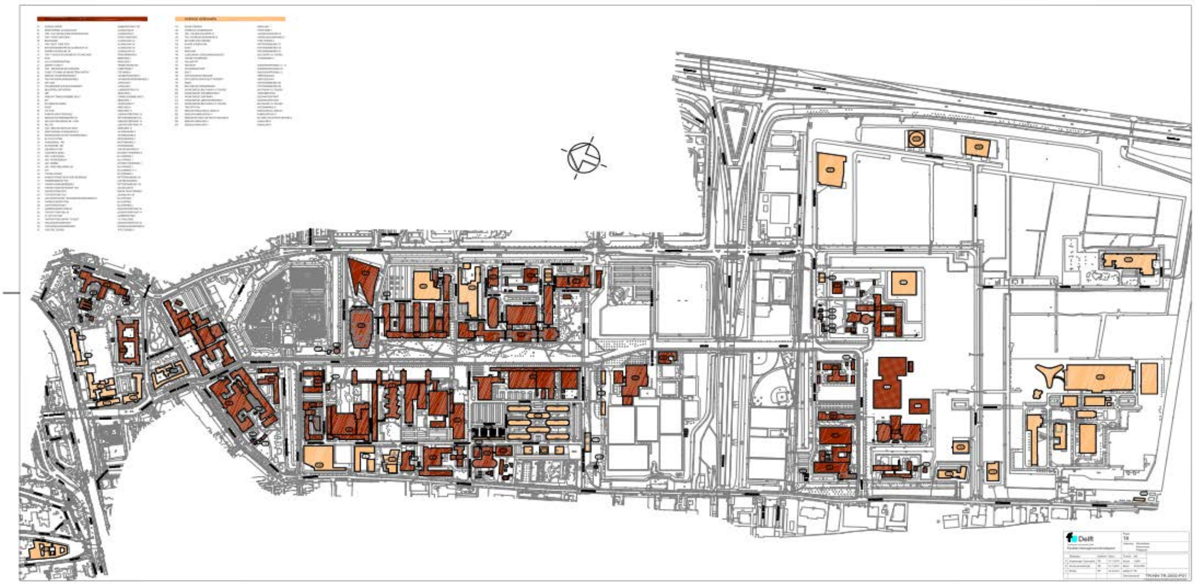
Energy Flexible Buildings, Case study: TU Delft campus, The Netherlands



A technical report from IEA EBC Annex 67 Energy Flexible Buildings

Energy Flexible Buildings, Case study: TU Delft campus, The Netherlands

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Preface

According to the IEA EBC Annex 67, for the effective management of future energy grids, there will be a need for 'Energy Flexible Buildings'; buildings that are able to manage their demand and generation according to local climate conditions, user needs and grid requirements. It is expected that Energy Flexible Buildings will aid demand side management/load control and thereby demand response based on the requirements of the surrounding grids.

The aim of the Annex is to increase knowledge on the Energy Flexibility buildings can provide for the energy grids and to produce insight into how much Energy Flexibility different building types and their operations may be able to offer to the future energy systems, and to identify critical aspects and possible solutions to manage this Energy Flexibility. Particularly there is a need to investigate the user barriers and motivations associated with the introduction of Energy Flexibility.

In-depth knowledge from demonstrations aiming for Energy Flexibility may provide important insights about the future development of energy systems and, related to that, the need for Energy Flexible Buildings that are able to respond to changing grid requirements. In this context, there is a need to understand better how stakeholders perceive the needs for Energy Flexibility and how the concept of Energy Flexibility can effect energy saving strategies and innovation decisions. This report describes practical experiences from the deployment of Energy Flexibility strategies during the implementation of a smart district heating network, using the TU Delft campus development project in the Netherlands as a case study example.

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Summary

In-depth knowledge from demonstrations is needed for the future development of facility management, related to the introduction of energy-saving devices, buildings and energy systems. Particularly there is a need to understand better how the concept of Energy Flexibility can effect energy saving strategies and innovation decisions. Using a district heating network installation as a case study (TU Delft university campus in the Netherlands), this research investigates the opportunities and barriers that stakeholders encounter.

To save energy and to deploy renewable energy systems, the Technical University of Delft is looking for ways to lower the heat supply temperature in the local (heat) grid on its campus. This implies that the connected individual buildings on the campus will need to be able to manage their energy demand more effectively, taking into account the new grid requirements, as well as the local climate conditions and user needs for indoor comfort, while delivered network supply temperatures for heating are lowered.

This innovation adoption study first analyses the motivations of stakeholders to change grid requirements at the TU Delft campus and the opportunities and barriers they encounter for introducing energy flexibility in the campus buildings, due to these changing grid requirements. The transition from a high to a medium supply temperature has far-reaching consequences on the facility management of the buildings and the redevelopment of the heat grid.

Secondly, this study looks at the main results from comfort simulations and real-life experiments to transform the heating network with a smart control system, with the aim to provide relevant information on encountered opportunities and barriers regarding facility management.

Thirdly, the study discusses the encountered portfolio management opportunities and barriers from the viewpoint of innovation adoption.

The research concludes that the introduction of a smart heat network can be successfully tested on an estate of buildings with one estate operator. The smart control system can lower the heat network supply temperature in an individual heat network branch, which can support the implementation of renewable energy systems. However, this requires a time shift in the energy use of individual buildings and technical modifications of hardware, devices, buildings and systems.

The visibility of energy flexibility still needs to be improved and research results show an urgency to lower complexity for facility management. The lack of interoperability of building management, control and data transfer systems is an important practical barrier for facility management. Limited suitable business models, the lack of framing of energy flexibility for sustainable portfolio management, and legal barriers can further hinder adoption of energy flexibility.

Contents

List of Figures

1. Introduction

Portfolio managers, facility managers and energy providers are becoming increasingly engaged in achieving energy savings by improving the energy performance and energy management of districts, buildings and energy networks. Smart thermal grids can play an important role in the future “smart” districts and cities by ensuring a reliable and affordable heating and cooling supply to various buildings through low-carbon and renewable energy carriers such as waste heat, waste-to-energy, solar thermal, biomass and geothermal energy (European Commission, 2013). Connected to smart grids, buildings can becoming micro energy hubs consuming, producing, storing and supplying energy more flexibly than before.

To introduce energy flexibility in buildings connected to smart thermal grids it is important to engage with and motivate interested stakeholders and end-users. The end-user acceptance and behaviour resulting from grid changes may interact directly with the energy provision to individual buildings and thus influence the need for additional control systems to maintain the regular activities, comfort and health of occupants. User acceptance of energy flexibility has rarely been researched. Most of the studies on building energy flexibility focus on measurements, modelling, and simulation (Jensen et al., 2017; Li et al., 2017). Occupancy evaluation research based on smart grid demonstration projects has focused on the use of smart grid technologies (Li et al., 2017) and current social studies are limited to understanding the perception of end-users, such as homeowners (for example: Dam, 2013; Li et al., 2017) and office workers (ongoing IEA EBC Annex 67 activity). There is however a need to better understand the implications for other users, such as facility managers, who will potentially play a pivotal role in the delivery of energy flexible services.

Campus development can also be an agent in urban transformation, and researchers such as Magdaniel (2016) emphasize the need to include different stakeholders in campus development. The introduction of energy flexibility requires learning and establishment of agreements between facility managers and other stakeholders. In-depth knowledge from demonstrations is needed to understand the future development of the innovative concept of energy flexibility and its possible implications for management in the built environment, related to the adoption of energy-saving devices, buildings and energy systems. The aim of the study is to better understand which opportunities and barriers are associated with the concept of energy flexibility and how energy saving strategies and decisions influence the adoption of energy flexibility.

As energy flexibility is perceived as a new concept by facility managers, it can be discussed from the viewpoint of adoption of innovation. This research uses the theoretical framework of adoption of innovation, which was introduced already during the 60’ies and which has been applied on hundreds of adoption problems (Rogers, 2003), including the adoption of energy-saving and environmental technologies, concepts and demonstration buildings (Mlecnik, 2008).

The aim of this research is to better understand experiences from a real-world case study, assuming that this is likely to unravel important contextual conditions for the adoption of energy flexibility. Methodologically, the research, therefore, uses a case study approach (Yin, 2014), using the energy management experiences from a university campus in the Netherlands as an example of a building portfolio in a specific district in Western European climate conditions (see Figure 1).

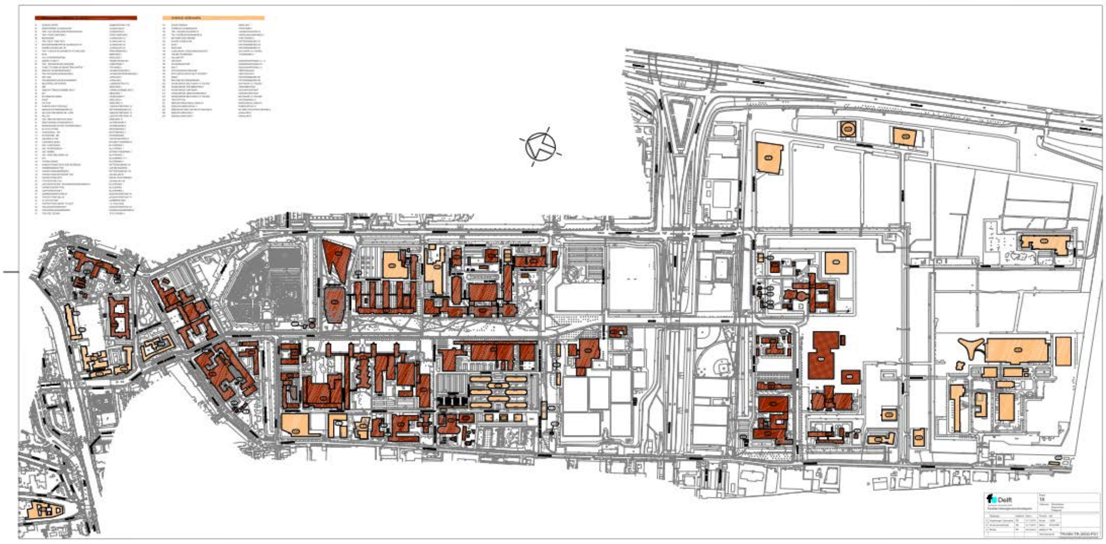

Figure 1. Site plan of the TU Delft campus

In section 2, the research begins by investigating the typical motivations of facility managers and perceptions of campus stakeholders, to define the need for grid changes and to explore the consequences on management in the built environment, related to the adoption of energy flexibility as an innovation. There is a wide range of methods that can be used for stakeholder analysis (Reed et al., 2009). For the ease of securing interviews, in this case study a snow-ball sampling method was used: initial campus stakeholders are interviewed, identifying new contacts. On the one hand, this has the disadvantage that the sample might be somewhat biased, on the other hand it leads to securing input by individuals who are interested in the subject. Adoption issues of TU Delft campus stakeholders were explored, starting from the Facility Management department, and following subsequent leads to influencing campus stakeholders, such as collaborating scientists from the Delft Energy Initiative (DEI), stakeholders from an innovative campus development (The Green Village), and professionals engaged in the development of energy saving devices, systems, buildings and grids. This approach resulted in interviews on energy flexibility (23 interviewees), and document analysis (dedicated meetings and written correspondence) to understand innovation adoption decisions.

In section 3 thereafter experiences are collected from testing and implementing grid changes. A previous project (Imtech et al., 2011; Deerns, 2015) engaged with various stakeholders to develop a smart control system for the district heat network on campus. This resulted in numerous technically detailed simulation reports and measurements, that indicate possible changes for devices, buildings and grids. This section analyses and distils the available information and consequences for management in the built environment.

In the last two sections 4 and 5, the experiences, interviews and document analysis are readdressed in the context of innovation adoption theory and conclusions are presented that have implications for facility management in the built environment.

2. Energy management experiences on a campus

2.1. Towards a strategy for portfolio energy management

The TU Delft campus can be considered as a small village with its own production of heat and heat distribution using a high temperature water grid with supply temperatures of about 100 to 130 °C. The gross floor area of the buildings linked to the network varies from 3.072 to 46.860 m^2. The installed power (TSA) varies from 407 to 13.410 kW. Every building's use of electricity, gas and heat is metered using an energy monitoring system (TU Delft, 2017) that provides an online report of monthly and annual energy use. Figure 2 presents an example chart of the annual energy consumption for various campus buildings in 2017. It shows a comparison and substantial differences between the energy consumption of the various buildings per square meter of floor space (gross). These differences are mainly due to the age of buildings and/or their level of maintenance, but also due to the building functions. Some laboratories or IT-departments (data centers) for instance can be (very) high consumers of electricity.

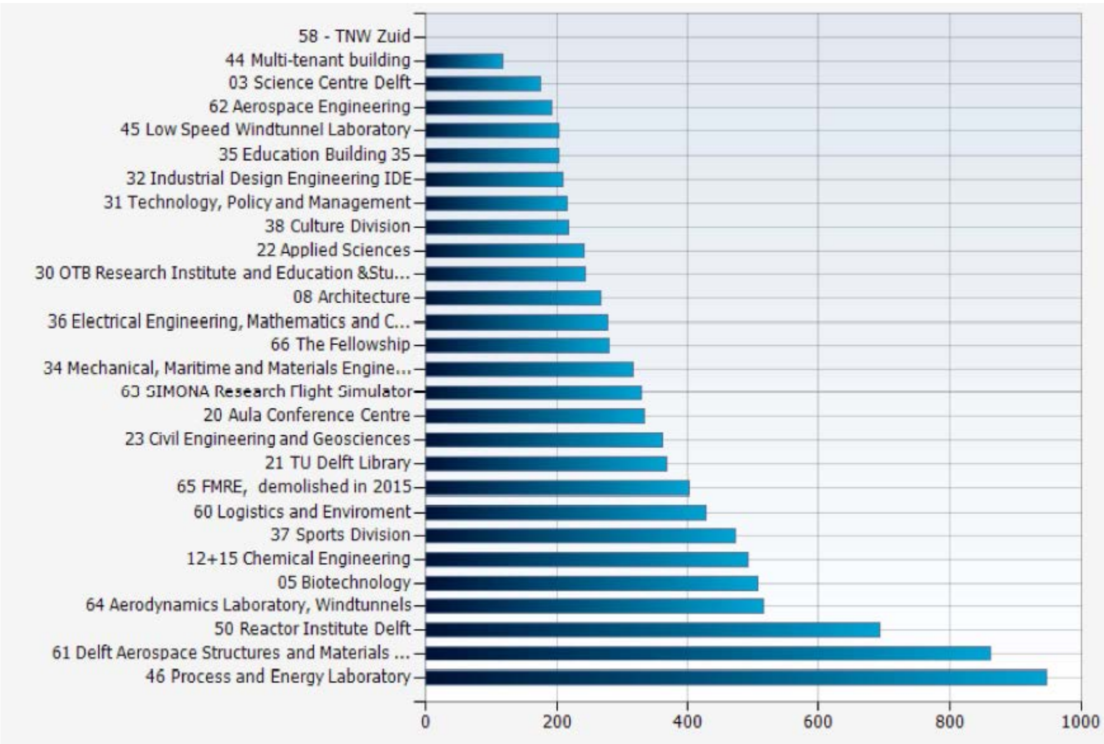

Figure 2. Primary energy use in 2016 of TU Delft campus buildings connected to the energy monitoring system (in kWh/m^2/year). Source: TU Delft Energy Monitor 01/08/2017.

Hellinga (2014) remarks that currently only the larger buildings have a programmable building management system that allows for climate control and detailed information about the destination of the energy streams. This information cannot centrally be requested and is mostly at a spatial resolution (building wings, spaces and rooms for example) instead of specific end-use or systems (lighting, cooling, ICT, and so on). The detailed monitoring is still not disaggregated enough for determining priority energy saving measures and for determining who can influence what on the level of energy flexibility.

The facility management department (Hellinga, 2014) drafted a comprehensive strategy document regarding energy saving on campus, which is not common practice for campus portfolio managers. The strategy document outlines the needs for achieving overall energy saving targets, for including energy saving in regular maintenance, for energy renovation and rejection of buildings with a poor performance, and for a transition of the energy grid to include more renewable energy sources.

2.2. Portfolio energy targets

According to Hellinga (2014), the campus uses about 117 million kWh energy per year, most of which is electricity (47%), heat (39%) and gas mainly used for heating in older buildings (14%). In 2012, the average heating demand for a campus building was 90 kWh/m^2 per year and the average primary energy demand was 400 kWh/m^2 per year (Hellinga, 2014). One third of the annual primary energy demand (211 million kWh/ year) goes to heating, and two thirds to electricity. In 2012 the campuses' primary energy use was 1458 MJ/m^2/year = 405 kWh/m^2/year, which is substantially higher than other Dutch campuses which average 937 MJ/m^2/year (Agentschap.NL, 2012), mainly due to a relatively large number of high energy-consuming research facilities such as a reactor institute, wind tunnels, two data centres, a process & energy lab, a high tension lab, a micro manufacturing lab. The number of students is also increasing each year since 2005, which results in a growing number of energy users and longer opening hours of buildings.

The TU Delft campus is thus urged to save energy. Hellinga (2014) proposed to reduce campus CO_2 emissions with 50% by 2020, aiming to stop using natural gas for heating purposes by 2030 and CO_2 neutrality for the campus electricity use by 2035. This goal follows earlier agreements signed by TU Delft, such as the multi-annual agreement 3 (a covenant engaging 14 Dutch universities) to reduce primary energy use per square meter of floor surface by 30% compared to 2005, and the TU Delft internal agreement for sustainable generation of 25% of the existing energy demand by 2020.

2.3. Previous energy saving actions

Hellinga (2014) argues that since 2005, energy was saved on campus using planned maintenance actions, such as the setting of control systems, the replacement of lighting and ventilators, and so on. The largest energy saving interventions to date were found in the replacement of the cogeneration plant, the intervention in active cooling of data centres and combining various measures in one department (Hellinga, 2014). By 2020, all lighting and ICT equipment will be replaced by energy saving options (Hellinga, 2014). Also, it is the intention to revise control systems especially for controlling energy use outside of office hours.

Although the campus consists of buildings mainly designed to support academia, the various campus buildings have very different characteristics, which makes it difficult to develop maintenance plans that are applicable for all buildings. The energy using functions of each department or building can be very different. For example, the buildings with the highest monitored energy use might need a higher energy supply for experimental setups or might include outdoor facilities connected to its energy meters. This makes the approaches for interpreting energy saving measures for each building also very specific. Also, in light of the changing campus needs, for each building it has to be considered if energy saving measures need to be taken or if deep renovation, demolishment or sale is preferred.

More recent data show again a trend of increasing campus energy demand, despite an increase in electricity production onsite and regular energy saving and maintenance initiatives (see Figure 3).

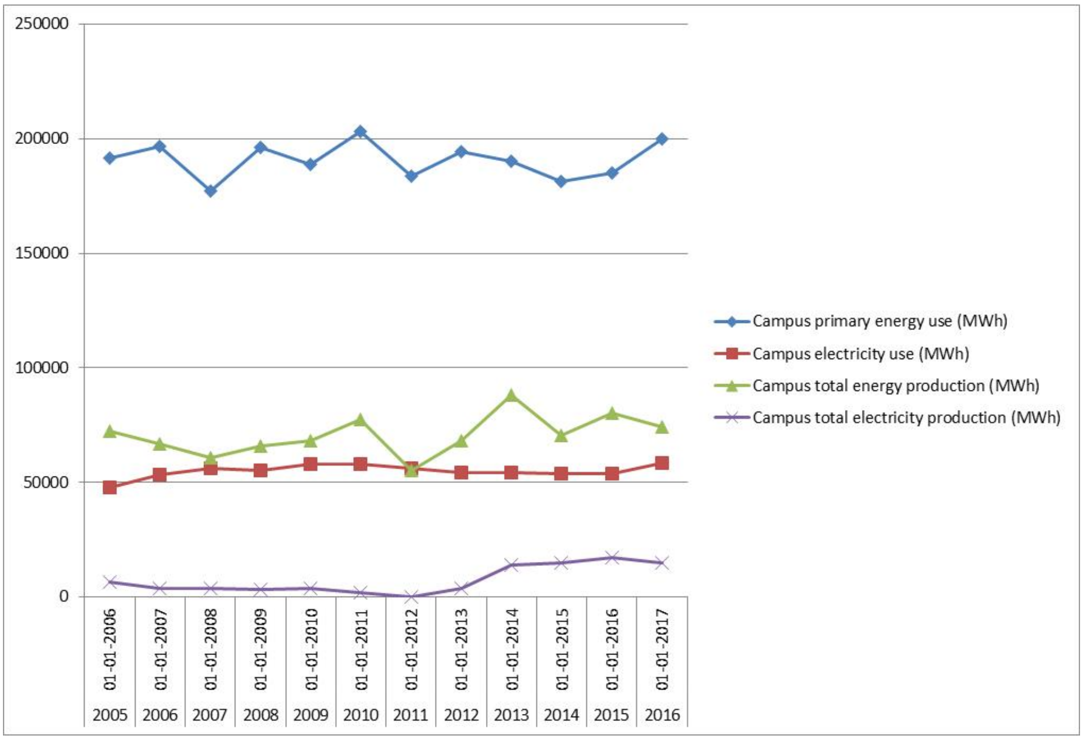

Figure 3. Evolution of the total primary energy and electricity use of the campus TU Delft and the total energy and electricity production in the years 2005-2016 (in MWh/year). Source: TU Delft Energy Monitor 01/08/2017.

2.4. Deep renovation and replacement of buildings

The lack of realised energy savings due to regular maintenance means that the university campus has to look towards deeper interventions in buildings and grids. Facility management strategies now also consider the regular deep renovation of university buildings and/ or the replacement of existing real estate, knowing that new campus buildings might be more energy-efficient. A set point to determine renovation strategies is to reduce electricity use by 25%.

Next to general campus concerns, the building energy data (see Figure 2) are also used as arguments to determine which buildings have a priority for energy saving measures, renovation or demolition. For example, the buildings with the highest energy demand not related to special research energy needs (buildings 5, 12+15 and 23 in Figure 2) will be rejected in the near future (Hellinga, 2014). Until 2020, seven older buildings will be rejected with a total gross floor area of 78.000 m^2 (TU Delft, 2013), which, when compared to 2012 figures, will lead to avoiding 33.800 MWh primary energy use (Hellinga, 2014).

It is estimated that real estate deep renovation and replacement of buildings on the TU Delft campus can save 17% primary energy use by 2020, reaching about half of the needed campus target (Hellinga, 2014).

2.5. Transition of the energy grids and sources

As it is not feasible to have all buildings deeply renovated or replaced by 2020, the TU Delft is looking towards a transition of the heat grid and energy sources to reach its goals. The TU Delft already invested in a new cogeneration plant. Hellinga (2014) argues that part of the campus real estate strategy is to continue increasing the use of sustainable heat sources without setting extreme requirements for the thermal insulation of buildings.

To facilitate the introduction of sustainable heat sources such as heat and cold storage in aquifers, the current heat grid needs to work on lower supply temperatures. Facility management explored the transition of the heat grid to medium supply temperatures of 70 to 80 °C instead of low supply temperatures. Their main arguments were to avoid high investment in long-term measures such as thermal insulation of buildings and to optimally use available deep geothermal energy and aquifers for heat storage (Hellinga, 2014).

To support the business development of the deep geothermal heat source exploitation, TU Delft contractually agreed to take 70.000 GJ (19.400 MWh) geothermal energy in 2020 (Hellinga, 2014). It is expected that this way 20% of the energy demand from campus buildings can be covered by using geothermal energy.

By 2020, TU Delft also wants to cover 5% of the energy demand from buildings using other renewable energy systems. This can for example be realized by implementing 5 MWp (MegaWatt peak) solar PV power or by installing 3 MW wind power generation (Hellinga, 2014). Restrictions on available roof surfaces and sites will probably lead to a combination of both systems. Also, the heat and power production can be optimized to help meet the 5% target.

2.6. Stakeholder concerns

Campus users can include different stakeholders such as end-users (staff and students), building owners (TU Delft facility managers and real estate spin-offs), but also specific researchers (for example energy technology labs, experimental buildings and chemistry departments) with a specific need for energy use and building, energy system or HVAC control.

Next to these users, also HR officers, project developers, installers, architects, engineers, consultants, energy suppliers and others regularly intervene or consult on building use and development. Stakeholders involved in the TU Delft heat grid/ energy smart campus development also include more than 20 TU Delft researchers, the Direction Facility Management and Real Estate (FMVG), the Delft Energy Initiative (DEI), Green Village and more than 70 participating companies.

A heritage of large old buildings, a shortage of modern buildings and (changing) needs for study places are a constant concern for campus stakeholders (Heijer et al., 2016). With the development of new buildings there is also a strong interest to include experiments, innovation and sustainability at a higher scale. This is for example observed in the reuse of the “Prêt-à-Loger” demonstration building (Dobbelsteen et al., 2015), the co-creation of the Delft Green Village (Wijk & Spanjer, 2015) and the Residential Living Lab, and the construction of the new Pulse Learning Center (Ector Hoogstad Architecten, 2015). In all these projects there is a stronger involvement of additional stakeholders such as industrial partners and researchers, which makes the portfolio management processes somewhat more complex. These projects also show a push for the implementation of deep renovation and nearly zero-energy buildings; Direct Current electricity networks; sustainable energy sources such as heat and cold storage in aquifers and PV electricity generation; energy storage in batteries, vehicles and building mass; and to promote internet-of-things control systems.

A sustainability lighthouse project for the TU Delft campus is the development of the Green Village as an inspiring environment for professionals, researchers and students to develop sustainable energy innovations. Initiated with the moving of the TU Delft Solar Decathlon project ”Prêt-à-Loger” – a demonstration energy renovation of a typical Dutch terraced house - from the contest location to the campus, the surrounding areas are developed to host living labs, including offices, services and residences. The innovations to be implemented are also beyond the energy scope, including for example robotics, cars as power plants, new water, lighting and communication systems (Wijk, 2013). Key for the area development is the availability of a direct current source (solar PV park) which is meant to be used for feeding DC grids without conversion to AC. By avoiding AC/DC conversion, energy and material can be saved, with electricity savings of about 10 to 20% (Hellinga, 2014). The Green Village has the advantage that it is developed as a zone for experimentation with less restrictions regarding urban development.

In the other part of the campus, some new campus projects include ambitious energy and sustainable goals. For example, the new construction of the PULSE learning centre was designed to include, amongst other features, seasonal energy storage in thermal mass (Ector Hoogstad Architecten, 2015). A building from Hogeschool InHolland is situated on campus grounds and provides information about opportunities to include thermal storage in building mass. This building’s operators are also experimenting with adaption of the building information system for maintenance purposes.

There are still many opportunities to explore the transition to using decentralized heat grids and geothermal energy. Supply stations and distribution networks need to be adapted to support various temperatures and the supply and demand sides need to develop trade agreements (Waerdt & Buitenhuis, 2013). There might be potential for using phase change materials (Vliet, 2013) or other methods of thermal storage to increase the thermal buffer capacity in the current network. Also, there are various electricity storage methods that could be utilized.

Some ongoing experiments include off-grid solutions, for example, the mobile Delft Experience Tomorrow pavilion was developed by TU Delft and students and includes battery storage. Such experiments can provide added value, particularly as temporary events such as festivals on the campus might also cause power peaks that otherwise would have to be covered by generators.

Research projects on the TU Delft campus also explore new business opportunities such as façade leasing for renovation, electricity storage systems (batteries, hydrogen-based, and so on), electricity producing windows in buildings (PV, algae, and so on) and digital manufacturing (for example solar shading).

Spin-offs from the TU Delft also provide new opportunities such as using server heat for heating buildings, or specialized real estate management software for condition analysis of buildings.

Some interviewees stated that, although business development and research projects provide important insights, innovation lessons are not systematically addressed in campus facility management. Some stakeholders expressed specific concerns to better include lessons from surrounding buildings and (their) research projects.

Stakeholders also expressed the specific need to look beyond the current campus stakeholders for developing portfolio strategies. Facility managers are urged to work together with cities, energy providers and industry players to establish a better dialogue between public and private sectors. Innovative developments require a special relationship with policy stakeholders such as the city of Delft, and energy suppliers. For example, the Green Village could only develop in an experimental zone where not necessarily all building regulations apply. The city of Delft is also looking for a wider partnership for a Green Deal for actions in surrounding areas, for example for implementing neighbourhoods without natural gas supply. Energy providers comment that the development of the exploitation of a geothermal energy source only becomes financially interesting when a larger area beyond the campus can be serviced with the heat network.

2.7. View on energy flexible buildings

The previous sections show that campus stakeholders' view on energy flexible building is much wider in the framework of facility management. Decision perspectives go far beyond control, comfort and health concerns of individual buildings. Real estate energy development strategies include optimization of maintenance and out roll of energy saving measures, renovating and replacing buildings, building innovative new buildings and transition of energy sources and grids. Beyond the pure "energy" perspective there is also a need to include other sustainable innovation scopes simultaneously.

Energy flexible buildings' energy demand and generation is determined according to local climate conditions, user needs and grid requirements. The grid requirement in the TU Delft campus case – the transition of a heat grid to medium supply temperatures - is that buildings by means of building technical measures should allow to deliver water with a lower temperature back to the heat grid. Also, to avoid extra investment, all buildings on the same heat network branch should fulfil the same requirement.

It could be argued that the transition of the heat grid from high to low temperature is more problematic than converting from a high to medium supply. In practice TU Delft could have opted to run a low-temperature grid at supply temperatures of around 45°C, as demonstrated in Norway (Clauss, 2015). Various researchers (for example: Connolly et al., 2014; Lund et al., 2014) emphasize that present district heating systems already undergo a radical change into low-temperature district heating networks interacting with low-energy buildings as well as becoming an integrated part of smart energy systems. Next generation heat networks are also expected to find more synergies with the electricity sector as well as the transport sector (Jiang et al., 2014; Lund, 2014). However, this was not further explored in this case study and the TU Delft decided to lower the supply temperature to a medium temperature.

The impact of possible changes in the local district heat grid was previously explored by a research consortium, that aimed to investigate the opportunity for implementing an intelligent district heat network on the campus TU Delft (Imtech et al., 2011; Deerns, 2015). Specifically, they focused on optimal control of future heat grids using a deep geothermal heat source, using both simulations and real-life experiments. This work was carried out thanks to a subsidy in the framework of the Dutch IPIN programme (Agentschap.NL, 2013; RVO, 2017), as one of 12 research projects that investigated the impact of intelligent grids.

The next chapter explores in more detail how the heat grid development influences the (needed) energy flexibility of buildings.

3. Experiences with implementing energy flexibility on campus

In 2012 the project “Intelligent heat network Campus TU Delft” was started (Imtech et al., 2011; Agentschap.NL, 2013; TU Delft, 2016), as part of the Dutch Innovation Programme for Intelligent Networks (IPIN) programme hosted by the Netherlands Enterprise Agency (formerly Agentschap.NL).

This project aimed to investigate the opportunity for implementing an intelligent district heat network on the campus TU Delft, particularly looking at optimal control of future heat grids using a deep geothermal heat source. The challenge was to guarantee a comfortable indoor climate in buildings for various heat demand conditions, while making sure that the return temperature of the water leaving the buildings is as low as possible.

To enable this control requirement, a model predictive control (MPC) system was developed, coupled to simulation packages. In 2014 a detailed dynamic model was constructed to simulate the building energy demand, the energy supply and the heat transport (transmission losses) for the TU Delft heat network, to determine needed temperature levels, pressures and flows. A number of campus buildings served to determine the needed energy flexibility, particularly to calibrate the model and future control systems.

Without going into too much technical detail, the following sections describe some of the main approaches and findings, based on the final project report (Stoelinga et al., 2016).

3.1. Characteristics of the district heat network

The studied campus TU Delft district heat network consists of thermal energy generation (84 MW) – 3 heating plants (15, 30, 35 MW) and 2 cogeneration plants (2 x 2000 kW thermal) - 4 main distribution branches, and 101 heat exchangers (91,500 kW). The layout of the network is shown in Figure 4.

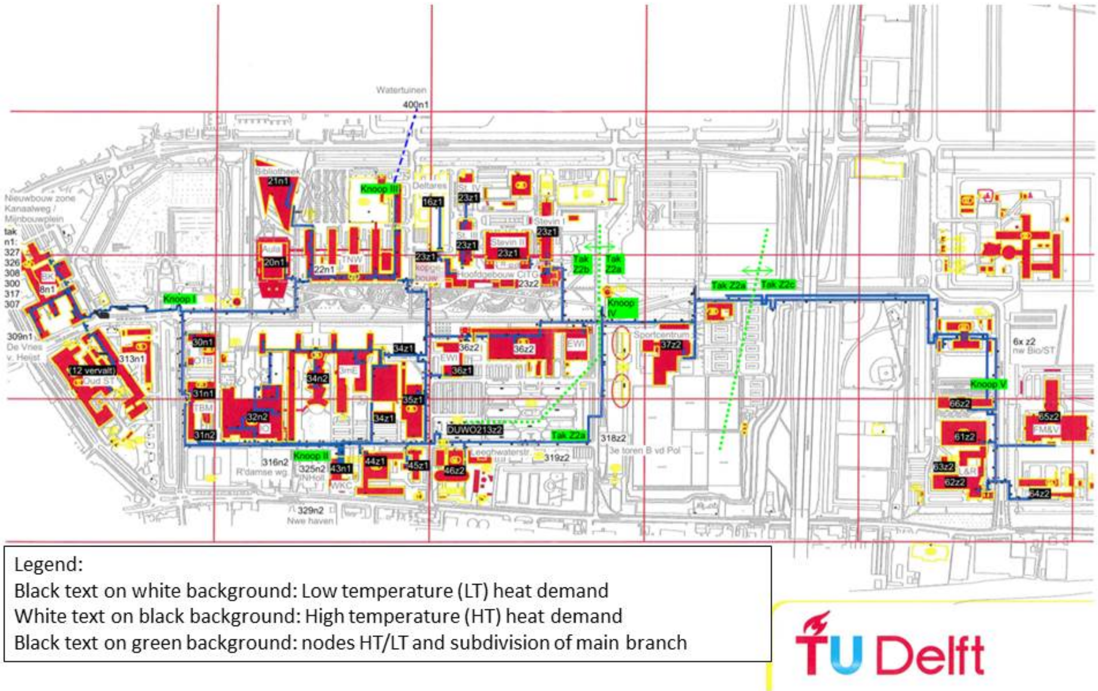

Figure 4. TU Delft campus district heat network. Source: TU Delft/ Deerns, 2015.

3.2. Expected transition of the district heat network

The transition of the district heat network from high to medium temperature and the addition of sustainable heating sources are important challenges at TU Delft aimed at creating a more sustainable campus. There is a need to reduce the demand for natural gas and the CO_2-emission without compromising the comfort of the building occupants.

The transition from a gas-fired heat network to a hybrid network is one of the measures and will help to achieve the sustainability goals of the TU Delft. On the other hand, investment from an external partner is needed to develop the 3 MW ground heat source that should supply water at 75 °C from 2 km depth. The TU Delft would pay this partner an equivalent amount of money for heat comparing with gas prices. The development of the heat source becomes more profitable for this partner when third-party grids outside of the campus stock can be connected.

Facility managers propose that, when compared to low supply temperatures, medium supply temperatures can be arranged on a large part of the campus within two years (Hellinga, 2014). The combined heat and power station will be modified so that a different water temperature can be sent down four different pipelines. TU Delft expects to reduce its gas consumption 10 to 15% in this way (TU Delft, 2016).

During this transition, the buildings as well as the combined heat and power station will be readied for the change from heating at the high temperature of 130 degrees to a medium temperature of 80 degrees, without concessions regarding thermal comfort. This will enable sustainable energy sources such as geothermal energy, that operate at lower temperatures, to be connected to the heat network. Heat storage in underground sand layers may also help to stabilize currently fluctuating heat supply (Hartog et al., 2015). A lower supply temperature also enables a larger share of energy efficient cogeneration units for heating, and facilitates the introduction of sustainable sources. Adding biomass-fuelled power generation could be an additional way of reducing the use of natural gas.

The renovated smart district heating grid is expected to optimally attune heat supply and balance demand. Alongside modifying the combined heat and power station, and the buildings, a supervisory control system is developed with commercial partners that is linked to the building management systems and to the power station's software. Five-day weather forecasts, updated every hour, will be used in conjunction with building models to predict the expected heat demand. Heat supply to the buildings is expected to be minimized this way, without loss of comfort.

The main control strategies are to:

- Reduce excessive flow (check the required ΔT)
- Reduce supply temperature
- Control the supply temperature per building cluster
- Apply cascade circuits in heat connectors

The supply temperature of a district heat network is determined by the building with the highest temperature requirement. Therefore, it makes sense to cluster buildings with a similar temperature requirement in different branches of the network that can be controlled individually. The highest demand of a building per pipeline will then determine the temperature for just that pipeline, not for the heat network as a whole.

Also, major repairs and renovations are expected to have an immediate, positive effect on heating costs and campus sustainability. The supply temperature can further be reduced if critical buildings per pipeline are improved. Per building, the most effective measures have to be selected, that have an immediate, positive effect on the supply temperature. This reduces the average supply and return temperatures of the network.

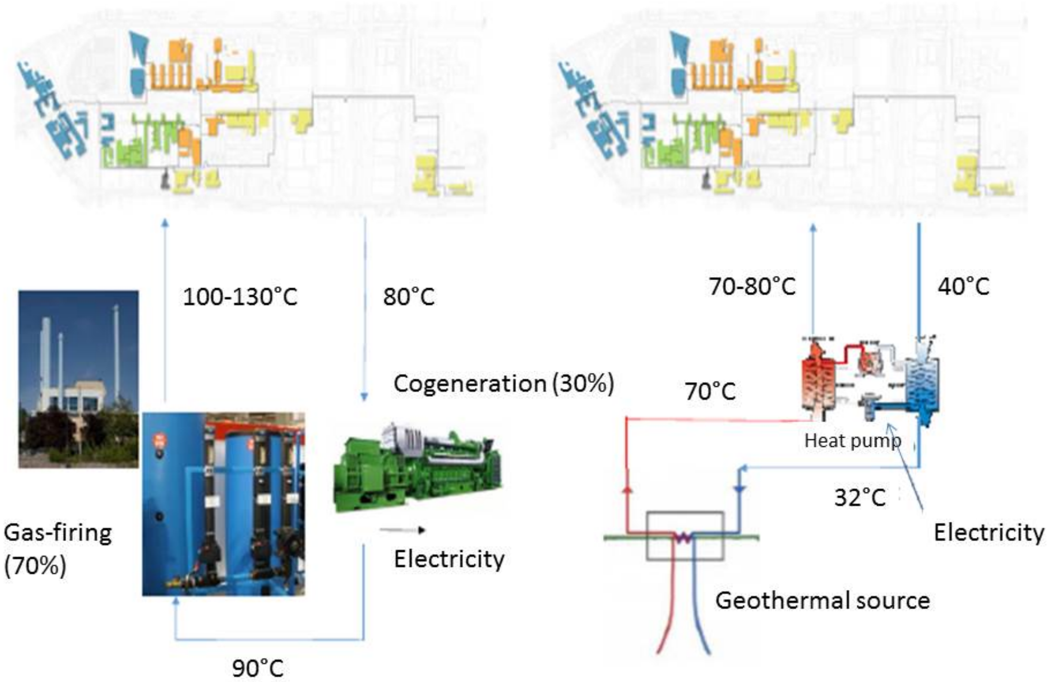

Figure 5. Expected changes in the TU Delft campus district heat network: from high (left figure) to medium supply temperature (right figure). Source: P. Stoelinga, Deerns.

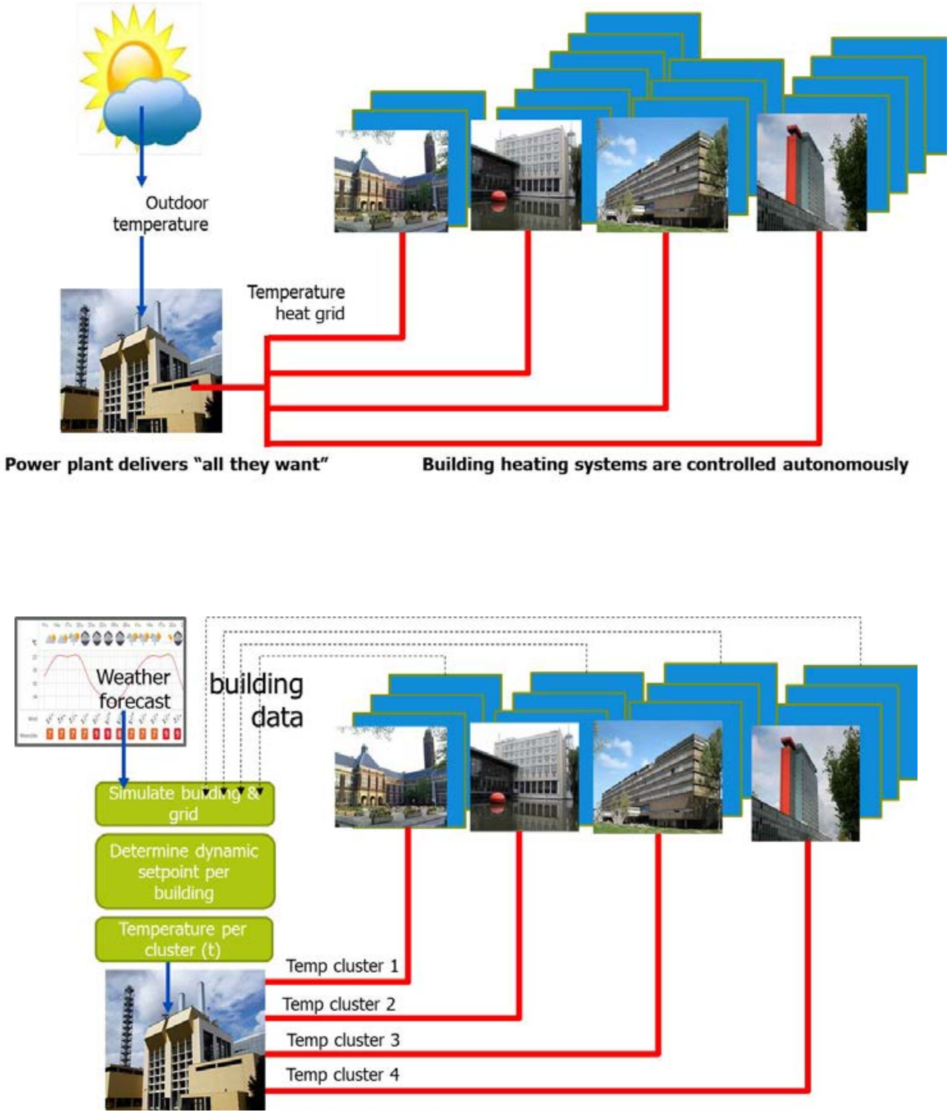

Figure 6. Expected changes in the TU Delft campus district heat network: branching and control strategies (above: existing situation; below: future situation). Source: TU Delft/ Deerns, 2015.

3.3. Experiences from simulation studies

The potential for lowering the temperature in the heat network without compromising thermal comfort in buildings was investigated using various scenario studies and building simulations. Thermal comfort was evaluated using the Fanger method as expressed in the Dutch standard NEN-EN-ISO 7730 (2005), using predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) values to evaluate thermal comfort. For the simulations, a reference climate year was used according to the Dutch standard NEN 5060 (2008). Two simulation packages were combined, LEA (Low Energy Architecture) which minimizes the supply temperature and Wanda, which simulates hydraulic and thermal transients in pipeline systems.

3.3.1 Model for Predictive Control

The building simulations were carried out in the software Low Energy Architecture (LEA), developed by Deerns, which estimates the hourly energy need for building related heating, cooling, air-conditioning, lighting, ventilation and equipment.

This model assumes that all spaces in one building have the same function and indoor climate: the model is as such highly simplified but allows to deal with a large amount of buildings at the same time. LEA also requires certain input information that might be unavailable or difficult to interpret, such as building characteristics parameters, internal heat gains (occupancy, lighting and equipment) and operating conditions, which can vary in real situations.

For estimating these uncertain parameters, a validation was done for each of the buildings with measured consumption data. Building characteristics were collected and models were calibrated by using available daily, weekly and seasonal metering data.

With the purpose of reducing the needed expert work, the possibility of using simple and fast mathematical models was studied, obtained from a heating demand database. In contrast to law-driven physical models, which are based on the analysis of physical processes such as heat transfer, the proposed prediction model is data-driven. More details about the prediction model can be found in the project report (Stoelinga et al., 2016).

The simulations of the heat grid were done in the package Wanda, developed by Deltares. This software simulates the hydraulics of heat networks, taking into account pumps and supply stations. Both simulation tools were adapted so that they could exchange data for performing an integrated annual simulation. As LEA delivers the heat demand per building and supply and return temperatures, Wanda determines the return temperature and the thermal demand at the heat generator.

The LEA model had to be adapted to fit the purpose and to introduce an optimisation cycle that expresses the need to minimize the supply temperatures for the district heat network without compromising thermal comfort. Instead of the traditional hourly heating power demand as an output, the output now concerns room temperature that allow to determine heating set points. Also, the required comfort level is expressed as an input parameter. The model also needs to include information on whether radiators and heating coils in air-handling units are available or needed for activation (in relation to Wanda output).

The changes in the model are expressed in the following Figure 7. The LEA optimisation cycle is illustrated in Figure 8. First the comfort level is determined with high supply temperature and maximum available power. The same calculation is done with medium supply temperature and the comfort difference is calculated. Furthermore it can be determined if the heating of the building should start earlier, resulting in an estimate of the increase of the supply temperature taking into account the weather prediction. The cycle is then repeated to determine the comfort levels reached when using the medium supply temperature range.

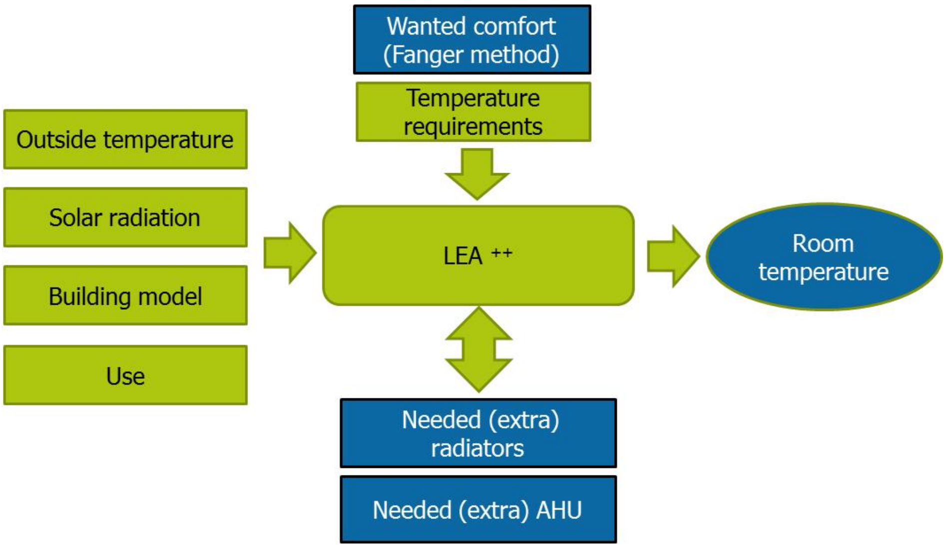

Figure 7. Changes (indicated in blue) made in the LEA building simulation software. Source: Deerns, 2015.

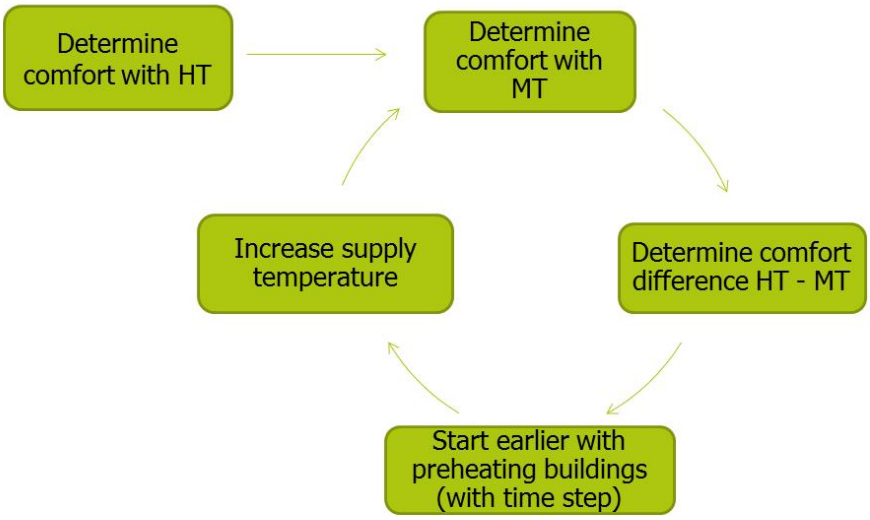

Figure 8. Illustration of the applied LEA optimisation cycle. Source: Deerns, 2015.

The overall MPC system strategy combining the LEA/ Wanda models uses control simulations that are carried out each hour using the following steps. First, the control system defines its input by reading the actual space temperatures in each building from the building management systems and the weather prediction for the next 24 hours from a meteorology service. Second, LEA performs a building simulation for each building during a period of 6 previous hours plus 24 hours, to evaluate if peaks can be avoided by starting a building heating cycle earlier, taking into account the heat storage in the building mass. The simulated needed supply temperatures for the buildings' central heating system for the next hour are then forwarded to the district heat grid control system and relevant data (heating demand, needed supply and return temperature of the building central heating system, required supply temperature of the district heating grid) are transferred from LEA to Wanda. Wanda then uses this information to generate hourly set points for the district heating control (needed supply and return temperature at the production unit, flow in the heat grid).

3.3.2 Simulation results

The simulation research examined various scenarios. The scenario analyses led to the conclusion that a dynamic heat grid control system is required. This control system needs to determine the set points, the data communication and the control of the heat production unit and central heating systems of the buildings.

The simulation results show that conventional building control strategies, based on a simple linear relationship between supply temperature of the district heat grid and outdoor temperature, do not offer the opportunity to lower the supply temperatures without a loss of thermal comfort. The needed building supply temperature is only partially related to outdoor temperature; this is more obvious for heating coils in air handling units that require direct air heating.

Simulations also confirmed that, for buildings with a central water-based heating system, starting earlier with heating the building can lead to maximising the number of hours that a heat grid branch supply temperature is equal to or below 103 °C. Whether the heating needs to start earlier depends on the daily need for peak shaving. A lower return temperature at the CHP units, also allows for an increase, in the optimal scenario of 20%, in the number of full-load hours. An extensive review of the simulation results can be found in the project reports (Deerns, 2015; Stoelinga et al., 2016).

Simulations for a standard climate year show that the supply temperature for the buildings can be reduced, but that some modifications are needed to the building envelopes and systems, particularly regarding control and data management.

3.4. Experiences from practical testing of the prototype model

3.4.1 Challenges during implementation

The implementation of the dynamic control system required some technical changes, such as the integration of servers, the placement of district heat grid controllers at each station, communication equipment for the data coupling between the simulation environment and the control of the heat production, the heat grid and the buildings' heating systems.

The data coupling and the robustness of LEA had to be tested for use in a control environment and a practical test was done in spring 2016 on one building (Faculty of Industrial Design), without coupling to Wanda and grid control systems. The data coupling between the heat grid control and the LEA simulation environment and building control systems could be implemented after solving some minor technical problems and doing initial reference checks. The data storage was regularly interrupted due to installation updates. LEA also appeared not to take into account the holidays, thus predicting an unnecessary heating demand.

The implementation also showed that a variety of data sources from different manufacturers needs to be connected, such as those from simulation tools (LEA, Wanda), various building management systems (Johnson Controls, Siemens, Honeywell), installation controllers (ABB in the heat production unit and, Priva for connecting to LEA and Wanda), meters (GMC in buildings), campus energy monitoring system (Erbis) and meteorology data (meteorology service). This proved to be quite a challenge.

3.4.2 Metering results from one building

As already found from software validation, the cumulative energy demand calculated by LEA appeared to be somewhat lower than the measured values. The hourly heating demand by LEA follows a peak demand in the morning and a smaller peak in the afternoon; while the measured energy demand shows a more constant profile, with a lower decrease in the afternoon. There were incidental peaks in heating demand which could not be explained.

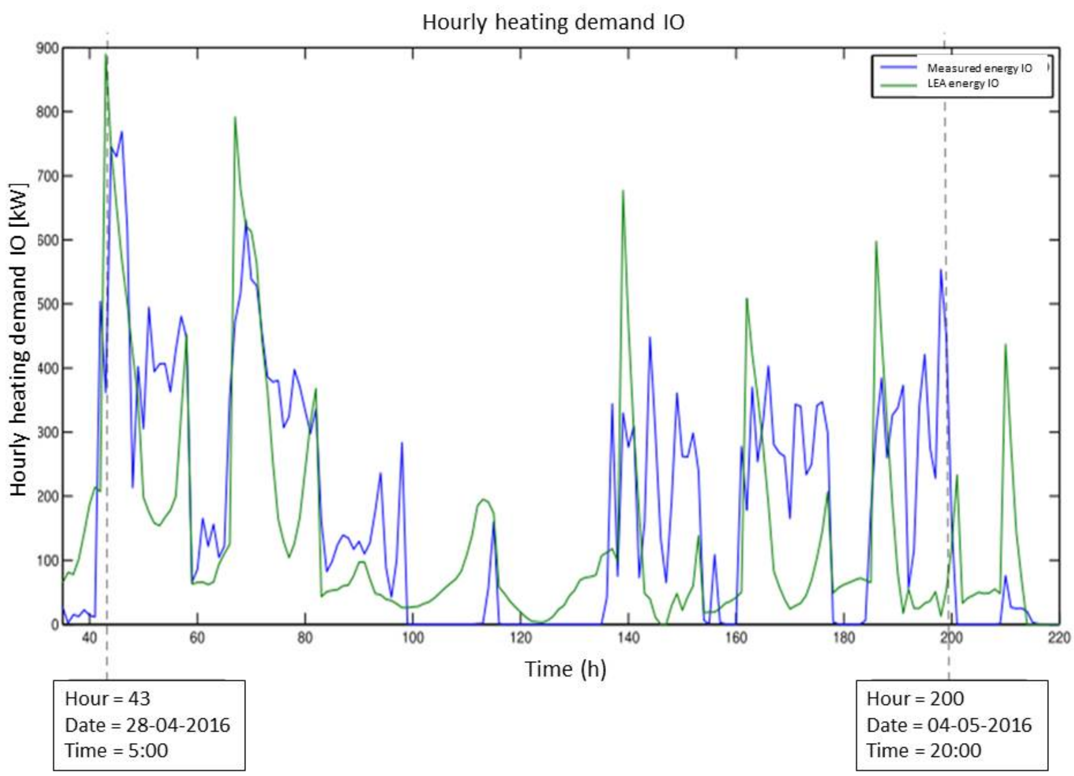

Figure 9. Predicted hourly heat demand resulting from LEA (green) compared to measured heat flows (blue) in the Faculty of Industrial Design (Spring 2016). Source: Stoelinga et al., 2016.

Besides the energy demand during the day, also cumulative energy demand was calculated per week and per season. During the reference period, LEA calculate a weekly cumulative energy demand that is somewhat lower than the measured values. In spring and autumn LEA calculates a seasonal energy demand that is somewhat lower than the measured values, in winter the calculated value is higher than the measured value.

There were no comfort complaints during the testing period, but the outdoor temperatures were also relatively high.

3.4.3 Testing the prototype model on a branch of the district heat network

The modification required to couple the heat production unit was done from March 2015 to May 2016. An operational prototype of the control system was implemented in one branch of the district heat network covering three buildings (11 heat delivery stations). This is shown in the following Figure 10. A public dashboard was created on https://ipin-tudelft.erbis.nl/.

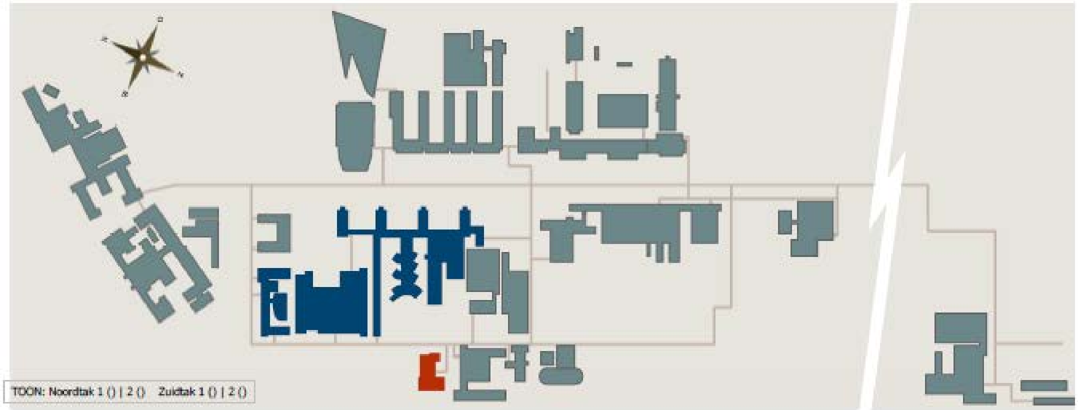

Figure 10. Tested branch and buildings of the TU Delft campus. Source: https://ipin-tudelft.erbis.nl/.

The LEA/ Wanda Model Predictive Control (MPC) system began operation in September 2016 and was validated during the winter period. The technical feasibility of the implementation was successfully demonstrated, but the simulation models appeared to be insufficiently stable for control operations, mainly because of server problems (restarts, updates) and crash situations from corrupt input data. Some heating units also received a central heating temperature input that was too low, due to oversimplification of the LEA model or wrong estimation of the heating power of heating coils and radiators or the factor between primary and secondary supply temperature.

Measurements during one week in October show that the heating demand data delivered by LEA are lower than measured values. This might be caused by the fact that the indoor temperature predictions by LEA are below the measured values, which results in a higher than required indoor temperatures increase. There is a limited match between the Wanda results and measured values.

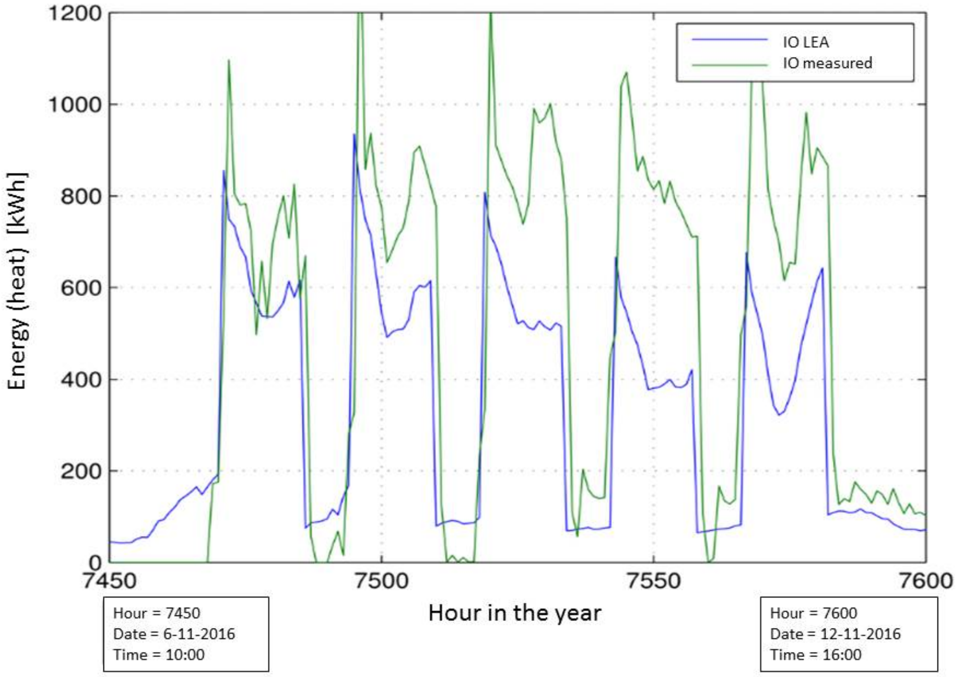

Figure 11. Predicted heating demand resulting from LEA (blue) compared to measured heat flow (green) in the Faculty of Industrial Design (IO) (November 2016). Source: Stoelinga et al., 2016.

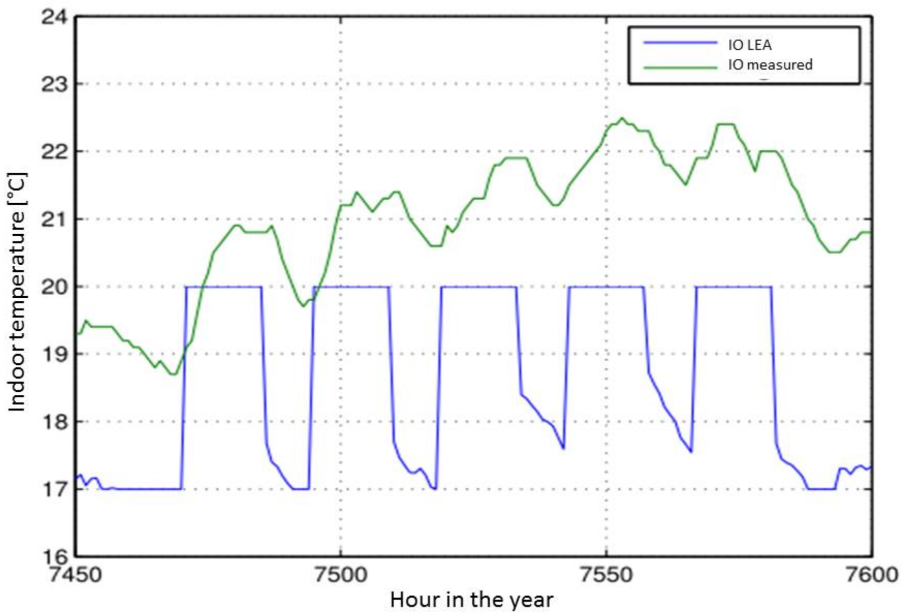

Figure 12. Predicted indoor temperatures resulting from LEA (blue) compared to measured indoor temperatures (green) in the Faculty of Industrial Design (November 2016). Source: Stoelinga et al., 2016.

On the other hand, the testing showed that the supply temperature from the heat grid can be effectively lowered using the LEA/Wanda predictive control model. Figure 13 shows the measured return temperatures in the heat network branch North 2 (blue), compared with the supply and return temperatures in heat network branches South 1 (green) and South 2 (purple). We can assume that cogeneration can be used at a return temperature equal to or below 83°C, and that geothermal heat can be used at a return temperature equal to or below 65°C. The graph shows that in February 2017 for the purpose of using these heart sources, sufficiently low return temperatures were measured due to the activation of LEA.

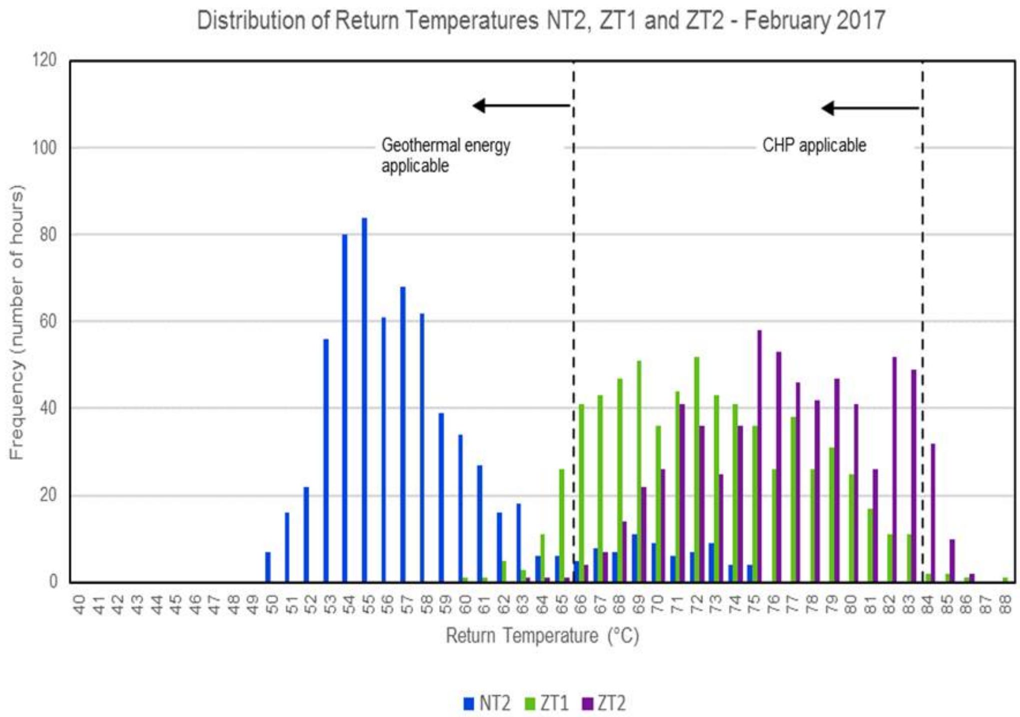

Figure 13. Frequency diagram of the measured supply and return temperatures for three heat network branches, using a LEA set point activation period (February 2017). Source: Stoelinga et al., 2017.

4. Challenges for introducing energy flexibility

4.1. Lessons from the case study

This section summarizes findings from the case study interviews and document analysis related to the opportunities and barriers encountered by portfolio managers, from the viewpoint of innovation adoption. From innovation literature (Rogers, 2003) it is known that adoption of an innovation can be advanced by increasing testability, relative advantage, compatibility, visibility, and by decreasing complexity.

The case study shows that energy flexibility of buildings was not a direct concern for portfolio managers. In this case, the estate manager was mainly concerned with a more efficient use of renewable heat sources to reduce CO_2 emissions and primary energy use. This thought provoked the effort to investigate if the supply temperature of the heat grid can be sufficiently lowered to support renewable heat sources. The possible consequences for buildings and their services were initially taken for granted. Now the simulations show that some buildings might have to start earlier with their heating regime to compensate for the lower supply temperature, thus introducing a need for energy flexible buildings.

The case study shows that it is possible to test the reduction of the supply temperature of heat delivered to buildings by means of an intelligent district heating network, without comfort complaints, although it is important to note that measurements were taken outside of the coldest periods. The technical implementation of a prototype intelligent district heat network can be relatively fast, but the validation needs detailed monitoring and verification of metering results and models. Installers need to make sure that data transfers function properly and that control algorithms are realistic and checked in practice. It is recommended to alert dedicated managers 24 hours a day about possible control problems and to develop a user-friendly interface for visualising real time results of simulations and for (overriding) the setting of control parameters.

The advantage of using an MPC system is that it allows to significantly reduce the supply heat for buildings during a large number of hours. Real estate professionals see the benefit that in this way older buildings can be made suitable for low supply temperature with fast and relatively small investments. Although this might result in buildings having to start earlier with their heating regime, such a strategy allows for more efficient use of geothermal heat sources and cogeneration plants, reduction of primary energy use and CO_2 emissions, and overall financial and energy savings. An MPC system combining data from buildings, grids and weather also has the potential to deliver an image of the real energy use and profile of buildings, which can help determining if a building functions properly. If the supplied temperature is too low, the cause can be traced. This might for example be an air handling unit that needs to deliver process heat continuously, or a malfunctioning heat exchanger. Adapting the control systems in turn can lead to better comfort and energy saving.

It can be argued that the TU Delft campus case study would probably not have been realised or visible without subsidies covering the innovation risks. Existing real estate assemblies and networks usually do not allow an undisturbed space for testing as experiments can be hindered by daily facility management and building use. Errors can immediately lead to complaints. Practical experiments were double-blind, so the user was not informed about ongoing tests and changes in the building management.

Today's roll-out of energy flexibility is hindered by low compatibility due to the existence of different standards and programs for control systems, building management systems and data transfer. Also, there can be a lack of data about buildings and existing metering results. Additional interventions, such as the installation of flow controllers, servers, interfaces, sensors, back-up heating units, and so on, need to be foreseen, both in buildings (management and energy using systems) and networks (production units, controllers and branches). Emergency switches need to allow for taking over (manual) control.

From a management perspective, various issues regarding complexity were observed. The dynamic control of heat networks and energy use of buildings offers high potential for business development but requires integrated control of supply and demand. It appears to be mainly interesting in situations where supply and demand is controlled by one actor, such as is the case for campuses and large building complexes, such as hospitals. An important lesson is that one person needs to be in charge to determine the viability of proposed modifications, and that structured communication is needed with IT departments.

The planning of the transition of the heat network still has to be established and a connection has to be made with the planning of deep renovations and new buildings. When considering a long-term plan, Hellinga (2014) argues that the deep geothermal earth heat source can deliver a majority of the needed annual heat demand. The supporting installations such as the cogeneration plant will also probably need replacement by 2030. If the cogeneration is replaced by another production system, requested supply temperatures might be changed again. In the current setting, winter peaks regarding heat demand are still not sufficiently supported. To deal with such peaks more efforts will be needed, such as thermal insulation measures.

The development of the intelligent heat network is only one item that is expected to contribute to the overall energy savings. Despite the expected savings for heating, the 25% electricity savings target by 2020 still seems very ambitious, particularly when related to the increase of the campus density. There is still no clear view how the peak load of the campus energy buildings can be shaved, taking into account all ongoing developments (including deep geothermal energy, cogeneration, heat and cold storage in aquifers, innovative buildings, implementation of PV and wind parks and battery storage).

4.2. Lessons from other Dutch intelligent energy networks

The development of the smart district heating network on the TU Delft campus is only one of the 12 experiments, supported by the Dutch government in the framework of the IPIN programme (RVO, 2017), for implementing intelligent networks in the Netherlands. It is also a unique case as it is an educational complex, where grids and buildings are owned by the same actor. The other IPIN projects provide additional insights for innovation adoption of energy flexibility (RVO, 2015), also using various energy vectors and buildings from other sectors.

Most projects are positive about the technical feasibility for developing intelligent networks and energy flexibility. For example, the project Couperus also finds positive results for housing, by delaying the activation of heat pumps of houses 6 to 8 hours with an indoor comfort deviation of 0.8 °C.

However, there are some concerns about developing suitable business models for energy flexibility, particularly if the network and the buildings have different owners. Three projects (INZET, 2015; Heijplaat, 2015; Texel, 2015) found it difficult to establish a customer value for energy flexibility. The project Heijplaat (2015) had some difficulties to motivate (social housing) homeowners and suggested facilitating group trajectories. The project DeCent (2015) finds a business case for DC networks, but using greenhouse cultivation. The project Lochem (2015) was concerned about avoiding black outs of overcharged electricity networks and experimented with tariffs and demand side management. The project PMC2 (2015) notices that a market actor is needed to manage and distribute energy flexibility.

Also, legislation for facilitating energy flexibility can be improved. The project JEM (2015) advocates introducing variable tariffs. The project INZET (2015) recommends that the current legislation needs to be adapted to facilitate business models for energy flexibility. The project DeCent (2015) suggested a Green Deal for developing DC networks, so that initiatives from greenhouse cultivation can find contact with housing, solar PV parks and public lighting. The Project EVANDER (2015) finds that legislation is hindering the large-scale roll-out for combining sustainable energy and electrical transport. Also, Modienet (2015) experiences difficulties to connect office developments with wind parks.

Preparing for intelligent networks and energy flexibility is also socially no easy task. It means developing capabilities for an expected digital future in which facility managers appoint responsible persons, instruct people, embrace a digital culture and digital business roles, and structure their activities according to sustainability goals. When making real estate decisions, prioritizing cost issues over attracting and retaining talent can be a threat to innovation (Magdaniel, 2016).

These considerations show that the case campus TU Delft is quite unique and that in general, there is still a lot of work to do to develop business models and supporting legislation for introducing energy flexibility and smart networks. There is a strong need for innovation in business models and procurement related to the implementation of energy flexibility. The various projects can be lauded as they apply innovative solutions to large scale problems at a potential cost risk. However, there are still many barriers to go from innovation to early adoption of intelligent grids.

Most intelligent grid innovation projects started from a similar reasoning that changes in the grid can support energy saving and CO_2 reduction. However, changing grid conditions have direct consequences for the needed energy flexibility of buildings and service systems. These consequences are not always clearly demonstrated and the future role of the portfolio manager is not always clearly expressed. Therefore this report provided reflections on this matter for one case (TU Delft, 2015). A future study on portfolio management experiences - reflecting on multiple cases - might result in practical policy recommendations.

5. Conclusion

The research aimed to provide in-depth knowledge from a case study for the future development of facility management, related to the introduction of the concept of Energy Flexibility. The energy demand and generation of energy flexible buildings is determined according to local climate conditions, user needs and grid requirements. Changing grid requirements requires the adoption of innovations, such as smart control systems, which in turn can effect energy saving strategies. For example, control systems allow a better follow-up of energy saving and tuning of comfort.

The adoption of energy flexibility has to be compatible with the expected transition of energy sources and grids. From a management perspective, the effectiveness of energy flexibility strategies always has to be compared with other real estate energy development strategies, such as the optimization of maintenance and out roll of energy saving measures, renovation or rejection buildings, building new buildings and grid transitions. Comfort concerns of individual buildings are limitations for the adoption, which can be translated into a penalty function for optimizing control algorithms

The TU Delft campus case - the transition of a heat grid to medium supply temperatures - shows that by means of the implementation of building technical measures, energy management, data transfer and control systems, the supply temperature for the buildings can be lowered. To avoid extra investment, it is important that all buildings on the same heat network branch fulfil the same requirements. The transition from a high to a medium supply temperature thus has far reaching consequences on the (complexity of) facility management of the buildings and the redevelopment of the heat grid.

The introduction of a smart heat network can be successfully tested on an assembly of buildings with one building owner. A smart control system can lower the heat network supply temperature in an individual heat network branch, which can in turn support the implementation of renewable energy systems. However, this requires a time shift in the energy use of individual buildings and technical modifications to the building systems.

The testing and validation shows that a well-functioning MPC system can be implemented to lower the heat supply for buildings connected to a district heat network. Currently there are still some concerns regarding tuning and control, but the actors involved in the projects are positive that a control for the whole TU Delft grid can be implemented. However, this requires further integration and adaptation of building and heat grid models and the development of a more standardised platform for data exchange. Also, heat exchangers, air handling units, servers and building management systems have to be adapted to fit the implementation of energy flexibility. The visibility of the existing experiments and initiatives for intelligent grids still needs to be improved. The lack of compatibility of building management, control and data transfer systems is an important barrier for facility management.

Compared to deep renovation of buildings, the adoption of energy flexibility does provide an important economic and environmental opportunity to reduce energy use. But the adoption of energy flexibility is not merely an optimisation problem and a software issue, as changes are needed in hardware, devices, buildings and systems. Facility managers also will need to embrace innovative procurement, a digital culture and new business roles in the energy market. A lack of standardisation, (suitable customer values for) business models and legal barriers can further hinder the adoption of energy flexibility.

On the local level it is recommended to pursue a dialogue, beyond campus stakeholders, including public and private actors, to address these challenges. For the wider picture, a more detailed inventory and exchange of knowledge from national and international smart grid initiatives might provide further insights for innovation adoption.

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