different fields name Artificial Intelligence (AI), Internet of Things (IoT), and cloud computing and infrastructure. It was co-developed by VITO/Energyville[1] within the EU H2020 project named after the same acronym STORM[2]

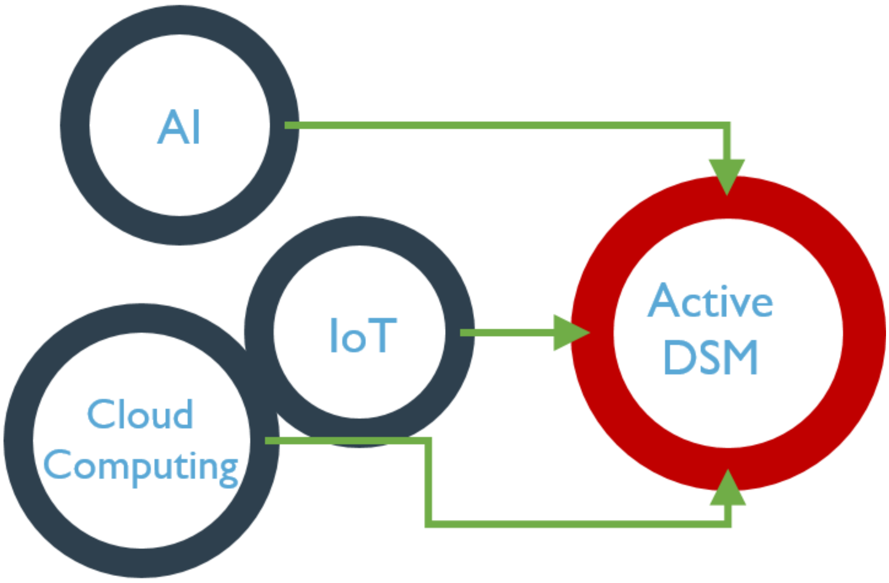

Figure 1: Confluence of three fields of technology in the STORM controller for DSM in DH networks

STORM basically utilizes the thermal mass of the buildings connected to a network as distributed storage. When buildings are heated, the walls, air, and other objects inside the building which together constitute the thermal mass of the building are also heated essentially storing thermal energy. In a hypothetical situation, where the heating supply of the building is reduced or switched off completely, the thermal mass of the building can release this energy into the building's indoor environment without loss in thermal comfort for a few hours. The duration may vary for each building depending on its construction and other energy related parameters. Based on this principle, STORM can shift and managing thermal demands in time, unlocking thermal flexibility in buildings to improve the operational performance of an entire DHC system.

The STORM controller controls the heating supply of multiple buildings connected to a district heating network simultaneously, such that the overall energy demand at the grid level can be reduced. This

[1] https://www.energyville.be/en/storm-district-energy-controller
[2] https://www.storm-dhc.eu/en

can be coordinated in such a way that a pre-defined control objective is fulfilled. Some examples of control objectives include peak shaving, load curve flattening, etc.

The STORM controller basically influences the measurement taken by the outdoor temperature sensor installed locally within the building and connected to the BMS system. Typically, the supply temperature on the secondary side of the district heating substation is controlled according to the outdoor temperature, based on an in-built heating curve. According to this curve, lower outdoor temperature would result in a higher supply temperature and vice versa. The STORM controller adds a discharging (and charging) offset to the measurement of the outdoor temperature sensor to have influence on the secondary supply temperature and effectively reduce (or increase) the heat input to the building(s).

2.2 This report

In this report, the concept of the STORM controller is used as the underlying operating principle/innovative technology for the evaluation of the potential for heat demand management at the Balmatt site.

CHAPTER 3: Simulation model for assessment of DSM potential on DH networks

3.1 Methodology

The methodology to assess the potential of DSM on DH networks described in this section, aims to reproduce the operational behavior of the above described STORM controller with peak shaving as its control objective. To achieve this, a simulation-based approach is adopted, which implements a simplified mathematical formulation of the controller algorithm under a set of assumptions. Possible extensions to the methodology that include other control objectives are also discussed briefly.

3.1.1 Assumptions

In practice, the STORM controller is a complex web of interconnected software modules that implement various advanced algorithms to control large DH systems in real time. These systems have with several constraints and operate under uncertainties, which are taken care of by the overall control algorithm. In this study, the complexity of the controller algorithm is cut down, and simplifications are made to create a simulation model with the help of a set of assumptions that are listed below.

The model assumes;

- Perfect foresight about the total heat consumption of the network and weather parameters such as outdoor temperature.
- There are no indoor thermal comfort violations, if the constraints limiting control actions are satisfied.
- The peak shaving objective is always achieved optimally. The model ignores the effect of a highly likely sub-optimal operation of the controller in real time due to uncertainties, forecasting errors, etc.
- The energy consumption of building is highly correlated with outdoor temperature.
- The response factor encapsulates all the factors that separate the realistic and theoretical response of a building to the control signal.
- All buildings react immediately to the control signal and reach a steady state within the minimum defined timestep (1 hour in this case).

3.1.2 Problem formulation

The simulation model is formulated as a constrained linear optimization, where the objective function replicates the peak shaving control objective. The objective function is subject to constraints related to overall energy balance, upper and lower bounds of the production unit capacities, flexibility and controller related constraints. All the above are described in detail below. Note: the decision variables are highlighted in bold font.

Objective function: It is defined as the total cost of energy production for all the production units combined as described by equation 1, where $\lambda_{geothermal}$, λ_{gas} are the marginal cost of production, $Q_t^{geothermal}$, Q_t^{gas} are the time dependent energy production for the geothermal and gas unit respectively. In this case study, there are only two production units operating; a geothermal unit covering the base load, and a natural gas unit covering the peak load.

1. $Obj = \sum_t [\lambda_{geothermal}\boldsymbol{Q_t^{geothermal}} + \lambda_{gas}\boldsymbol{Q_t^{gas}}]$ $\qquad \forall\, t \in [1, h]$

Subject to:

Energy balance constraint: As the name suggests, this constraint expressed in equation 2, describes the balance between the total energy produced by the two production units and the total energy consumed by the DH network. In this constraint, $Q_t^{gridconsumption}$ is the time dependent grid consumption of the entire DH network, and Q_t^{flex} is the total network flexibility available and extracted out of all the connected buildings at any given time as a result of the control actions.

2. $\boldsymbol{Q_t^{geothermal}} + \boldsymbol{Q_t^{gas}} = Q_t^{gridconsumption} - \boldsymbol{Q_t^{flex}}$ ∀ t ∈ [1, h]

Capacity bounds for production units: These constraints expressed in equation 3 express the upper and lower limits for the production capacity of each production unit.

3. $\boldsymbol{Q_t^{geothermal}} \leq Q^{geothermal,\,max}, \boldsymbol{Q_t^{gas}} \leq Q^{gas,\,max}$ ∀ t ∈ [1, h]

Aggregated flexibility constraint: This constraint expressed in equation 4, calculates the total flexibility available in the network at any given time because of the control actions. This is done by summing up the individual available thermal flexibility for each building at any given time, described by the variable $\Delta Q_{bc,t}^{flex}$. In this constraint, N_{bc} is the total number of connected buildings.

4. $\boldsymbol{Q_t^{flex}} = \sum_{bc} \Delta \boldsymbol{Q_{bc,t}^{flex}}$ ∀ t ∈ [1, h] & bc ∈ [1, N_{bc}]

Flexibility constraint: This constraint expressed in equation 5, calculates the available flexibility for each individual building using the energy signature model and control action. In this constraint, $f_{response}$ is the building response factor, and $E_{bc}^{signature}$ is the energy signature of a given building *bc* both as defined in preceding sections. $\Delta T_{bc,t}^{discharge}$ is the temperature offset control signal sent to a given building *bc* at any given time *t*. Notice that the temperature offset signal is always a discharge signal since we are investigating the impact of peak shaving. This implies that this signal increases the actual reading of the ODT value by a certain amount, to steer the building to cut its energy consumption in that given moment. This cut in energy consumption is what we call thermal flexibility.

5. $\Delta \boldsymbol{Q_{bc,t}^{flex}} = f_{response}\, E_{bc}^{signature} (\Delta \boldsymbol{T_{bc,t}^{discharge}})$ ∀ t ∈ [1, h] and ∀ bc ∈ [1, N_{bc}]

Bounds for the control signal: The total amount of control action sent to each building must be limited. This is important because, the direct impact of the discharging control action is the reduction in energy input to the building. The indirect impact of this could be the drop in indoor temperature if the thermal mass of the building does not discharge sufficient energy to maintain it at a constant level. Therefore, by limiting the amount of control action, we are reducing the risk of loss of indoor thermal comfort. This constraint is expressed in equation 6, where $\Delta T_{bc}^{discharge,\,max}$ is the upper bound of the discharging temperature offset and the lower bound is set to zero.

6. $0 \leq \Delta \boldsymbol{T_{bc,t}^{discharge}} \leq \Delta T_{bc}^{discharge,\,max}$ ∀ t ∈ [1, h] and ∀ bc ∈ [1, N_{bc}]

Degree-hour constraint: In addition to the upper and lower bound, a degree hour constraint is defined to further limit the control actions. This constraint expressed in equation 7, helps in limiting the total control actions over a rolling period of 24 hours. The key metric used here is degree hours. The total degree hours defined by the product of the discharging temperature offset sent to a given building and the duration for which this offset was sent. The maximum value of the degree hours is specified by

$Tt_{max-discharge}$. This constraint limits the upsides of the controller further to ensure no loss of indoor thermal comfort.

7. $\sum_t \Delta \boldsymbol{T}_{\boldsymbol{bc.t}}^{\boldsymbol{discharge}} dt \leq Tt_{max-discharge}$ ∀ t ∈ each rolling 24h period and ∀ bc ∈ [1, N_{bc}]

3.1.3 Input data and parameters

The input data required for the model are listed below.

- Monthly values of total energy consumption for all the buildings to be connected to the Storm controller. If available, hourly values are preferred for better accuracy of results, however this data is generally unavailable. Aggregated monthly data on the other hand is relatively easily available.
- Hourly values of outdoor temperature for the location of the DH network for the same time period as the total energy consumption values (see point below).
- Hourly values of the total energy consumption of the DH network for the same time period as the ODT values.

Input Parameters required for the model are listed below.

- Building response factor: A correction factor that represents the ratio of the realistic to theoretical response of a building to a control signal.
- Upper and lower bounds for the temperature offset control signal.
- Upper and lower bounds for the degree hours budget for the temperature offset control signal.
- Various optimization parameters

3.1.4 Data pre-processing

Before the simulation model is deployed a data pre-processing step is necessary. This pre-processing step excludes the general data cleaning related processing required. The main aim of this step is to calculate the energy signature of each building that is essential in calculation of its flexibility potential. The energy signature is basically the change in energy consumption per unit degree change (kW/^{0}C) in the outdoor temperature. It is calculated as the slope of the linear regression between energy consumption and outdoor temperature. The stepwise details are provided below.

- Key steps:
    1. Calculate monthly DHW consumption for all buildings using two summer months July and August. In this step, it is assumed that in summer space heating (SH) consumption is negligible and the entire
    2. Calculate the net SH consumption for all winter months October to March by subtracting the DHW consumption from step 1 from the total monthly consumption
    3. Estimate the energy signature (E_{sig}) and heat demand at 0°C (Q_0) through a linear regression ($\boldsymbol{Q} = E_{sig}\boldsymbol{T} + Q_0 + \varepsilon$) between monthly energy consumption ($\boldsymbol{Q}$) and monthly average of hourly ODT values ($\boldsymbol{T}$)

3.2 Possible extensions and improvements

The simulation model described above can be extended in many ways to investigate the DSM potential for DH networks for different control objectives. The STORM controller is also designed to easily integrate new objectives without changing a majority of parts of the larger system.

- Evaluation of a new objective such as load curve flattening in place of peak shaving. This requires modeling of the building as a storage such that both charging and discharging of the building can be studied. When flattening the load curve, it is essential to pre-charge the building before the peaks and re-charge the buildings in during the troughs in addition to shaving the peaks. Therefore, modeling of the building as a storage becomes important. An example of this is discussed in the subsequent section.
- The model can also be extended to include a statistical approach to estimation of the building response factor using historical data. This will aid in improving the accuracy of the simulation results. This is only possible if hourly consumption data from each building is available.
- The energy signature estimation can be improved by using hourly consumption data from all buildings. Doing this would also greatly improve the accuracy of the simulation results.

CHAPTER 4: Case study: Balmatt

4.1 Balmatt pilot site

The Balmatt site consists of a 3rd generation DH network which uses geothermal energy to serve its base load and natural gas for peak load. In total, forty-two buildings are connected to this network. The network is in Mol, Belgium and is jointly operated by VITO and SCK domain[3] and serves as a site for experiments with innovations in district heating and demand side management as well.

4.2 Input parameters

The table below lists the input parameters used for the subsequently described scenario.

Parameter name	Value	Unit
$\lambda_{geothermal}$	20	EUR/MWh
λ_{gas}	30	EUR/MWh
$Q^{geothermal,max}$	3.5	MW
$Q^{gas,max}$	10	MW
$f_{response}$	0.8	Dimensionless
$\Delta T_{bc}^{discharge,max}$	10	°C
$Tt_{max-discharge}$	40	°C h
N_{bc}	5	Dimensionless

Table 1: Values of input parameters of the simulation model for the chosen case study

4.3 Scenario definition

The STORM controller offers most advantages in scenarios where a minimum the set of buildings connected to it cover a large part of the energy consumption. In this case, the integration costs are which rise by the number of connected buildings can be limited. At the same time, the total available thermal flexibility can be maximized since this is a fraction of the total energy consumption by the connected buildings. This strategy also reflects and is aligned with the go-to-market approach when looking for pilot projects for the Storm controller. Keep this in mind the following scenario was selected for evaluation.

- Storm controller is connected to the following 5 largest buildings that cover 50% of total consumption
    - SCH, ENE, LMA, GKD, MAT (MET)
- Other scenarios with different combinations of buildings with different coverage ratio are also possible but not investigated in this report.

[3] https://www.sckcen.be/en

4.4 Results and discussion

4.4.1 Energy signature for all connected buildings

The values of the energy signature (slope) and the average space heating power demand at 0°C ODT (intercept) for all buildings are listed in the table below. Figure also illustrates the linear regression through which these values are estimated. The energy signature values also indicate the absolute and relative flexibility available for each building in kW per degree change in ODT, also interpreted as MWh per degree discharge temperature offset control signal sent to the building. From the table below, the most thermal flexibility is offered by the building ENE at 45.8 kW/°C and the least by the building MAT(MET) at 22.1 kW/°C. The list of buildings ordered according to decreasing flexibility is ENE, SCH, LMA, GKD, MAT(MET).

Building	Energy Signature (kW/°C)	Average space heating power demand at 0°C ODT (kW)
ENE	-45.8	863.2
SCH	-40.2	882.9
LMA	-27.7	515.0
GKD	-27.1	484.4
MAT(MET)	-22.1	413.6

Table 2: Table summarizing the energy signature and average space heating power demand at 0°C ODT for the 5 buildings connected to the STORM controller for DSM

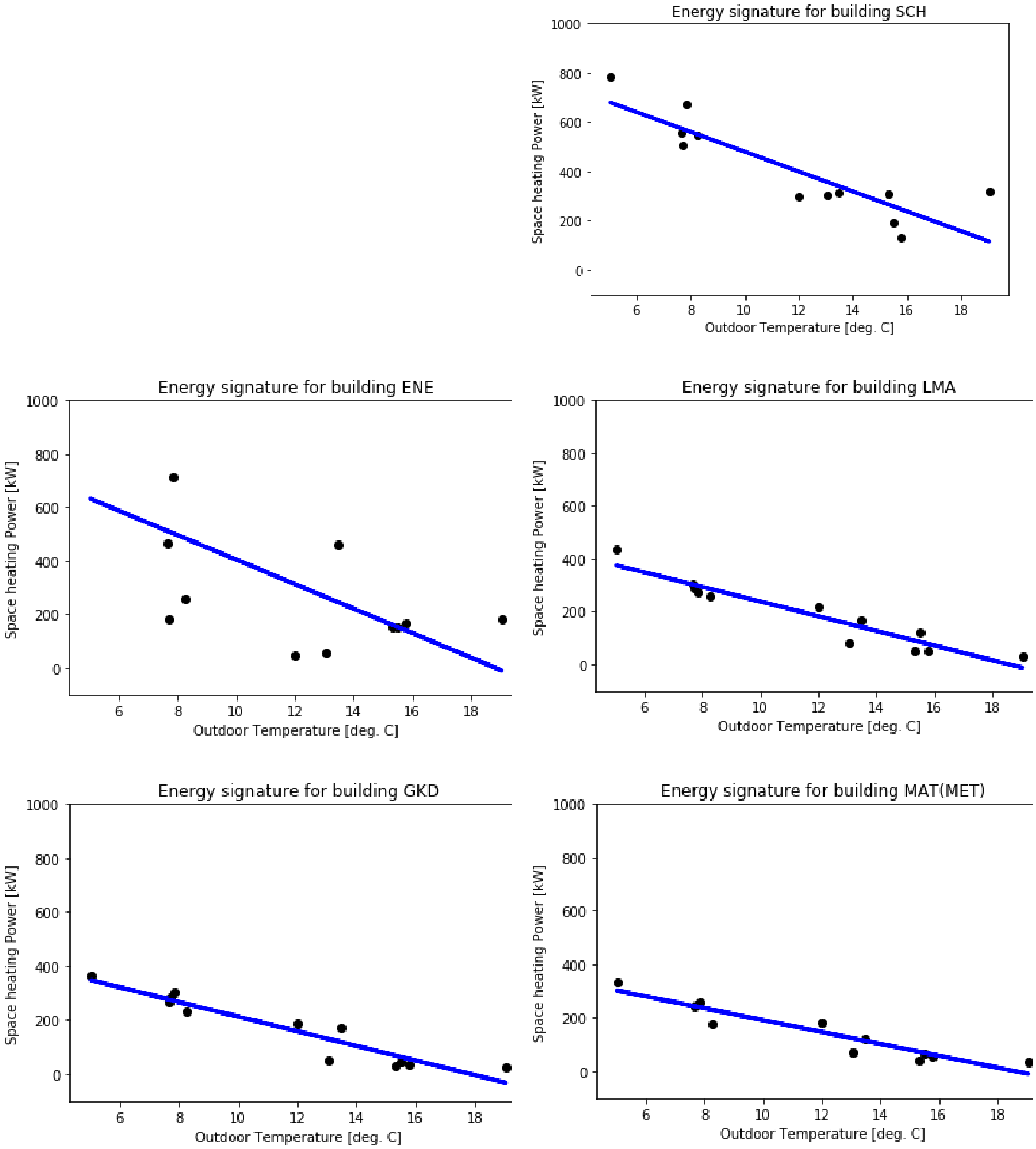

Figure 2: Energy signature curves for all buildings derived using monthly consumption data

4.4.2 Hourly controller operation

The hourly controller operation for all winter months for the year 2018 is illustrated below in figures 3-8. The load profiles without and with STORM controller active are compared. Furthermore, the total discharging temperature offset for each building is overlaid with the measured values of ODT to visualize the extent of control. The shaded region in the plot highlights the coverage of the base load geothermal unit (<3.5MW).

A general observation from the hourly controller operation is that the controller is active mainly during the periods where the peak load gas unit is active (>3.5MW). Rest of the time, no control signals are sent to any of the buildings. This is expected behavior since the control objective is peak shaving. The total DH network heat load with DSM (blue) is lower as compared to the heat load without DSM, especially during the times when the controller is active and sending signals to the connected buildings. The extent to which the total heat load is lowered, depends on the aggregated flexibility of all buildings combined in addition to the control actions.

It is also observed that in most cases the controller activity results in peak reduction but not shaving in a strict sense i.e. a situation when the peak is shaved entirely such that the network operator is able to avoid starting the peak gas unit. The start/stop of a production unit also incurs additional costs that could be saved.

There are however some instances when the controller results in the complete shaving of the peaks. It can be seen for example in the month of January between hours 285-300 and similarly between hours 560-570. This effect is also observed in other months such as March, October, and December, although always for short durations and when the peak demand is relatively low.

The controller parameters can be adjusted to increase the DSM potential, but this comes at the cost of reduced indoor thermal comfort for occupants of the connected buildings. Without the availability of indoor temperature data, it is impossible to guess the impact of DSM on the indoor thermal comfort. For this reason, the boundaries of control are kept strict, which limits the overall potential. A better approach is to use building models to accurately predict the impact of the controller on the indoor temperature and relax the controller parameters accordingly.

January

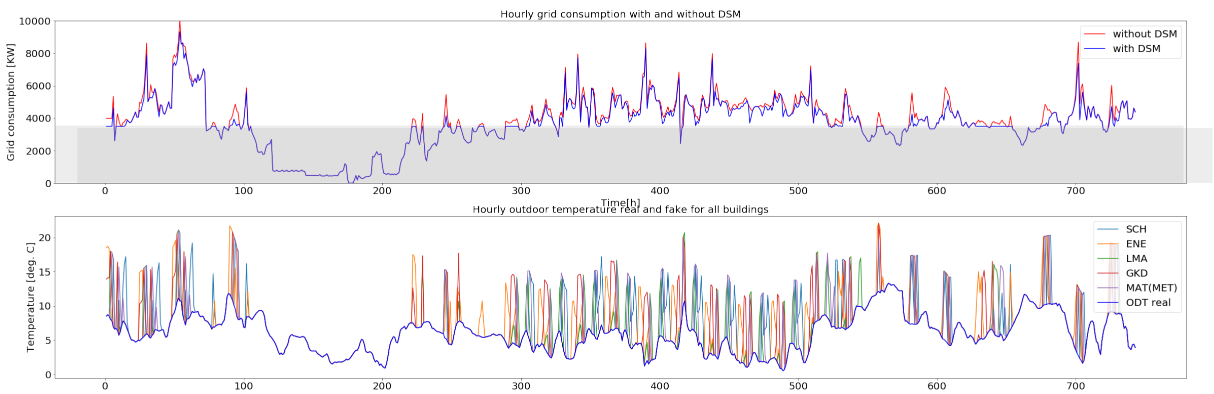

Figure 3: Hourly STORM controller operation for peak shaving through DSM for the month of January 2018

February

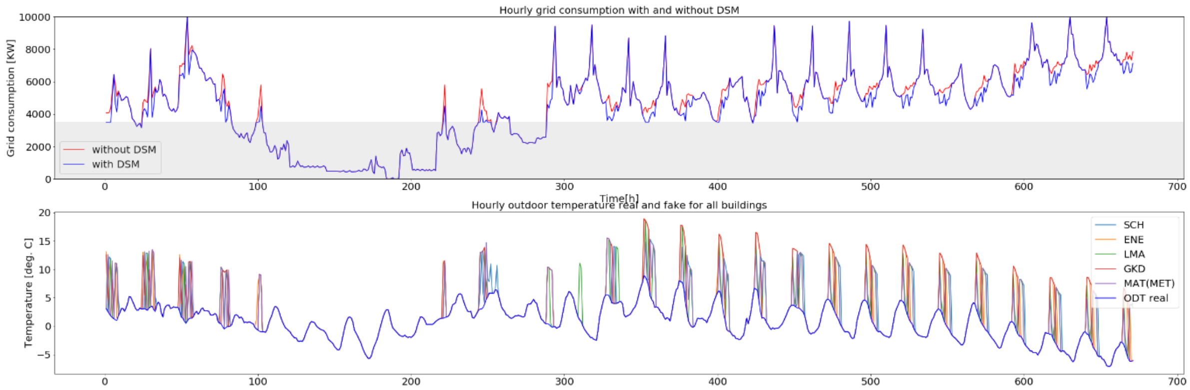

Figure 4: Hourly STORM controller operation for peak shaving through DSM for the month of February 2018

March

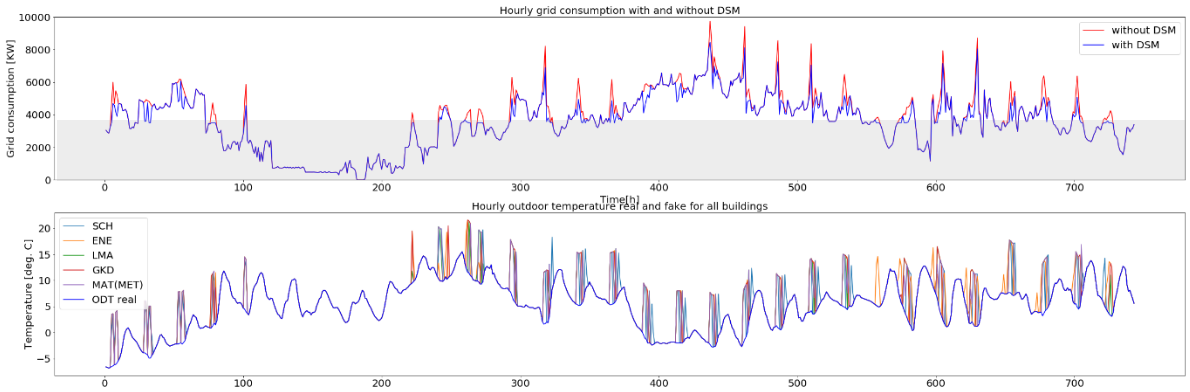

Figure 5: Hourly STORM controller operation for peak shaving through DSM for the month of March 2018

October

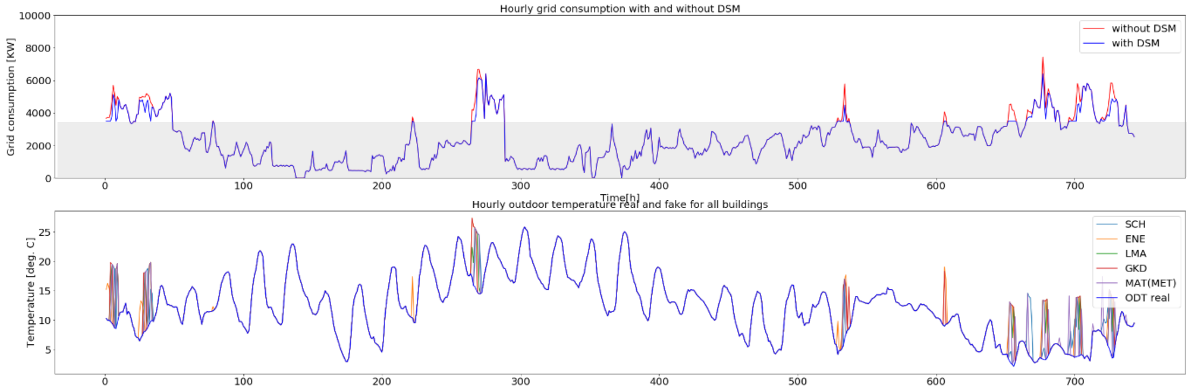

Figure 6: Hourly STORM controller operation for peak shaving through DSM for the month of October 2018

November

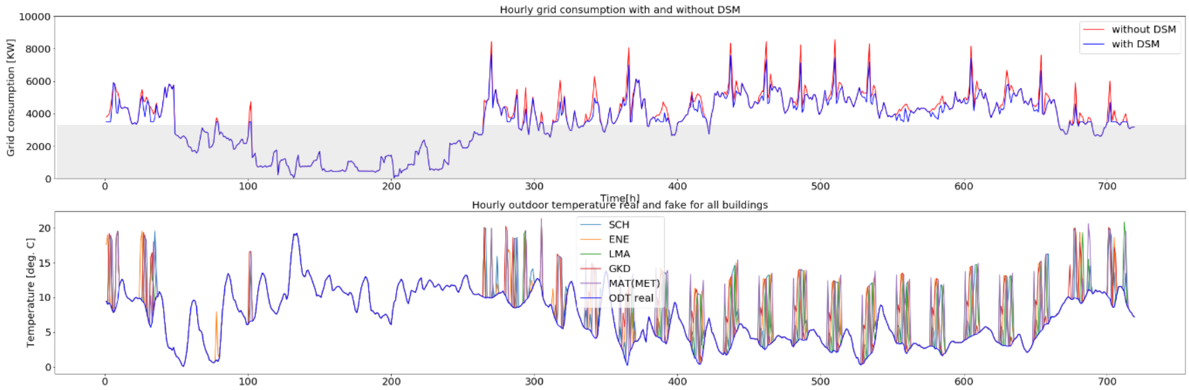

Figure 7: Hourly STORM controller operation for peak shaving through DSM for the month of November 2018

December

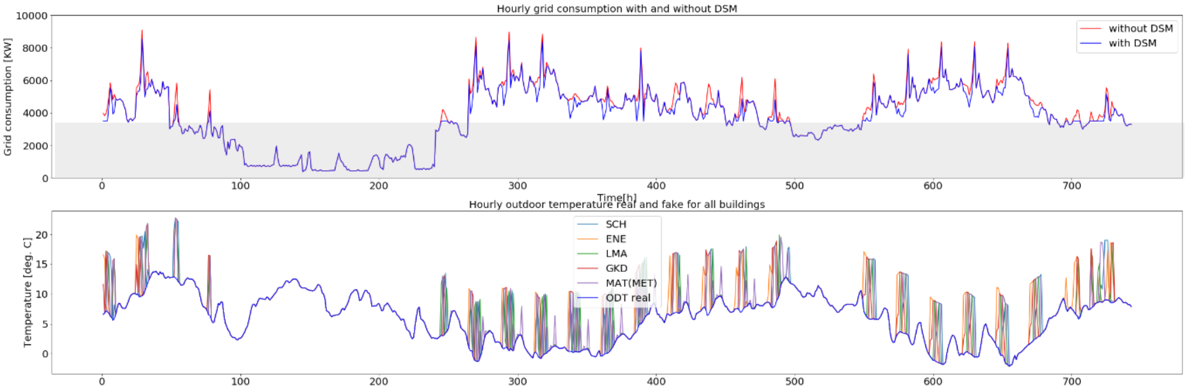

Figure 8: Hourly STORM controller operation for peak shaving through DSM for the month of December 2018

4.4.3 Flattening the load curve example

Figure 9 demonstrates the impact of DSM in case the control objective was changed to flattening the heat load curve. Such an objective could be useful for DH networks where a stable load profile is preferred to increase certainty. This increase in certainty can help operators plan dispatch better, avoid high ramp up/down rates thereby increasing the life of their infrastructure and saving large amounts of costs. In situations, where there is a lack of peak load units, this control objective may prove very useful. For example, a CHP with a heat led operation must sacrifice electricity production whenever the heat load increases, resulting in opportunity cost of reduced electricity sales, especially if these are not offset by heat sales.

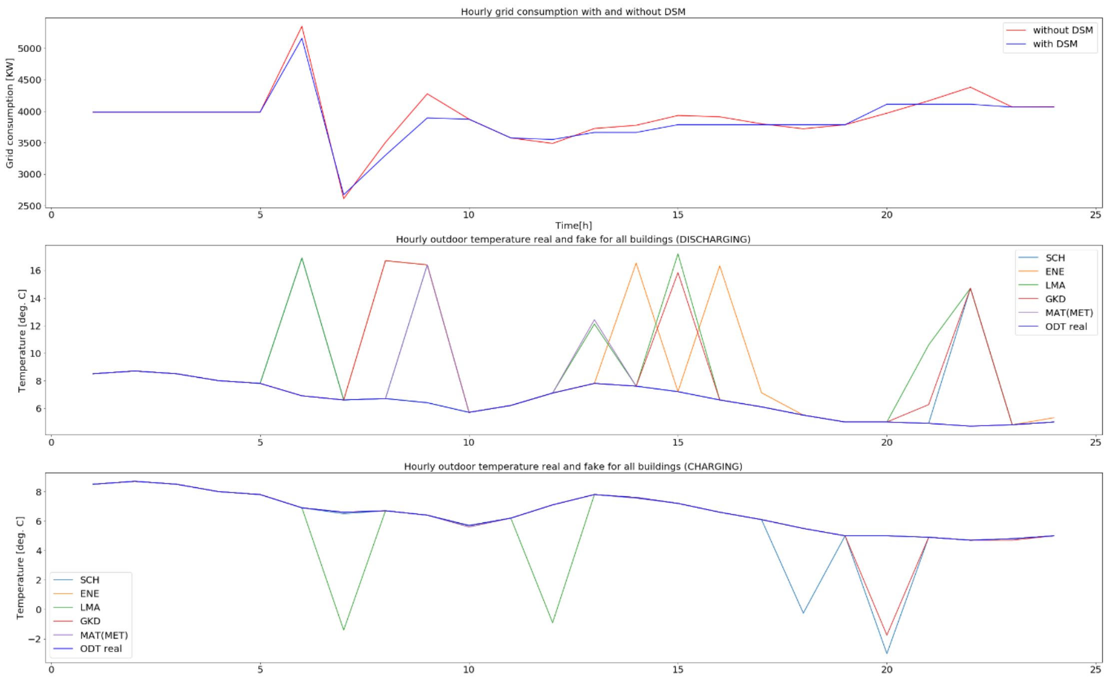

Figure 9: Hourly STORM controller operation for heat load curve flattening through DSM for a single day as an example

To demonstrate this control objective, the buildings were modeled as a storage and included both charging and discharging functions. It is observed that the heat load curve with DSM (blue) is flatter as compared to the curve without DSM (red). However, it is no completely flat as expected. This is due to limitations in available thermal flexibility and constraints that limit controller operation to protect indoor thermal comfort for the building occupants.

It can also be seen that during the 7th hour, a charging control action is sent to decrease the depth of the trough of the heat load curve. This thermal energy stored in the buildings' thermal mass is then discharged during the subsequent peak at the 9th hour to lower the heat load curve. The net effect of this charging and subsequent discharging operation is relative flattening of the heat load curve. Similar charging and subsequent discharging actions are observed during the rest of the day as well.

4.4.4 Annual flexibility and cost savings potential

The annual flexibility potential is reported in MWh of natural gas consumption reduced and the associated cost savings potential is calculated by assuming the price of natural gas at *30 EUR/MWh* based on latest available data for Belgium from December 2020[4]. This price could vary for country to country based on local tax situation, local distribution costs, market fluctuations, and specific contractual environment of the network operator for procurement of natural gas. It is advised that this price be adjusted to get reliable cost savings estimates. The table below shows the month wise total flexibility and cost savings potential for this case study. Note: 1) the simulation model is only executed for winter months as the STORM controller is not operated outside of the winter period. 2) A 95% efficiency for the peak gas unit is assumed to calculate gas consumption from reduction in heat load.

Month (year 2018)	Thermal Flexibility (Gas consumption reduction in MWh)	Cost savings (EUR)		Marginal cost of peak production for 1 MWh delivered =	30	EUR/MWh
Jan	116.3	3488.7				
Feb	114.4	3433.2				
Mar	121.7	3650.7				
Oct	39.6	1189.2				
Nov	107.9	3238.2				
Dec	108.8	3263.1				
Total	608.8	18263.1				

Table 3: Monthly overview of potential thermal flexibility (MWh) in the Balmatt DH network activated by DSM and respective cost savings (EUR)

[4] https://www.globalpetrolprices.com/Belgium/natural_gas_prices/

The total annual thermal flexibility potential for the Balmatt DH network is 610 MWh equivalent to 18kEUR savings in natural gas consumption.

4.5 Conclusion

This report presents an evaluation of the potential of innovative and efficient demand side management (DSM) for the Balmatt district heating (DH) network located in Mol, Belgium. The concept of the STORM controller, which is an innovative and proven technology co-developed by VITO for DSM in DH networks, is used as the underlying basis for this evaluation. The Balmatt site consists of forty-two buildings connected to a 3rd generation DH network, which uses geothermal energy to serve the base load and natural gas for the peak load. Out of all the buildings, only the five largest consumers are responsible for a massive 50% of the total energy consumption. This makes these buildings ideally suited for DSM.

The STORM controller concept is simplified and reduced to create a simulation model for this evaluation study. The model uses constrained mathematical optimization which implements peak shaving control objective. An example of another control objective, flattening the heat load curve is also demonstrated to emphasize that the same DSM means can be used towards different ends.

The results indicate that the total annual flexibility potential in terms of natural gas consumption savings is 610MWh, which translates to a 18kEUR savings in operational costs.

PROJECT PARTNERS

PROJECT SUP-PARTNERS

MORE INFORMATION

Dr Martin Salamon (Project Manager)

Martin.Salamon@gd.nrw.de

+49 2151 897 230

www.nweurope.eu/DGE-Rollout

@DGE–ROLLOUT

SUPPORTED BY

europiZe UG

Dr Daniel Zerweck

+49 176 6251 5841

www.europize.eu