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Cluster analysis of residential heat load profiles and the role of technical and household characteristics

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ABSTRACT

Demand-side management methods are expected to play a key role in future energy systems. These methods are making energy demand adaptive to fluctuations inherent to intermittent renewable energy sources. In order to develop feasible demand-side management solutions, a better understanding of the temporality of the energy demand is needed. This paper contributes to this by focusing on the daily load profiles of energy demand for heating of Danish dwellings with heat pumps. Based on hourly recordings from 139 dwellings and employing cluster and regression analysis, the paper explores patterns (typologies) in daily heating load profiles and how these relate to socio-economic and technical characteristics of the included households. The study shows that the load profiles vary according to the external load conditions. Two main clusters were identified for both weekdays and weekends and across load segments; a main cluster with a relatively constant load profile and a minor cluster with a more distinct variation during the day. The difference between the clusters is primarily correlated with building characteristics like floor area, building year and type of space heating distribution system, while the existence of children and teenagers in the household were the only significant socio-economic variables.

1. Introduction

Decarbonising the energy system is presently a high priority on the political agenda in response to the climate change challenge and political ambitions of a higher degree of national energy sovereignty. However, with increasing levels of renewable power sources follows new challenges of balancing electricity demand with intermittent power supply. Demand-side management (DSM) in the form of time shifting the energy use is one of the solutions that has been advised, and many trials have been carried out in order to test and estimate the potential of different DSM solutions [5,6,8].

While we have witnessed an impressive technological development and uptake of renewable electricity generation within the latest 25 years (in 2014, 25% of the EU-28 gross electricity consumption was covered by renewable energy; [11], other consumption areas have proven more difficult to decarbonise. One of these are the heating of buildings, as this is in many countries partly based on oil and gas. In 2012, heating of dwellings represented about 67% of the residential energy consumption in EU [24]: 26). Replacing oil and gas-fired burners with heat pumps has become an energy policy target in many EU countries in order to base the energy consumption for heating on low-carbon power generation from renewable sources [12,13]. In Denmark, oil, natural gas, coal, coke and gas works gas made up 27% of the final energy consumption for residential heating in 2013, while district heating represented 45%, biomass 22%, direct electric heating 4% and heat pumps 2% [7]. The overall aim of the Danish Energy Strategy *Energistrategi 2050* [26] is a complete phase out of fossil fuels in the Danish energy system by 2050, and the Danish *Energy Agreement of 22 March 2012* includes, among other initiatives, a goal of replacing oil and gas-fired burners with renewable alternatives (including heat pumps).

However, the electrification of heating increases the challenges of balancing the power grid and might contribute to grid capacity problems due to higher maximum loads in the morning and afternoon peak hours with risks of blackouts [13]. In this regard, DSM can become an important solution in order to handle both system balancing and network capacity challenges. The increased use of heat pumps not only represents a new challenge to the electricity grid, but also a new possibility for including heating as a flexible load. Thus, a better understanding of the time-patterns related to heating is needed in order to assess and quantify the potentials and limitations of time shifting heating loads through DSM. Also,

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mapping differences between households with regard to time-patterns of heating can contribute to the development of strategies and technical solutions targeted specific groups of households with similar time-patterns.

This paper analyses the temporal patterns related to the heating of Danish dwellings. The guiding research questions are: What kind of different patterns (typology) of heating load profiles can be identified for Danish dwellings? How do these patterns correlate with socio-technical characteristics of the households?

The analysis is based on a statistical cluster analysis of a data set consisting of hourly recordings of the energy consumption for heating in 139 Danish dwellings (single-family detached homes). Cluster analysis groups objects (e.g. individual load profiles) into homogenous groups (e.g. with similar load profiles) and is a useful tool for exploring large data sets. The cluster analysis is combined with an explorative statistical analysis of the correlations between the identified clusters and socio-technical data of the dwellings.

Cluster analysis is increasingly being used to analyse load profiles related to electricity consumption (see next section), whereas it has only to a limited extent been used for studies of heat load profiles. Within the latest years, an increasing number of studies have combined statistical analysis with data mining techniques to explain how occupant behaviour influences energy consumption of residential buildings (e.g. [14,25]. However, only few studies at the same time focus on the temporality of energy consumption for heating (24 h heat load profiles) and are based on measured data of the actual energy consumption (like this study). Thus, of the three referenced studies, only Ren et al. [25] make a cluster analysis related to the temporality of occupant behaviour, and in this case on basis of the measured room temperature of residential buildings (affordable housing) and not the measured energy demand.

In the following (Section 2), we present a literature review of previous studies of factors influencing energy consumption for heating as well as energy load profiles in dwellings (including also cluster analyses of electricity load profiles due to the limited number of previous studies of heating load profiles). The literature review informs the methodological design (Section 3) as well as the discussion of the empirical results (results are presented in Section 4 and discussed in Section 5). The paper ends with a conclusion (Section 6).

2. Literature review

2.1. Factors influencing energy consumption of heating

While only few studies have analysed heating load profiles, much literature exists on how the size of the energy consumption for heating (space heating and DHW) depends on various factors (e.g. [20,28]. These indicate that energy consumption for heating is determined by a multiplicity of factors and cannot be reduced to a single aspect (e.g. building characteristics). Based on statistical studies of energy consumption in Danish households, Gram-Hanssen [17] finds that building characteristics (including size and year of construction) explain about 40–50% of the variation between households. In addition, socio-economic household characteristics such as age, number of residents, income and education explain only little of the remaining variation. On a basis of this, and previous studies showing great variation in the energy consumption between similar households living in similar dwellings, Gram-Hanssen concludes that "user behaviour is at least as important as building physics when it comes to energy consumption related to heating, though the user behaviour can only to a very limited degree be explained by objective characteristics of the inhabitants" (Ibid.: 455). Similar results are found in Guerra Santin et al. [20].

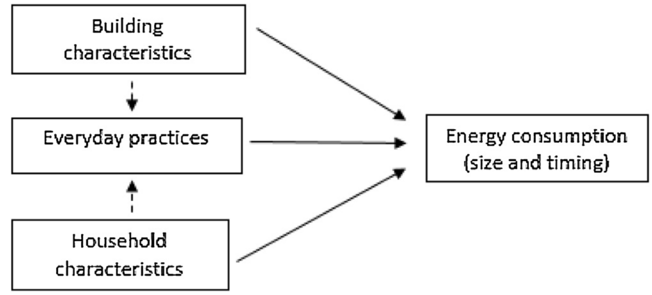

Fig. 1. Research framework.

While most studies distinguish between the role of (technical) building characteristics and socio-economic household characteristics, researchers like Gram-Hanssen [17] and Guerra Santin and Itard [19] also include user behaviour, or patterns of *everyday practices*, as a third category of factors. This includes daily routines of the household members such as habits of airing, indoor temperature settings, turning off heating during working hours, showering practices etc. Along with building characteristics and socio-economic household characteristics, patterns of everyday practices are also included in the research framework of our study (see Fig. 1). This framework is similar to the framework adopted by Guerra Santin and Itard [19]. However, this paper will primarily focus on the correlations between clusters of load profiles and building and household characteristics due to the lack of access to quantitative data on the everyday practices of the dwellings participating in this study.

Correlations might be expected between building and household characteristics (on one side) and everyday practices (on the other side). For instance, Guerra-Santin and Itard [19] find that the presence of elderly persons in households (household characteristic) influences the use of the heating system and ventilation. Also, the type of temperature control (building characteristic) influences the practices of the residents with regard to how many hours the heating is turned on; households with a programmable thermostat "were more likely to keep the radiators turned on for more hours" (ibid.: 138) than households with a manual thermostat or manual valves on radiators.

2.2. Studies of energy load profiles of households

Only few studies have focused on load profiles related to heating of dwellings, while there is a growing research literature within studies of load profiles of residential electricity consumption. This follows from the increasing use of smart electricity meters in many countries, which provides access to detailed data sets. Several of the studies apply cluster analysis methods in order to identify different groups (clusters) of households with similar daily load profiles (e.g. [15,21].

Hellman et al. [21] compare daily electricity consumption profiles (including also electrical appliances etc.) for customers with ground source heat pumps (GSHPs) and direct electric heating. Their study shows, among other things, that direct electric heating customers have a higher peak in the evening (compared to GSHP customers). Flath et al. [15] develop a cluster analysis of electricity load profiles with the aim of identifying customer clusters (not only households). Even though the study focuses on electricity consumption in general, and the perspective is business oriented, the methods applied have inspired the methodological approach of this paper (see also later section on methods). Flath et al. studied both day and week load profiles – both separated into three segments of the year: summer, winter and transition periods. In addition, the analysis was divided into weekdays and weekends in order to take