Large-scale implementation of peak heating power optimization and demand-response in residential buildings connected to district heating systems

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Abstract

Digitalization is an important trend in the district energy (DE) sector. A key area of interest is the use of intelligent demand-side management technology for peak heating power reduction, and the minimization of district heating (DH) grid bottlenecks. Peak power optimization (PPO) using demand side management through predictive control, has been a significant research area for several years, but its full-scale implementation on large DH networks is not trivial. This paper documents the experience of implementing PPO on a population of 45 k apartments. Firstly, it outlines the challenges of optimizing the overall energy performance of an entire district-heating system with multiple energy carriers. Secondly, a description of the model predictive control (MPC) approach is given, listing the challenges presented by the trade-offs between i) the end-use energy performance of both building space and water heating systems, ii) the comfort of the occupants, and iii) the economic optimization at the network level through the profiling of heat generation. It is shown that, on average, peak power savings in the order of 20 % were achieved for connected buildings. This approach also leads to an increase in the utilization of low-carbon energy carriers by the DE utilities, thus achieving further CO_2 emission reductions. Potential market barriers for a larger-scale rollout of PPO technology are outlined. The paper concludes with suggestions on how energy and climate policies could improve the overall building/district-heating system performance, for a successful energy transition in the DE sector.

Introduction

Traditionally seen as a conservative industry, the DE sector has undergone significant transformations in recent years. In the Nordic countries, where DE forms a high proportion of the heat supply, this is in part explained by market forces. Many municipal DE companies have faced a stagnation problem due to the saturation of the growth in heat demand. This can be explained by the following factors: Firstly, considerable energy efficiency improvements have reduced space heating energy use in retrofitted existing and new buildings. Secondly, mature DE networks present few opportunities for expansion. Thirdly, the competition with individual building-level heat pumps has also been considerable. These factors have led DE utilities to restructure themselves and to change their value proposition for heat, by diversifying their offer for new services (monitoring, maintenance agreements) for customers. This customer pull in mature Nordic DE markets has driven companies to transform their relationship with their customers through the use of digital services. This trend has naturally coincided with the recent developments of the Internet of Things (IoT) and artificial intelligence technology, which provide a wealth of possibilities to offer value in terms of improved energy efficiency and consumer engagement. This has resulted in new opportunities with multiple potential benefits for a successful energy transition.

From an overall energy system perspective, digitalization is considered as a key enabler of cost-efficient decarbonization. The EU "Clean Energy Package" and the "2050 decarbonisation strategy" foresee increasing shares of DE, in some scenarios, up to about 50 % by 2050 in conjunction with increasing contributions from sustainable energy carriers, such as renewables and residual waste heat; the target set by the 2018 Directive on

Renewable Energy being an annual increase of 1.3 %. For the electricity system, interactive electricity demand-side management (DSM) is seen as a key enabler for the transition from a system dominated by firm generation capacities, to a system with a high amount of non-programmable capacities. For DE, interactive heat DSM will become a key enabler for the transition to sustainable energy carriers, and the coupling of heat and electricity sectors, e.g. by short and long-term thermal storage of electricity enabled by DE infrastructure. These trends will be facilitated by the so-called "4th generation district energy" (4GDE) systems which are highly efficient, run on low temperatures, and integrate a variety of renewable energy carriers and heat sources, such as biomass, waste-to-energy, geothermal heat, waste heat from industry, and heat pumps.

In 4GDE systems, the most sustainable available heat sources are used in exact balance with the heat demand and distributed efficiently. Thus, a core principle of 4GDE is system optimization across the entire value chain from sustainable energy carriers, efficient distribution grids, and optimal building operations. This is only possible with digital solutions that allow real-time management of heat demand and supply.

The "smart buildings" market targets, amongst other objectives, the optimized comfort and energy use within buildings; The interactive integration of buildings with DE infrastructure via interactive heat DSM has been one of the strongest areas of digital innovation in the DE sector. For DE utilities, a reduction in peak heating power represents significant savings (in the order of 200–1,000 kEuro), and heat demand side management initiatives have better payback periods than investments in peak power plants, and centralized heat storage (opportunity costs for the allocated space). For building owners, investment in digital control technologies also delivers quick paybacks in buildings with better-insulated envelopes.

Smart predictive controls and predictive maintenance based on IoT technology and artificial intelligence have become commercially available. These are two key factors which enable interactive heat DSM reducing peak heat demand, and hence are particularly relevant for a successful energy transition. We will consider their impact both from the end-user point of view, and from the utility point of view, as a good understanding of benefits and motivations of value-chain stakeholders is important for identifying success-factors for the further roll-out of digital technology, possible market barriers, and the shaping of suitable policies.

The subsequent parts of this paper are structured as follows: Firstly, an overview of the technology is given, with a focus on interactive heat DSM targeting peak heating power optimization. The paper will present the findings of Leanheat Oy, a Finnish cleantech company which has developed an IoT powered predictive control technology currently in operation in over 100,000 apartments in both EU and non-EU markets, (although the general principles presented in this paper are also valid for commercial solutions marketed by providers). Secondly, statistics and techno-economic key performance indicators will be presented and discussed. Finally, a discussion will be provided on the various business models and challenges for scaling up this technology in entire housing estates.

The concept and the technology in a nutshell

MODEL PREDICTIVE CONTROL

The core of Leanheat's technology for PPO is based on model predictive control. The predictive controller is based on a grey-box model which comprises both a physical description of a residential building and a substation (usually a 4-pipe system). The physical first principle model is postulated, and its parameters are (continuously) estimated from sensor data. Thus, the system can learn the specific thermodynamics of the building using a grey-box approach. Overlay charts illustrating model fit are displayed in Figure 1.

From these grey-box models, an optimization problem is formulated using a 48-hour horizon. The objective function of this optimization problem consists of a combination of key economic objectives i.e. energy reduction, power profiling, and depending on cases return temperature minimization (which is also factored in the price of heat for some DH networks).

The system is mainly actuated by modulating the substation's secondary side temperature (and circulation pump speeds depending on the use-cases). Traditionally, the secondary side temperature is modulated using feed-forward control consisting of a weather compensation curve assigning temperature levels based on current external temperatures. This is generally coupled with local actuation at apartment levels.

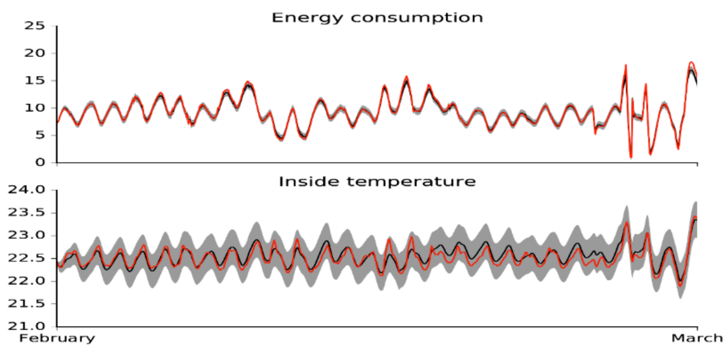

Figure 1. Overlay comparison of predicted and actual energy consumption and indoor temperatures with prediction confidence intervals (greyed areas).

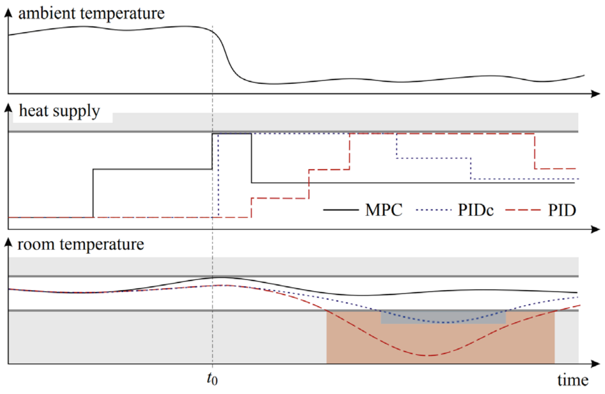

Figure 2. Illustrative comparison of MPC and reactive PID control.

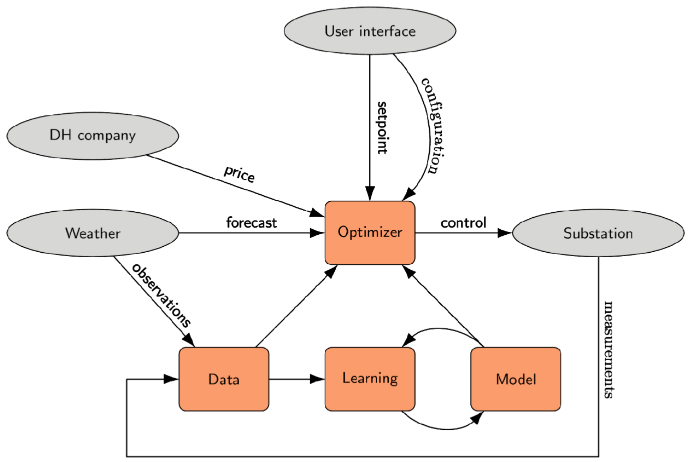

Figure 3. Schematic of the model predictive control framework.

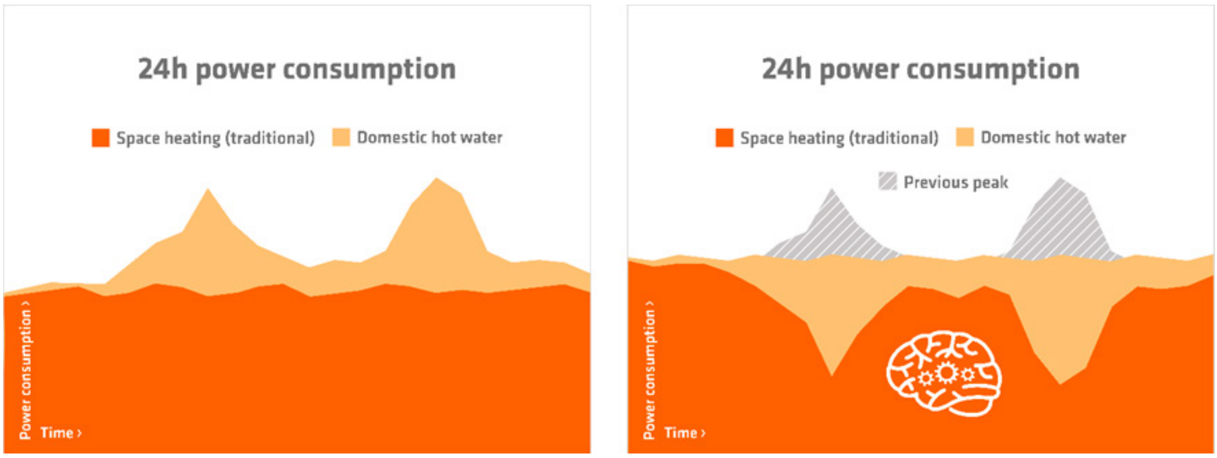

Figure 4. Traditional control vs Leanheat predictive control for peak power optimization.

More generally the model predictive control represents a compromise between the weighted set of economic objectives and the occupant comfort constraints usually consisting of indoor temperature setpoints defined by the building owners. It is well known that model predictive control outperforms reactive proportional controllers by minimizing overshoots and undershoots of state and measured variables (amongst other advantages, as illustrated in Figure 3). In the case of the control of a building connected to a DH network, the stabilization of indoor temperatures is associated with a reduction in heat demand and power (suppressing the peaks) and an increase in occupant comfort (removing troughs).

In terms of external signals, the system is fed with time series prediction from weather data services and, in the case of demand response, signals indicating the cost of the production of heat for the utility company (Figure 3).

Two types of demand-side management are considered in this article:

Local peak power optimization (PPO)

Local PPO consists of suppressing peaks to minimize the heating power cost for the consumer (building). This is achieved by combining substation meter data and using the predictive controller model to infer the space heating contribution and commensurately reducing it during peak times of domestic hot water (DHW) consumption (Figure 4). This entails preheating the building fabric ahead of this peak DHW consumption.

Demand response

Demand response proceeds differently from local PPO. It consists of modulating the heat demand based on price signals sent by the utility. The building will be controlled to consume more heat during low price periods and avoid consuming during high price periods. The purpose of the utility company is to reduce its heat production and distribution costs. At the production level, the interest of the utility companies lies in maximizing the utilization of baseload excess or renewable heat sources and avoiding using fossil fuels. From a transmission and distribution point of view, the utility company can send different signals to different areas of the network to decrease networks bottlenecks.

The two modes of optimization are potentially conflicting because requests by the utility company for the buildings to store heat during cheaper production cost periods can lead to local peaks in the heating power demand of the building. Therefore, special care needs to be taken to ensure the best trade-offs between these potentially conflicting objectives. In the absence of a rigorous way of quantifying the exact system-wide monetary benefits of demand response, heuristics are used. For example, in the municipality of Espoo where demand response services are provided from 15,000 apartments to utility company Fortum, local PPO is enforced as an objective when the external temperature is less than -10 °C. The rest of the time the controller is operated to provide demand response. In the long run, it will be beneficial for utility companies to allow local peaks to achieve system-wide benefit without penalizing their customers.

PHYSICAL IMPLEMENTATION

In terms of physical implementation, the system consists of

1. Integration with the current heating controller at the substation level
2. Sensors are installed in all or a subset (e.g. 25 %) of the flats

Communication is done using IoT data services such as Sigfox, Lora, GSM (depending on existing infrastructures or local prices) or using existing sensors already available in the building. Temperature and humidity sensors are placed in apartments. The choice of the number of apartments being fitted with sensors is an economic one. Whilst improving the overall accuracy of the control solution, installing sensors in each flat adds to the initial investment costs and may be impractical if access to individual apartments is restricted (by the tenants themselves or local regulations). The general objective is to be hardware and technology agnostic to make the solution scalable and to adapt to national and local supply chain ecosystems. Figures 5 and 6 illustrate the architecture of the Leanheat solution.

In terms of IT, the system is divided into a physical and an abstract layer. The abstract layer contains the predictive controller implementation. Practically, the solution is scalable and modular (containerized) to guarantee reliability even in the case of partial service downtime. Automatic vertical and horizontal scaling always ensure enough processing power. Dedicated servers are used for user interfaces and APIs are used to expose part of the system to the end-user for monitoring and predictive maintenance purposes (Figure 7). Whilst originally a by-product of the sensing capabilities of the solution, predictive maintenance is an increasingly popular feature for building owners (real estate companies, housing associations).

In the next section results of the implementation of Leanheat in over 2,500 buildings are presented and discussed.

Observed results: impacts on DE system and building efficiency

In this section, we present statistics of economic and technical key performance indicators using data collected from over 2,000 multi-dwelling residential buildings over a 2-year period. Typical dynamic behavior is first described qualitatively followed by an examination of energy and peak power reduction across a population of buildings. Other relevant considerations such as primary return temperatures of the substation and interactions with local thermostats are also discussed.

The results must be understood in the context of the "Nordic" heat tariff model. In general, this tariff model supports the market take-up of interactive heat DSM. For other tariff models, involving individual metering and billing of heat, split-incentive market barriers are expected. This is further discussed in sections "market barriers" and "conclusions".

THE ROLE OF END-USER HEAT TARIFFS: THE NORDIC MODEL

In this paper, we consider both PPO from the end-user point of view and from the utility point of view. In Nordic countries, the price of district heat is composed of both an energy and a capacity component. The peak capacity component is calculated based on the highest heating power peaks in the last 12 months. The consumer thus has an incentive to reduce his higher peak which occurs during the coldest period of the heating season. Although there is generally no incentive, from the customer point of view, to reduce the daily average peaks (other than broadly reducing energy consumption), PPO is valuable from

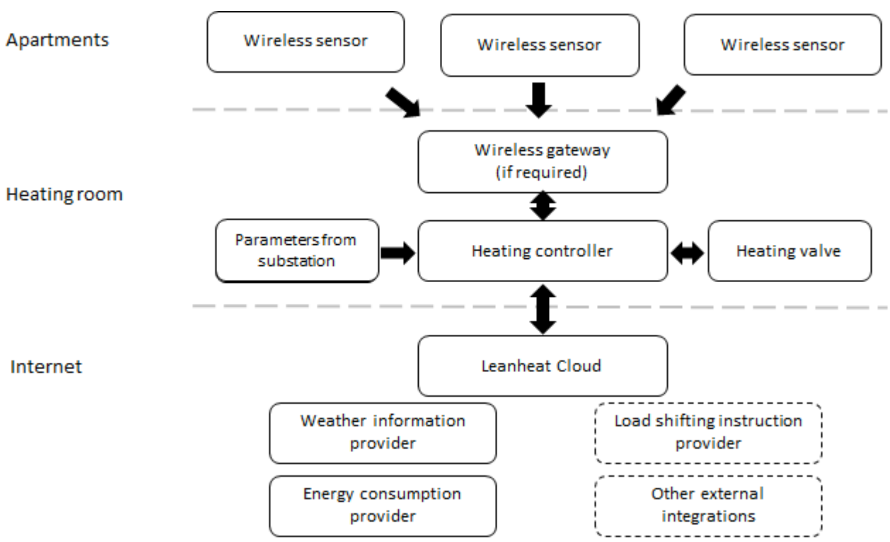

Figure 5. Representative hardware and IT architecture of the Leanheat solution.

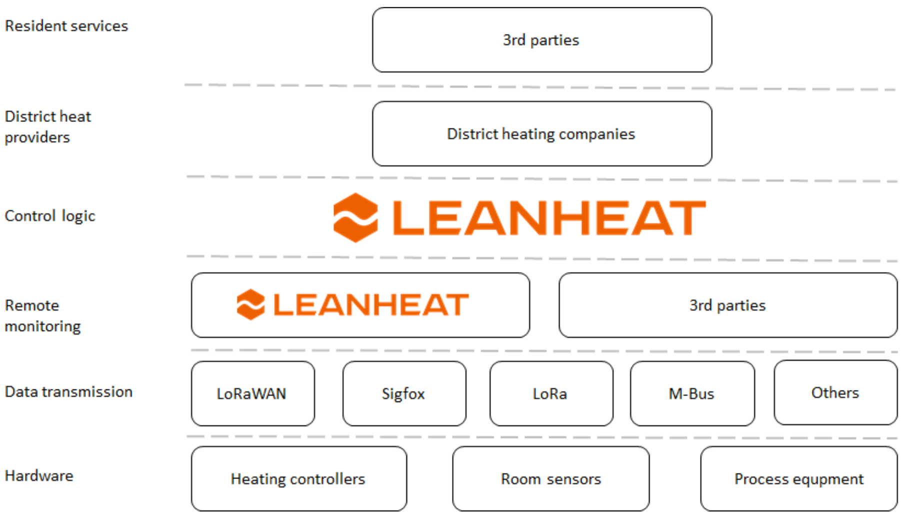

Figure 6. Hardware and abstract layers of the Leanheat solution.

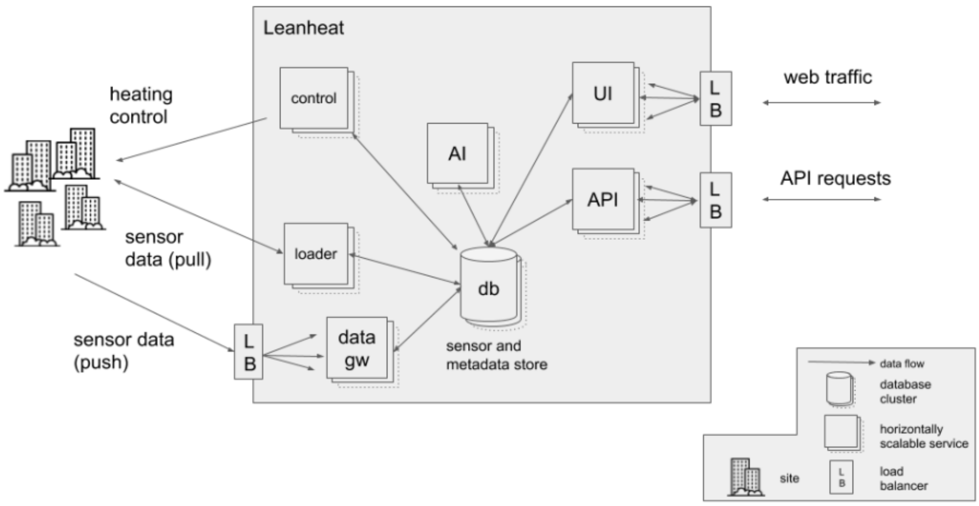

Figure 7. Architecture of the orchestration of the Leanheat predictive control solution.

the utility point of view to modulate the demand of the network based on the marginal cost of production of heat and electricity. For example, a utility company will have an interest into maximizing heat utilization from renewable heat production unit (e.g. biomass, or heat pumps during periods when the electricity generation mostly comes from wind power) and it will be possible to store this heat in the envelope of the buildings or in the network. Thus, a common approach is to combine both objectives and optimize for local peaks only during the coldest periods (peak shaving) of the heating season and provide demand-side response services to the utility the rest of the time.

ECONOMIC KPIS AND DISCUSSIONS

Overall Qualitative Behaviour

Across the population of buildings, it is observed that PPO leads to an average reduction of 17 % in peak heating power, as illustrated in Figure 8. This is observed in buildings where PPO is in operation, but demand response is not.

Figures 9 and 10 show illustrative behaviors of the system before and after Leanheat, (Figure 10 as displayed in the reactive user interface). The weather compensation reactive control lead to slow gradual trickle heating compensating for weather conditions (inverse correlation). In contrast, Leanheat control displays active modulation of the secondary side temperature; the observed oscillations correspond to the loading and unloading of space heat in the building envelope to reduce peaks and counteract the effect of simultaneous DHW consumption by occupants during these periods.

Figure 10 shows a typical profile of a residential building's space heating and DHW consumption under Leanheat optimization. The inverse relationship between space heating and DHW is clearly visible.

Figure 11 shows a scatter plot of heating power in a mixed local PPO and demand-side response implementation. With temperatures below -10 °C, a clear reduction of peak power can be seen. For temperature above -10 °C, demand response is in operation and heating power is profiled using signals from the

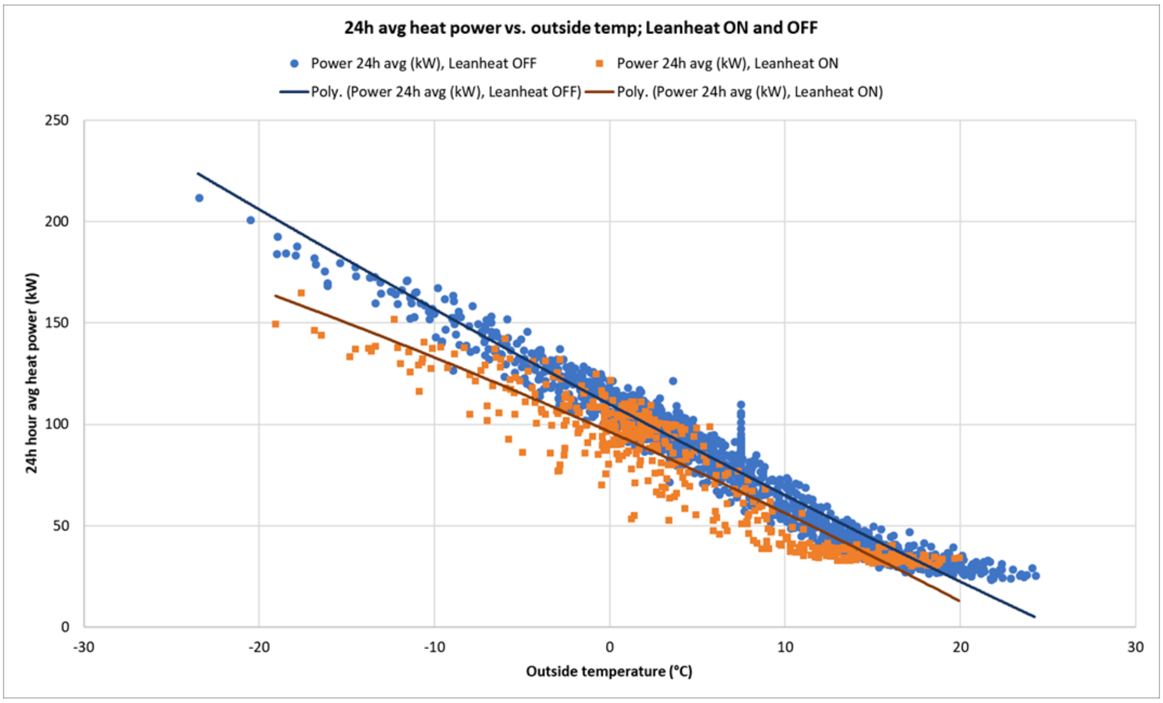

Figure 8. Comparison of heating power consumption between weather compensation driven control and Lean heat predictive control

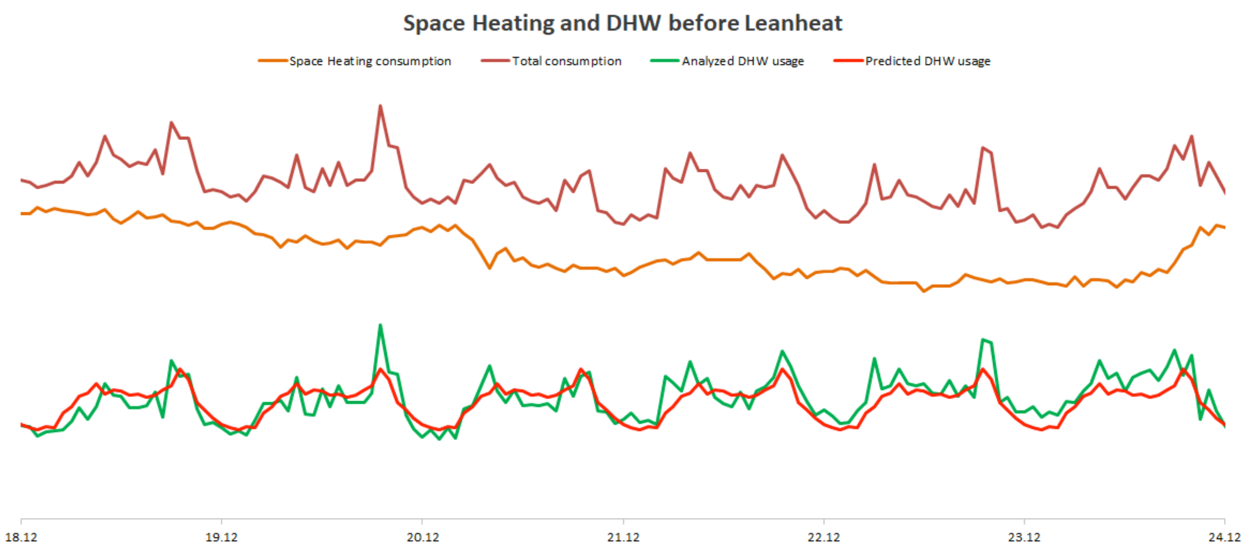

Figure 9. Overall building variable dynamics before Leanheat implementation.

DH utility. Trend lines were used extrapolating heating to calculate the expected power reduction for the lower temperature during the period.

PEAK POWER AND ENERGY CONSUMPTION REDUCTION

Energy and heating power consumption data were collected for a sample population of over 2,000 buildings with different years of construction. The buildings were binned into three different construction dates category. In Figure 12 three categories display a simultaneous reduction in both energy and peak power reduction. The highest peak reductions are visible on the left-hand side and can reach up to 40 % for a small subset of the buildings. On the right-hand side, some buildings show higher energy and power consumption than prior to Leanheat implementation. These cases correspond to a situation where insufficient heating and comfort (to achieve the target set-point) were previously being supplied to the occupant and which were subsequently addressed upon implementation of the predictive control approach. Although the relative reductions in energy and power demand are similar across the three categories, it is important to note the absolute reductions in kWh and kW (and monetary terms) are not unexpectedly higher for the older building stocks. A seemingly counter-intuitive result is a higher reduction in both energy and power achieved for more modern (and energy ef-

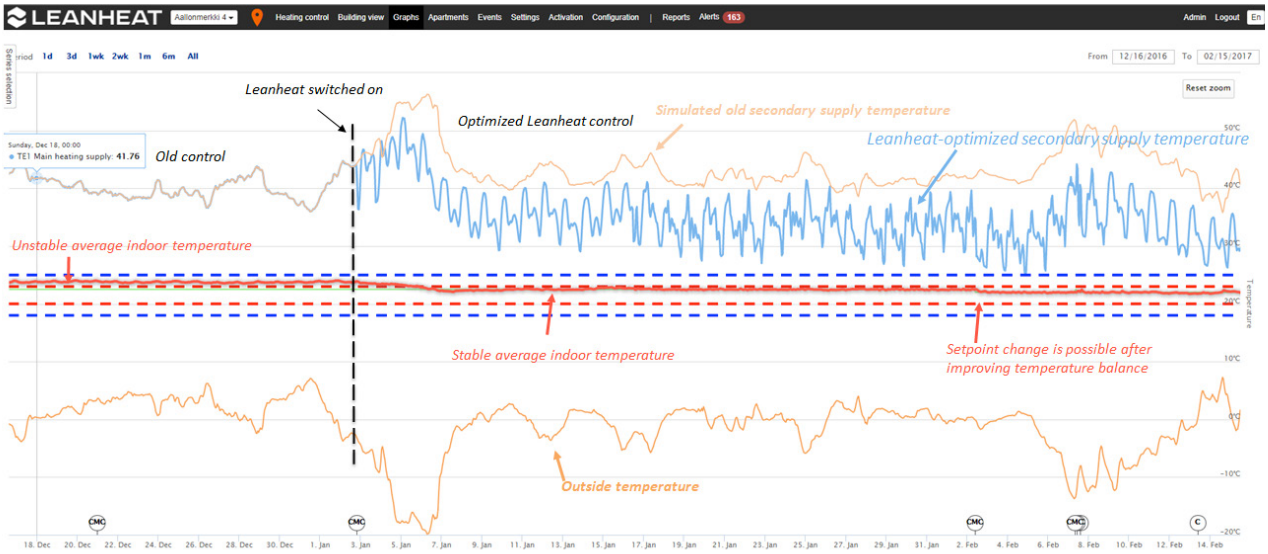

Figure 10. Screenshot of the Leanheat UI showing period before and after implementation of MPC.

ficient buildings). One possible explanation relates to the type of hydronic systems (radiator circuits or underfloor heating) and the higher heat capacity of the buildings. With traditional reactive control systems, the upside variations of indoor temperatures can be higher due to the combined effect of solar irradiance (through windows) and slow underfloor emitting system combined to internal loads which lead to overshoots. This behavior is corrected using a predictive approach because the system learns the building dynamics and anticipates the influence of the weather. However, as expected the absolute reductions are lower than for older stock in terms of kW and kWh. Nevertheless, these observations show that even for energy efficient and already manually optimized systems, a predictive control approach still brings additional cost reductions.

RETURN TEMPERATURES

By optimizing secondary side temperatures, Leanheat also affects primary side return temperature. Across all sites, Leanheat control produces on average a 2–4 °C lower primary side return temperatures than the same substation produced previously. For utility companies, this represents an additional benefit. For example, CHP systems and (condensing) biomass boilers have lower efficiency and heat recovery with higher temperatures. Other adverse effects of high return temperatures include, increase flowrates of DH water pumped through the network, a decrease in the overall thermal capacity of networks and, an increase of heat losses. Building owners are also affected where they are charged based on pricing which includes a return temperature component. Effects of smart controls on return temperatures are shown in Figure 13. Depending on the external temperature it is shown that Leanheat controls produce primary side return temperatures (red), which are, on average, lower than reference historical values.

ECONOMIC CONSIDERATIONS

From experience in a large population of apartments, Leanheat has been found to be an economically viable solution without any external support; the savings generated since day one allows

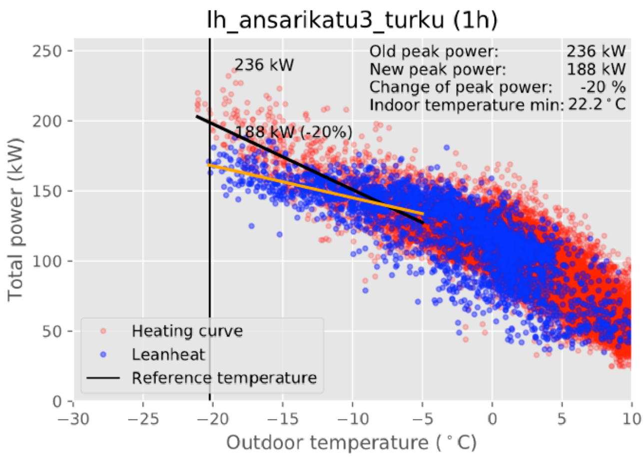

Figure 11. Scatter plot of heat power demand as a function of external temperature comparing traditional reactive control and the Leanheat solution.

internal rates of return in the range of 30–60 %. This is also amplified by the rapid decrease in IoT-sensor prices. Due to the reduction in sensor prices and increasing energy charges, it is expected that this type of control solution will be able to achieve a payback time of under 5 years by 2021–2022 for all residential DH buildings (4-pipe systems) regardless of their size, apartment count, initial energy consumption or other factors.

Experiences and outlook for scaling up rollout: challenges, business models, and the role of heat tariff models

It has been shown that a predictive control approach can bring significant savings in large-scale implementations for thousands of apartments. This confirms the already well-known theoretical expectation of model predictive control benefits and

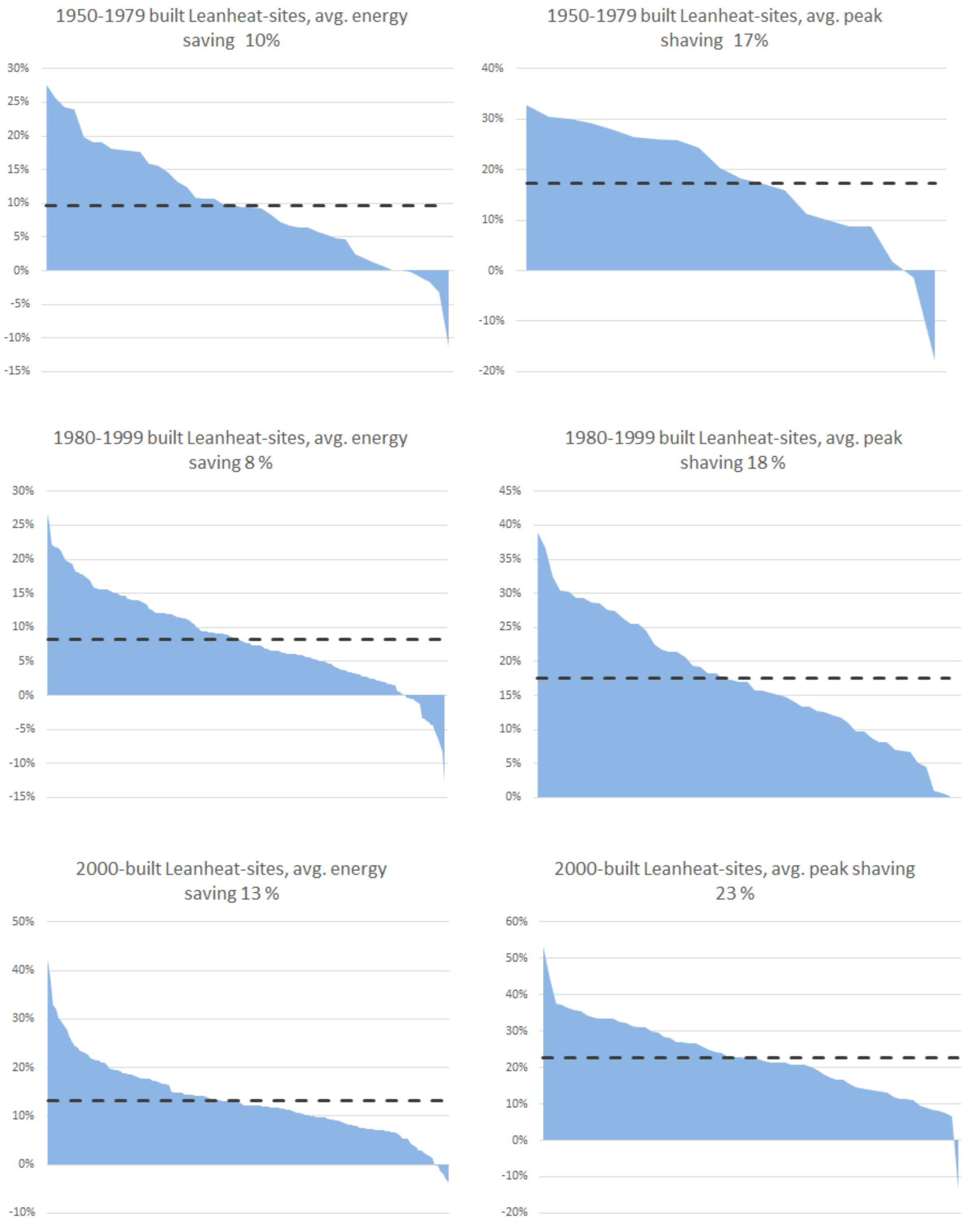

Figure 12. Distributions of energy and peak power reduction for three categories of buildings (respectively 450, 960 and 1,090 buildings in each construction year category).

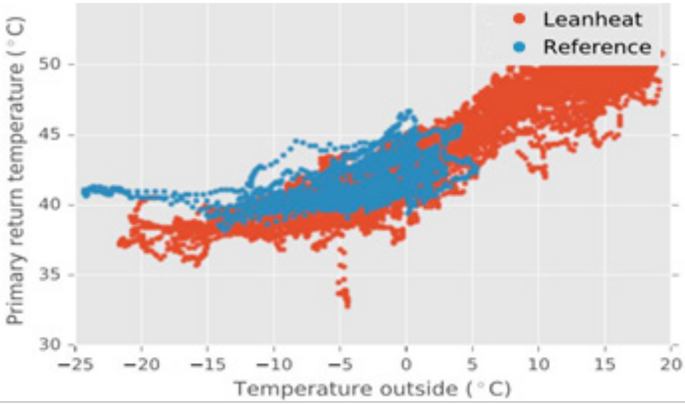

Figure 13. Comparison of primary return temperature between traditional weather compensation-based control and Leanheat model predictive control.

previous pilot academic studies. In general, there is great variability of heat demand reduction not only across different age of building stocks but also within single categories. At the estate level (e.g. a housing association), payback periods will be under 2–4 years and a rollout allows to meet the expected statistical averages. If building owners can identify buildings with significant energy consumptions and with known energy efficiency problems, reductions of more than 20–25 % are commonplace. Finally, it is important to highlight the challenges of large-scale implementation. Whilst several pilots and studies have been conducted by various organizations in academia and industry, scaling-up to the whole district also results in a qualitative leap complexity-wise. The challenges facing businesses are a mix of technical, organizational and business model factors.

TECHNICAL CHALLENGES

From a technical implementation point of view, recent advances in cloud computing make it very practical to scale the abstract layer. In terms of hardware, there are challenges to be overcome. Many hardware systems are closed or obfuscated, despite the utilization of 'standard' protocols. Another issue is the challenge posed by utility companies strict IT security policy which requires additional precautions to integrate with the company ERP and SCADA systems. In some markets, the hosting of the solution is also an important question and cloud-cloud integration is not always the preferred option.

Furthermore, varying engineering practices regarding local DH systems in different countries often require methodological adaptations to provide value. Some legacy systems which are less efficient, or cultural or regulatory constraints such as the ownership of the substation and the billing of the tenant also affect the implementation and replication of the solution. As mentioned above, an adaptation of the models to buildings with modern thermostats at apartment level was required to transfer the solution from a typical Finnish system to a Danish system. A similar adaptation is needed for systems where flat stations (heat interface units) are the norm (for example the UK).

ORGANIZATIONAL CHALLENGES

For utility companies, the choice of implementing a large-scale DSM policy typically present a make or buy situation. Organization resistance may occur when the service supplier is perceived as competing with the utility's own optimization initiatives (sunk costs). Other forms of organization resistance include the adaptation of the solution to daily processes such as maintenance and supervision. Ultimately for the digital supplier, this constitutes a delicate trade-off between providing a turnkey end-to-end solution, which can easily scale versus the effort required to integrate with existing SCADA enterprise systems to fit with the client's daily activities (e.g. integration to existing SCADA or cloud-cloud integration).

BUSINESS MODELS CONSIDERATIONS

Another important question is that of which business model to choose. Direct sales are suitable to individual owners, housing associations who see the value of using a reactive user interface and are willing to make changes in the way they manage their residential estate. For other organizations, indirect sales using a white modeling approach offers an attractive alternative. In this case, an overlap between organizational goals and strategic customer segments is to be sought by both the utility company and technology supplier. The objective here is to leverage an existing brand and customer relationship between the utility company and its customers to deliver additional value to the end-user. Again, this approach needs to be carefully evaluated to preserve the scalability of the system whilst attempting to fulfill the business objectives of the white-label companies (i.e. the endeavor to offer a "turn-key" value proposition). The technology supplier requires solving the problem of reconciling both the value proposition of white-labeling (for the DH utility) and the value proposition of the IoT solution for the consumer (property manager and building occupant). One example of such integration by Leanheat is Fortum Smart Living, a consumer engagement application designed by Fortum powered by Leanheat APIs.

MARKET UPTAKE: THE ROLE OF INDIVIDUAL CONSUMPTION BILLING AND HEAT TARIFFS

The Nordic heat tariff model for rented properties ensures that investors into advanced energy saving solutions and interactive heat DSM benefit from performance improvements. On the other hand, individual metering and billing of heating energy use, which is the general rule in the EU, implies a split of incentives between investors and the beneficiaries of impacts. This results in a market barrier that risks preventing the exploitation of the potential of heat DSM for optimizing the entire DE chain, leading to unnecessary costs e.g. linked to investments into more expensive dedicated heat storage facilities.

The flexibility and attractiveness of heat DSM can be enhanced by tariffs that provide incentives to end-user to "compromise" to a limited extent on comfort. In general, heating is always available, which means supply pipes need to be kept hot continuously. Financial compensation for end-users for agreeing on flexibility within upper and lower temperature limits can contribute to enhancing the operational efficiency of utilities aiming to use buildings and DE systems as energy storage, making investments more attractive.

Conclusion: elements of an effective policy framework

Energy and climate policy should provide an enabling framework for the digitalization of DE and the transition to 4GDE systems. The potential of integrated systems reducing end-use energy consumption and providing interactive heat DSM for optimizing DE on a system level – across supply, distribution, and consumption – should be evaluated and exploited. Individual metering and control have an impact on the applicability of DSM which requires flexibility in indoor temperature to modulate heating power. This could be resolved by using suitable tariff structures to favor indoor temperature flexibility within specified ranges. This could take the form of a lower energy charge for residents allowing a wider indoor temperature setpoint range or dynamic heat pricing similarly to what is already available for electricity. A careful consideration of these aspects is warranted to further existing EU regulations or to create policy instruments that will enable the rolling out of heat DSM.

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Disclosure Statements

1. Danfoss is a shareholder in Leanheat Oy, with a share ownership of 46 %.
2. Romain Lambert has worked as an external consultant for Leanheat Oy