ENER/FP7/609127/”READY”

Resource Efficient Cities Implementing Advanced Smart City Solutions - READY

Deliverable No.:	**D 3.5.5 preliminary**
Name of deliverable:	PostDoc: Data-driven demand side management in district heating (Originally intended to a Ph.D. thesis on pricing with the title: Cost and risk assessment in DH systems – Applications of heat demand forecasts)
Revision No.:	-
Due date of deliverable:	March 2018 (M40)
Actual submission date:	Draft 1: May 2018 (M42) Draft 2: November 2019 (M60) Final: May 2020 (M66)
Start date of project:	1. December 2014
Duration:	60 months + 8 months extension

Deliverable name of lead contractor for this deliverable: AVA/MUN-DK

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Scope of deliverable (PhD)

A research project on consumer incitements to be flexible in consumption patterns and the consequence of this on future RE-based supply systems. The research is conducted with an offset in statistical data analysis and building energy modelling by making use of high-resolution smart meter data obtained from district heating consumer substations.

Context of deliverable

The research project is part of work package 3: Proposing and developing integrated smart city heating/cooling system solutions.

Perspective of deliverable (PhD)

A better understanding of the mutual dependency between costs for operation and maintenance of the DH distribution network and the demand-side can point to business solutions that can ensure a more socio-economically optimal interaction between building renovation and a RE-based energy system. And new business models must be developed if such interaction is to be encouraged.

A greater interaction between the supply and demand might be of value for both AVA (the DH company) and the consumers. Can building renovation activity be aligned with DH system needs? Could all benefit from AVA offering to own and operate customer DH units and thereby moving the supply boundary across the household threshold? The network pipes usually have an expected lifetime of around 30 years. The cost of installation, maintenance, and expansion of the network are substantial. The economically best solution could in some cases be to avoid expansion by adapting consumption, so it best matches the network capacity. This might require that the end-users or at least their installations are activated in the system. Such solutions will require new business models to encourage more two-way interaction.

Involved partners

An industrial Ph.D. student was attached to AVA (Aarhus district heating company), represented by Adam Brun, and received tutoring from Aarhus University, represented by Steffen Petersen.

A Postdoc was employed by AVA (Aarhus district heating company), represented by Lasse Sørensen, and supported by Aarhus University, represented by Steffen Petersen.

Authors

Martin Heine Kristensen, Postdoc at Aarhus district heating company.
Kirsten Dyhr-Mikkelsen, Aarhus local coordinator.

Summary

The original work plan comprising three years of Ph.D. work (01 September 2015 – 31 August 2018) was extended due to paternity leave (24 October 2016 – 19 November 2016) to 01 September 2015 – 30 September 2018. However, the thesis work was terminated 01 September 2017 before completion. Only 2 publications were completed before interruption.

The remaining work was transferred to a **one-year industrial postdoc project** within the period 01 November 2018 – 01 November 2019. The postdoc project focussed on applying a data-driven approach to resolve the aims of this deliverable in terms of the hourly smart meter data obtained

from all customers in the district heating network of Aarhus. In particular, the project investigated the application of using customer data to setup, calibrate and validate physics-based archetype heating energy models of the different building typologies in the city, to be used for reproducing the district heating load in the system and subsequently forecast future loads. These archetype models could then be used to analyse the effect of different demand-side interventions on the system load, for instance the effect of typology-specific retrofits and energy flexible demand response schemes. Four formal publications were published based on the postdoc work: three in international journal magazines and conference proceedings, and one less formal article in a Danish magazine aimed at district heating professionals.

Furthermore, the postdoc project became involved in two field experimental sub-projects aimed at investigating the potentials and mechanisms of consumer flexible heating energy use (demand response); 1) a project in which 10 apartments were equipped with radio-controlled thermostats, and 2) a project in which two single-family houses were equipped with a radio-controlled heating systems. In both demand-response experiments, the goal was to evaluate the user experiences and their perception of the thermal environment when exposed to a scenario where their heating is shut off during the critical peak-hours, i.e. during morning-hours when the district heating capacity is stressed. However, none of these experiments were finalized before the deadline of this deliverable.

The work done in the postdoc is currently being used actively in the Energy Leap network initiated by the Aarhus Climate Secretariat. Here professional building owners commit to improving energy efficiency and use benchmarking as one of the tools in visualising potentials and the impact of efforts made. For more detail, please see D5.3.2.

Table of contents

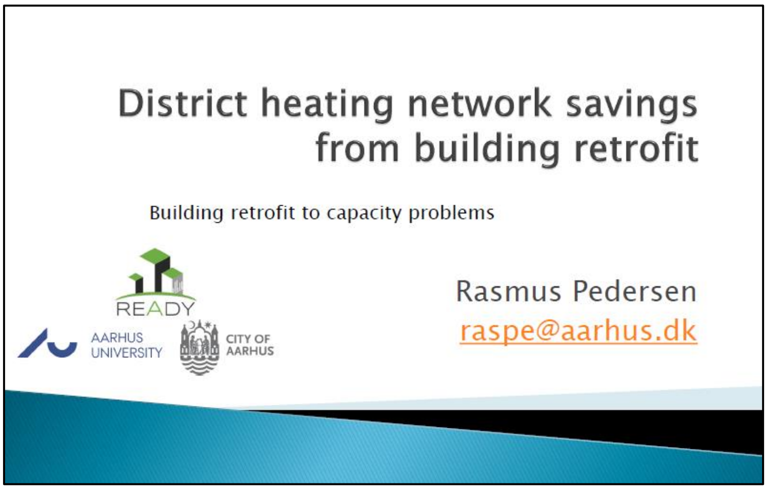
1. Overview of publications

Please find below an overview of the formal publications produced by the Ph.D. student and the PostDoc. Some of the PostDoc publications will be published after submission of this report but they have none-the-less been listed here for the sake of completion.

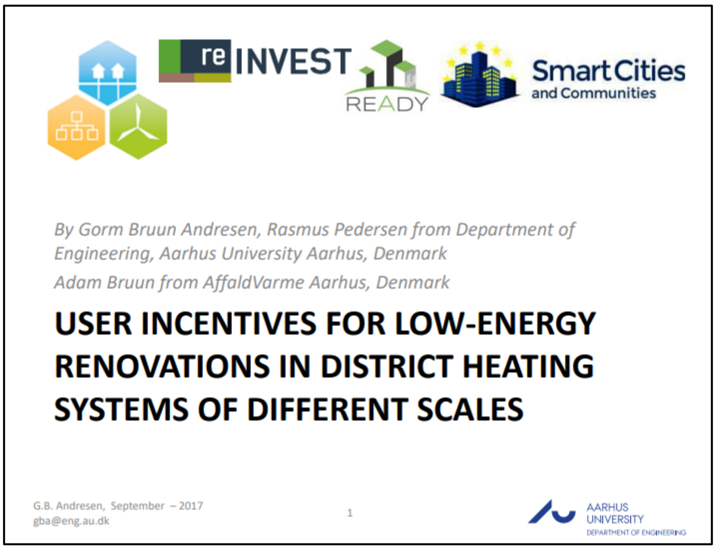
Publications by Ph.D. student

1. Direct and indirect district heating network energy savings from building retrofit	
Date	Sep 2016
Authors	R. Pedersen, M.H. Kristensen, S. Petersen, A. Brun, and G. Andresen
Place	2nd International Conference on Smart Energy Systems and 4th Generation District heating
Type of publication	Conference abstract in proceedings, 2 pages
Link	http://www.4dh.eu/
2. User incentives for low-energy renovations in district heating systems of different scales	
Date	Sep 2017
Authors	R. Pedersen, G. Andresen, and A. Brun
Place	3rd International Conference on Smart Energy Systems and 4th Generation District Heating
Type of publication	Conference abstract in proceedings, 2 pages
Link	http://www.4dh.eu/images/2__20170912_4GDH_-_GBA.pdf
Comment	Presented by co-author G. Andresen

Publication no. 1



Publication no. 2



Publications by Postdoc

3. Timeopløst forbrugsdata skaber viden om fremtidens fjernvarme [in Danish]	
Date	Aug 2019
Authors	M. H. Kristensen
Place	Fjernvarmen -- Dansk Fjernvarmes Magasin
Type of publication	Journal article
Link	https://www.danskfjernvarme.dk/nyheder/magasinet/online-magasiner/2019-23-august
Comment	Magazine for Danish district heating professionals. Article title in English: “Hourly consumption data creates knowledge about district heating for the future”.

4. Citywide hourly dynamic heat load forecasts using building archetype modeling	
Date	Sep 2019
Authors	M. H. Kristensen, R. E. Hedegaard, S. Petersen
Place	5th International Conference on Smart Energy Systems
Type of publication	Conference abstract in proceedings, 1 page
Link	https://smartenergysystems.eu/

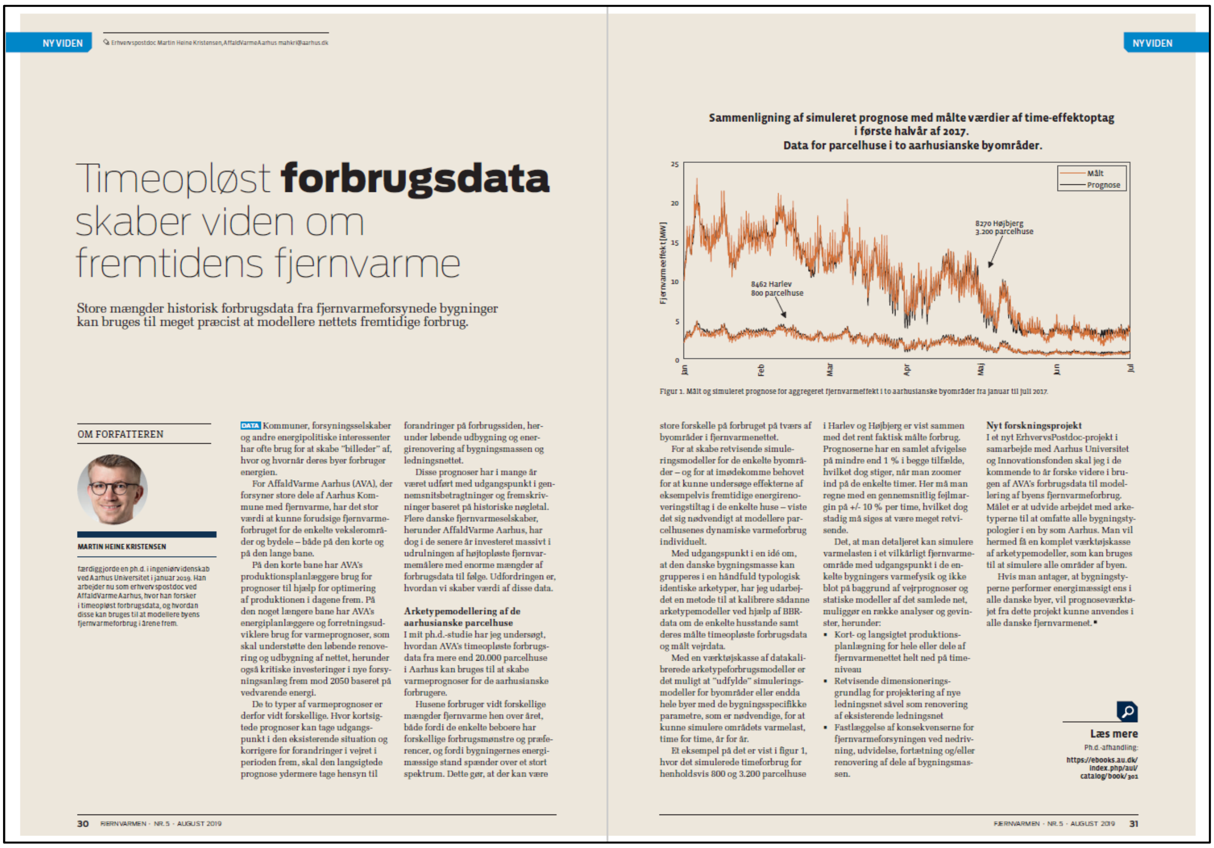
5. Long-term forecasting of hourly district heating loads in urban areas using hierarchical archetype modeling	
Date	Apr 2020
Authors	M. H. Kristensen, R. E. Hedegaard, S. Petersen
Place	Energy, The International Journal (Elsevier)
Type of publication	Journal article
Link	https://www.journals.elsevier.com/energy

6. District heating energy efficiency of Danish building typologies	
Date	May 2020
Authors	M. H. Kristensen, S. Petersen
Place	Energy & Buildings
Type of publication	Journal article
Link	https://www.journals.elsevier.com/energy-and-buildings
Comment	Manuscript is expected to be submitted for publication in June 2020.

7. Experimental validation of a model-based method for separating the space heating and domestic hot water components from smart-meter consumption data	
Date	May 2020
Authors	R. E. Hedegaard, M. H. Kristensen, S. Petersen

Place	NSB 2020: 12th Symposium on Building Physics
Type of publication	Conference paper in proceedings
Link	https://nsb2020.org/
Comment	Conference is to be held in Tallinn, September 2020.
8. Heat load demand response experiment in social housing apartments using wireless radiator setpoint control	
Date	May 2019
Authors	M. H. Kristensen, H. N. Knudsen, T. H. Christensen, L. S. Rasmussen
Place	SES 2020: 6th International conference on Smart Energy Systems
Type of publication	Conference abstract in proceedings
Link	https://smartenergysystems.eu/
Comment	Abstract submitted. Conference is to be held in Aalborg, October 2020.
9. Evaluating the temperature performance of Danish building typologies in district heating networks	
Date	May 2019
Authors	M. H. Kristensen, L. Sørensen, S. Petersen
Place	SES 2020: 6th International conference on Smart Energy Systems
Type of publication	Conference abstract in proceedings
Link	https://smartenergysystems.eu/
Comment	Abstract submitted. Conference is to be held in Aalborg, October 2020.
10. Long-term heat load forecasting under uncertainty of energy renovation and climate change	
Date	May 2019
Authors	M. H. Kristensen, R. E. Hedegard, S. Petersen
Place	uSIM 2020: 2nd IBPSA-Scotland conference on urban and community energy modelling
Type of publication	Conference abstract in proceedings
Link	https://usim20.hw.ac.uk/
Comment	Abstract submitted. Conference is to be held in Scotland, November 2020.

Publication no. 3



NY VIDEN

Erhvervspostdoc Martin Heine Kristensen, AffaldVarme Aarhus mahkri@aarhus.dk

Timeopløst **forbrugsdata** skaber viden om fremtidens fjernvarme

Store mængder historisk forbrugsdata fra fjernvarmeforsynede bygninger kan bruges til meget præcist at modellere nettets fremtidige forbrug.

OM FORFATTEREN

MARTIN HEINE KRISTENSEN

færdiggjorde en ph.d. i ingeniørvidenskab ved Aarhus Universitet i januar 2019. Han arbejder nu som erhvervspostdoc ved AffaldVarme Aarhus, hvor han forsker i timeopløst forbrugsdata, og hvordan disse kan bruges til at modellere byens fjernvarmeforbrug i årene frem.

DATA Kommuner, forsyningsselskaber og andre energipolitiske interessenter har ofte brug for at skabe "billeder" af, hvor og hvornår deres byer forbruger energien.

For AffaldVarme Aarhus (AVA), der forsyner store dele af Aarhus Kommune med fjernvarme, har det stor værdi at kunne forudsige fjernvarmeforbruget for de enkelte vekslerområder og bydele – både på den korte og på den lange bane.

På den korte bane har AVA's produktionsplanlæggere brug for prognoser til hjælp for optimering af produktionen i dagene frem. På den noget længere bane har AVA's energiplanlæggere og forretningsudviklere brug for varmeprognoser, som skal understøtte den løbende renovering og udbygning af nettet, herunder også kritiske investeringer i nye forsyningsanlæg frem mod 2050 baseret på vedvarende energi.

De to typer af varmeprognoser er derfor vidt forskellige. Hvor kortsigtede prognoser kan tage udgangspunkt i den eksisterende situation og korrigere for forandringer i vejret i perioden frem, skal den langsigtede prognose ydermere tage hensyn til forandringer på forbrugssiden, herunder løbende udbygning og energirenovering af bygningsmassen og ledningsnettet.

Disse prognoser har i mange år været udført med udgangspunkt i gennemsnitsbetragtninger og fremskrivninger baseret på historiske nøgletal. Flere danske fjernvarmeselskaber, herunder AffaldVarme Aarhus, har dog i de senere år investeret massivt i udrulningen af højtopløste fjernvarmemålere med enorme mængder af forbrugsdata til følge. Udfordringen er, hvordan vi skaber værdi af disse data.

Arketypemodellering af de aarhusianske parcelhuse

I mit ph.d.-studie har jeg undersøgt, hvordan AVA's timeopløste forbrugsdata fra mere end 20.000 parcelhuse i Aarhus kan bruges til at skabe varmeprognoser for de aarhusianske forbrugere.

Husene forbruger vidt forskellige mængder fjernvarme hen over året, både fordi de enkelte beboere har forskellige forbrugsmønstre og præferencer, og fordi bygningernes energimæssige stand spænder over et stort spektrum. Dette gør, at der kan være store forskelle på forbruget på tværs af byområder i fjernvarmenettet.

For at skabe retvisende simuleringsmodeller for de enkelte byområder – og for at imødekomme behovet for at kunne undersøge effekterne af eksempelvis fremtidige energirenoveringstiltag i de enkelte huse – viste det sig nødvendigt at modellere parcelhusenes dynamiske varmeforbrug individuelt.

Med udgangspunkt i en idé om, at den danske bygningsmasse kan grupperes i en håndfuld typologisk identiske arketyper, har jeg udarbejdet en metode til at kalibrere sådanne arketypemodeller ved hjælp af BBR-data om de enkelte husstande samt deres målte timeopløste forbrugsdata og målt vejrdata.

Med en værktøjskasse af datakalibrerede arketypeforbrugsmodeller er det muligt at "udfylde" simuleringsmodeller for byområder eller endda hele byer med de bygningsspecifikke parametre, som er nødvendige, for at kunne simulere områdets varmelast, time for time, år for år.

Et eksempel på det er vist i figur 1, hvor det simulerede timeforbrug for henholdsvis 800 og 3.200 parcelhuse i Harlev og Højbjerg er vist sammen med det rent faktisk målte forbrug. Prognoserne har en samlet afvigelse på mindre end 1 % i begge tilfælde, hvilket dog stiger, når man zoomer ind på de enkelte timer. Her må man regne med en gennemsnitlig fejlmargin på +/- 10 % per time, hvilket dog stadig må siges at være meget retvisende.

Det, at man detaljeret kan simulere varmelasten i et vilkårligt fjernvarmeområde med udgangspunkt i de enkelte bygningers varmefysik og ikke blot på baggrund af vejrprognoser og statiske modeller af det samlede net, muliggør en række analyser og gevinster, herunder:

- Kort- og langsigtet produktionsplanlægning for hele eller dele af fjernvarmenettet helt ned på timeniveau
- Retvisende dimensioneringsgrundlag for projektering af nye ledningsnet såvel som renovering af eksisterende ledningsnet
- Fastlæggelse af konsekvenserne for fjernvarmeforsyningen ved nedrivning, udvidelse, fortætning og/eller renovering af dele af bygningsmassen.

Nyt forskningsprojekt

I et nyt ErhvervsPostdoc-projekt i samarbejde med Aarhus Universitet og Innovationsfonden skal jeg i de kommende to år forske videre i brugen af AVA's forbrugsdata til modellering af byens fjernvarmeforbrug. Målet er at udvide arbejdet med arketyperne til at omfatte alle bygningstypologier i en by som Aarhus. Man vil hermed få en komplet værktøjskasse af arketypemodeller, som kan bruges til at simulere alle områder af byen.

Hvis man antager, at bygningstyperne performer energimæssigt ens i alle danske byer, vil prognoseværktøjet fra dette projekt kunne anvendes i alle danske fjernvarmenet. ▪

Sammenligning af simuleret prognose med målte værdier af time-effektoptag i første halvår af 2017. Data for parcelhuse i to aarhusianske byområder.

Figur 1. Målt og simuleret prognose for aggregeret fjernvarmeeffekt i to aarhusianske byområder fra januar til juli 2017.

Læs mere

Ph.d.-afhandling:

https://ebooks.au.dk/index.php/aul/catalog/book/301

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FJERNVARMEN · NR. 5 · AUGUST 2019 31

Publication no. 4

5th International Conference on Smart Energy Systems
Copenhagen, 10-11 September 2019
#SESAAU2019

Citywide hourly dynamic heat load forecasts using building archetype modeling

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Publication no. 5

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Long-term forecasting of hourly district heating loads in urban areas using hierarchical archetype modeling

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ABSTRACT

This paper demonstrates and validates the application of a recently proposed archetype modeling and calibration framework for setting up 11 stochastic archetype building energy models of Danish detached single-family houses (SFH's). For this task, the municipal district heating system of Aarhus, Denmark, and its associated building stock were employed as case study, together comprising a dataset of 18 475 SFH's with hourly time series heating data for two years (2017–2018). The 11 physics-based archetype models were each calibrated using a training building sample with data from a one-year calibration period (2017) and tested for their ability to forecast the heat load of another building sample in a previously unseen one-year validation period (2018). The calibrated archetype models were further tested for their joint forecasting ability to match the aggregated heat load of six suburban dwelling areas of different composition and location within the city region of Aarhus, and finally for their ability to forecast the entire citywide dataset of 18 475 SFH's. The modeling framework performs very well for the aggregated citywide predictions with a practically non-existent bias of the overall heat load during the validation period (NMBE < 0.5%) and with only moderate inaccuracies present in hourly load predictions (MAPE < 12%). The high forecasting accuracy validates the application of the demonstrated archetype modeling framework for long-term urban-scale predictions; however, analysis of the time series errors indicate that the performance could be further improved by focusing on a better representation of the holiday periods and by ensuring the training data to be adequately informative to enable a good calibration of the model parameters. The simplicity of the archetype models coupled with the applied physics-based model structure makes the framework suitable for general energy planning purposes. By adapting a more dynamic model structure, it would also be possible to apply the framework for more complex analysis of, for instance, the urban-scale demand response and the general heating flexibility of the building stock.

1. Introduction

Obtaining an energy-efficient building stock poses a critical challenge in the transition towards fourth generation district heating (4GDH) systems [1,2]. To this end, urban building energy modeling (UBEM) [3] can facilitate the various types of energy analysis of building stocks needed for informing the decision-making process. According to the reviews by Swan and Ugursal [4], Kavgic et al. [5] and lately by Li et al. [6], UBEM approaches can be categorized as top-down or bottom-up approaches as indicated by Fig. 1. The top-down approaches typically rely on highly aggregated energy consumption data in combination with statistical methods for energy modeling, while the bottom-up approaches focus on modeling the consumption of individual consumers through either physics-based models or statistical methods. Choosing one approach over the other depends on the purpose of the analysis. The top-down statistical approaches seems to be the most efficient for aggregated analysis, whether it being the aggregated load of a district heating grid forecasted using machine learning algorithms [7,8] or, for instance, for macro-level retrofit analysis of entire national building stocks [9]. The statistical bottom-up approach is appropriate if the purpose of the analysis is to forecast the aggregated energy use of buildings using a subset disaggregated features [10]. The physics-based bottom-up

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District heating energy efficiency of Danish building typologies

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Highlights:

- Hourly district heating energy use data from approx. 45 350 consumers
- Publicly available building and dwelling register data
- Building stock segmented into building typologies
- Annual heating energy use intensity
- Heat load variation
- Temperature efficiency

Abstract

The heating energy efficiency of Danish buildings is currently veiled by the lack of high-resolution end-user consumption data; a fact which apply particularly to the district heating-supplied buildings that make up approx. 54% of the Danish building stock. Providing this data has many benefits and applications in both district heating operation and system planning but could also find use in, for instance, evaluating the accuracy of energy performance certificates and to help evaluate the effect of building code energy requirements. In this study, we collected and categorized hourly district heating consumption data from 45 343 individual building substations located in the municipality of Aarhus, Denmark, for the year of 2018, which lead to a post-processed pool of 42 969 building-specific datasets. Through a combination of data segmentation and statistical analysis, we derived the heating energy efficiency of the five main building application categories, and the seven dwelling-specific subcategories, using three efficiency indicators: 1) annual heating energy use intensity, 2) annually accumulated daily heat load variation, and 3) cooling temperature of district heating water.

Keywords: Energy efficiency; Building typology; District heating; Heat load;

1 Introduction

Europe is roughly using 50% of its energy consumption for heating and cooling purposes, whereof the majority is used for building space heating (27%), industrial processes (16%), and domestic hot water applications (4%), respectively [1]. The heating sources are a mix of biomass, electricity, oil, gas, district heating, and coal-based technologies, but the specific composition of these sources varies considerately between countries [2]. In the case of district heating (DH), the market share is approx. 9% for Europe as a whole, while it constitute a share of 36-92% in the Nordic and Baltic countries, and a range of eastern European countries [3]. The century-long historic development of DH systems and its current state, as well as the further development needed for district heating to play a role in future sustainable energy systems, are featured in various publications, for example [4–9]. A general tendency in the historic development of district heating is the lowering of the distribution temperature from being steam-based in the first generation of DH systems (year 1880-1930), over >100 °C pressurized water in the second generation (year 1930-1980), to <100 °C pressurized water in the third generation (year 1980-2020). This trend is most likely to continue; the distribution temperature is expected to be around 30-70 °C in the fourth generation of district heating (year 2020-2050) – also referred to as 4GDH [4].

Lowering the distribution temperature has significant benefits in terms of energy efficiency of DH production and distribution systems, such as increased efficiency of heating plants and decreased grid losses [10]. Furthermore, a lower distribution temperature will free production and grid capacity to allow more consumers to be connected to the same (existing) grid [4,11], enable recycling of heat from low-temperature sources, like waste heat from processes in industry [12,13], and enable integration of renewable heat sources such as solar, seawater and geothermal heat [14,15]. In a study of low-temperature district heating concepts for Denmark it was found to be socioeconomically feasible to reduce the supply temperature to buildings to around 55°C; a limit defined by the minimum temperature needed for DH-based production of domestic hot water without an additional energy source e.g. an electric heater [16]. However, the extent to which the distribution temperature can be lowered is in general limited by the level needed to maintain thermal comfort at the end user. It is emphasized that 4GDH cannot be realized without an energy-efficient building stock in terms of both space heating and domestic hot water preparation [4].

New European buildings has been subjected to the energy requirements of the European Performance of Buildings Directive (EPBD) since 2006 [Directive 2002/91/EC] which demands a tightening of the national requirement for maximum energy demand for building operation every five years starting from 2006 and ending in 2020 where all new buildings should be so-called nearly zero-energy buildings (nZEB). In a Danish context, for example, it is anticipated that

Publication no. 7

Manuscript is expected published in September 2020.

Experimental validation of a model-based method for separating the space heating and domestic hot water components from smart-meter consumption data

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Abstract. Smart meters are currently being rolled out in European district heating (DH) systems at a large scale to enable time-varying district heating tariffs and improve consumer awareness about their own consumption. Smart-meter data can also be used in more advanced applications, e.g. for establishing model-based control schemes for demand response purposes and data-driven building energy performance labeling schemes. Many of these applications require separate measurements of the consumption for space heating (SH) and preparation of domestic hot water (DHW); however, smart meters often only provide the total DH energy consumption (SH+DHW) in truncated units (e.g. whole kWh on an hourly basis). Typical approaches for separating these two components of DH consumption require measurements with a high temporal and numerical resolution and are therefore not applicable to smart-meter data. New methods suitable for disaggregating the combined DH demand are therefore needed. This paper presents a validation of a model-based method for disaggregating DH consumption using ground truth data from 44 residential buildings.

1 Introduction

In an effort to improve the transparency and billability of energy consumption, a recent amendment to the energy efficiency directive (EED) of the European Union (EU) introduced a requirement for all newly installed district heating (DH) and cooling meters to be remotely readable by 25 October 2020, while all remaining non-remotely readable meters is to be replaced by 1 January 2027 [1]. Modern remotely read heat meters are capable of reporting consumption at an hourly or sub-hourlytemporal resolution, which is a significant leap forward compared to the annual temporal resolution that is often associated with manually read meters. The improved availability of high-resolution smart-meter consumption data is one of the cornerstones in enabling several new technologies to be implemented in building automation. One of these technologies is model-based control schemes for heating systems, which may improve the comfort of occupants while minimizing energy consumption by optimizing HVAC control [2,3]. These control schemes also allow for utilizing the thermal inertia of buildings to render part of the consumption in the buildings flexible, thereby enabling building owners to sell services to the heating utility. The models used to establish such control schemes need to describe the thermal dynamic behavior of the buildings accurately and are therefore typically obtained by calibrating the parameters of said models using measurements of internal temperatures, external weather conditions, and heating consumption. Since the latter of these measurements is often the hardest to obtain, the availability of data from already installed smart meters may be a decisive factor for the viability of such control schemes. Another promising use of high-quality consumption data is for generation of data-driven building energy performance certificates as a supplement or even an alternative to traditional energy audits. However, the applications outlined here require separate measurements of the energy consumed for space heating (SH); currently, DH smart meter measurements is a sum of the energy used for SH and for preparation of domestic hot water (DHW). Therefore, previous studies have investigated inference-based techniques for disaggregating district heating measurements to estimate the energy quantities consumed for each of these two purposes. Two prevailing approaches have been identified, which we shall refer to as the *summer methods* and the *inertia methods*, respectively. A third approach, which is not further discussed in this study due to a lack of data, relies on measurements of the cold water consumption together with the assumption that a certain fraction of the consumed water is heated before use.

The summer methods are based on the assumption that all DH consumption during the warmest period of the year can be attributed to DHW production [4,5], and that this is representative for the entire year. The period for which this assumption is reasonable depends of course on the climate that the building is situated in. Therefore, some implementations of the summer method attempt to account for space heating through various assumptions.

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Publication no. 8

Abstract has been submitted to conference organisers. Publication is expected in October 2020.

Heat load demand response experiment in social housing apartments using wireless radiator setpoint control

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Keywords: *district heating, demand response, flexible demand, radiator, setpoint control, thermal comfort, questionnaires*

In recent years, a significant number of studies have indicated a potential of utilizing the thermal mass in buildings to generate flexible heating demand through demand response (DR) schemes. Being able to provide flexibility to a district heating system this way may be used to absorb parts of the daily consumption peaks that often occur during morning hours. Different DR schemes and implementations have been proposed in the literature, but only a few studies have documented any practical effects.

In this abstract, we present the results of a field study concerning scheduled DR events on the radiator heating system in 10 social housing apartments during morning peak load hours. Based on initial focus group interviews of the tenants, three different DR schemes were tested using wirelessly controlled radiator thermostats over the course of two months: 1) radiators turned off for 1h [07.00-08.00]; 2) radiators turned off for 3 hours [06.00-09.00] with +1°C preheating for 2h [04.00-06.00]; and 3) radiators turned off for 3 hours [06.00-09.00]. In addition, a baseline was determined by periods of no DR actions. The heat load was measured using meters in each apartment and air temperature was measured separately in each room. Any potential thermal comfort issues were evaluated using weekly online questionnaires and a hand-written logbook filled out by the tenants. Finally, the tenant's experiences with the DR schemes was evaluated by interviews of the tenants.

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Evaluating the temperature performance of Danish building typologies in district heating networks

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Key words: *district heating; smart meter data, hourly time series; building typologies; archetypes;*

District heating utilities divide the expenses of operating and maintaining their heating systems among the customers based on: 1) the size of the customers' substation, 2) how much heating the customers consume in a year, and 3) the efficiency at which the customers make use of the circulated water before returning it to the grid. The first and the second cost elements are easy to justify and quantify. However, evaluating the efficiency of individual customers and buildings, and quantifying how this affects the overall system efficiency is more difficult. Often, utilities measure the annually aggregated cooling temperature, or just the return temperature, of each customer substation. If the cooling temperature is too low, the customer is charged accordingly. If it is very high, the customer is fine and may even receive a bonus. However, this may not be entirely fair because different building typologies and their location in the grid have different prerequisites for utilizing the supplied energy.

In this contribution we present a statistical treatment of temperature data from more than 45 000 consumer meters. By segmenting the buildings into typologies and by accounting for the available supply temperatures, we present a comprehensive overview of the temperature conditions at the consumer as basis for discussing alternative ways of distributing the costs of operating the grid.

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Long-term heat load forecasting under uncertainty of energy renovation and climate change

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It remains practically infeasible to gather all the required data inputs for physics-based urban building-by-building energy modelling. Simplifications may therefore be necessary, e.g. through archetype segmentation of the building stock to reduce the task of data acquisition and calibration of uncertain parameters. The authors of this abstract recently proposed a novel hierarchical archetype calibration methodology that allows a robust probabilistic inference of unknown archetype input parameters for unseen buildings belonging to an archetype. The methodology has been proven fast and accurate for urban-scale predictions of aggregated building energy use under uncertainty.

In this contribution, we extend the application of the hierarchical archetype modelling framework to be used for long-term energy planning and heat load forecasting. We initially calibrate models of the hourly district heating energy use of more than 20,000 single-family houses in the city of Aarhus, Denmark, using recent historical data to obtain a high accuracy of predictions. This urban-scale residential model is subsequently applied to forecast the heat load of each building individually up until 2050 under uncertainty of both energy renovation and climate change.

The modelling framework ensures the propagation of all layers of uncertainty throughout the predictions by relying on Bayesian inference to obtain the archetype models. The resulting data-informed heat load timeseries forecast can be used for robust planning of future investments in district heating infrastructure to accommodate the demand of the future.