Heat load profile detection with the use of individual thermostat settings

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Abstract—Natural gas is the predominant source of energy in the residential sector, primarily used for space heating. Reducing the consumption of carbon based sources is one of the pathways to reduce the worldwide temperature rise. Current European policy measures hinge on the energy assessment of dwellings with the use of labels. Energy labels estimate theoretical energy consumption on the basis of physical characteristics of dwellings. There are discrepancies between the estimated energy consumption in the determination of energy labels and actual residential energy consumption. In this paper, residential heat demand is assessed with the use of hierarchical clustering of thermostat programs of individual households, to analyse the influence of individual heat demand on residential energy consumption. The clustering of thermostat settings result in 6 distinct heat load profiles and the identification of two potential residential saving areas. The influence of individual heat load profiles is considerable and should be included in residential energy assessments, to adequately shape policy measures to move away from carbon based sources.

Index Terms—Heat load profile, Hierarchical clustering, Natural gas consumption, Energy label, Residential sector

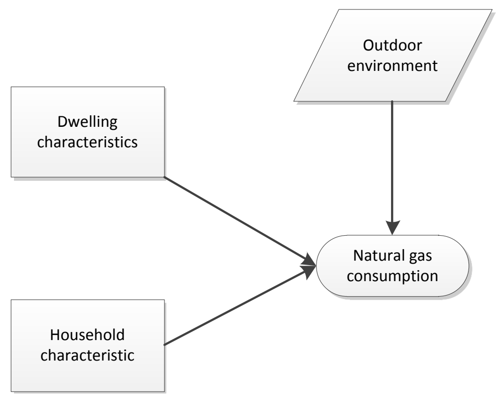

Fig. 1. Influencing factors residential gas consumption

1 Introduction

Reducing the consumption of carbon based energy sources is one of the goals set in the climate accord in Paris, to limit the world-wide temperature rise below 2 degrees [1]. The residential sector is responsible for over 55% of the natural gas consumption in the Netherlands [2], predominantly used for the heating of dwellings [3]. Residential energy policy objectives in the European Union to improve energy efficiency are based upon energy labels of dwellings [4].
The amount of natural gas consumed by individual households is dissimilar and dependent on multiple factors. The compulsory energy label of dwellings in the European Union, described in the Energy Performance of Building Directive (EPBD), is based upon theoretical energy consumption. The estimated heat consumption of a dwelling used for the classification of energy labels is based upon the physical characteristics of that dwelling. There are discrepancies between the estimated heat consumption based upon physical characteristics and actual heat consumption of dwellings [5]. Even households with similar dwelling and similar household characteristics have shown dissimilarities in their heat consumption [6]. Whereby residential behaviour is seen as the largest source of uncertainty in the prediction of energy consumption [7].

Individual residential natural gas consumption is influenced by 3 factors [8], graphically shown in figure 1. Dwelling characteristics and household characteristics can be adjusted by residents while the outdoor environment is dependent on the location of the dwelling. Dwelling characteristics account for the physical characteristics of a dwelling related to the thermal inertia of a dwelling. The influence of residential behaviour and household composition is embedded in household characteristics.
The influence of household characteristics in the form of thermostat settings is analysed by determining heat load profiles. Heat load profiles can be seen as the overall thermostat temperature settings of an individual dwellings. A heat load profile is the resulting thermostat setting dependent on the interaction of household composition and household behaviour. Similarities in heat load profiles are detected with the use of individual thermostat settings of dwellings. Individual household thermostat settings are assessed with the use of smart meter/ thermostat Toon. Individual heat load profiles in the form of thermostat settings are grouped with the use of unsupervised clustering. The impact of heat load profiles is assessed by determining the individual amount of natural gas consumed for heating a dwelling. Residential thermostat settings are clustered on the one hand to analyse

the degree of similarities in heat load profiles. And on the other hand, to analyse the impact of distinctive heat load profiles on residential gas consumption.
In section 2 the data gatherer to detect overall heat load profiles of individual dwellings is discussed. Followed up by the clustering method and type used to group similar heat load profiles. In section 3 the resulting heat load profiles are presented by discussing differences and similarities between heat demand profiles. The difference in natural gas consumption for each of the heat load profiles is discussed in section 4. The concluding remarks and recommendations are given in section 5.

2 METHOD

2.1 Clustering data

Clustering is used to group individual households with similar thermostat settings in the form of heat load profiles. The similar heat load profiles of household are assessed by analysing the thermostat settings and gas consumption of 1319 households. The data is gathered with the smart meter/ thermostat Toon. The thermostat settings are collected in the 3 coldest months of the winter of 2016-2017, December-February. The thermostat settings are collected in one hour intervals for all the weekdays in the winter period. The hourly thermostat settings consist of the average temperature settings within a dwelling for that hour. The thermostat settings for similar weekdays are grouped to produce a general thermostat setting overview of individual households for separate weekdays. To illustrate, the median is taken of the thermostat settings of every Wednesday at eleven within the three-month period for individual households. The heat load profile of households for similar weekdays is based upon the median hourly thermostat setting within the winter collection period. The weekends are left out of the scope due to disparate household habits between weekends. Because the median thermostat setting for similar hours in the weekend does not generate a representative overall thermostat setting program.
The amount of natural gas consumed for heating a dwelling is used to analyse the impact of separate heat load profiles. The natural gas consumption for heating is filtered out of the natural gas consumption by adjusting for non-heating events, with the use of smart thermostat and boiler communication.

2.2 Clustering method

The unsupervised clustering type of hierarchical clustering is used to determine similar heat load profiles. Unsupervised clustering is used to group sets of data that are unlabelled and is seen one of the most useful techniques for discovering patterns in underlying data [9]. Hierarchical clustering treats individual data cases as independent clusters and combines the clusters with the least distance between them. The distance between the clusters is based upon the similarity measure. The Ward similarity measure is used in the detection of overall heat load profiles. Out of the 7 clustering schemes provide by [10], the Ward similarity measure proofed most suitable in detection overall heat load profiles. The Ward similarity measure scored best on

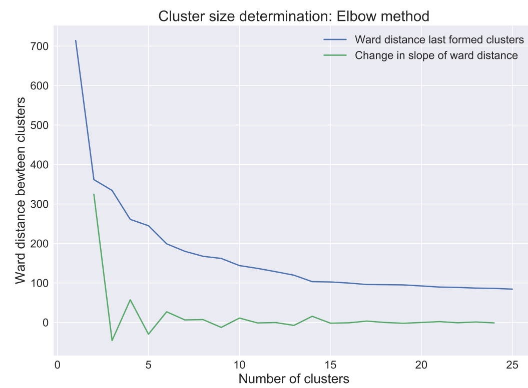

Fig. 2. Cluster size determination: elbow method

separating power and the resulting clusters demonstrate the lowest variance in thermostat settings within the separate heat load profiles.
The Ward similarly measure combines clusters on the basis of least variance between different clusters. The hourly variance in thermostat setting of the individual heat profiles is used in the Ward similarity method to determine the distance between clusters. The individual heat load profiles consist of the median thermostat settings of individual users. The heat load profile of each weekday is taken into account separately in the clustering analysis and henceforth called the user weekdays. User weekdays with the least variance in overall hourly thermostat settings are grouped together until a stopping condition is met.
The stopping condition for the ward similarity measure is determined with the use of the Elbow Method [11]. The Elbow method is used to distinguish the cluster sizes at which the drop variance within the clusters is largest. In figure 2 the Ward distance between the last formed clusters and the change in distance is shown. The distance between the last formed clusters demonstrates the largest distance between 2 clusters in the clustering analysis. Figure 2 indicates that the change in distance between the last formed clusters is largest at cluster sizes [4,6,10,14]. Each of the 4 cluster size stopping conditions are compared on the basis of similarities in resulting heat load profiles and representativeness of the resulting heat load profiles. A stopping condition of cluster size 6 scored best in the determination of similar heat load profiles. At cluster size 6, the similarity in heat load profiles is minimalised and the clusters that represent a substantial part of the population is maximised.

3 DETECTED HEAT LOAD PROFILES

The hierarchical clustering of overall thermostat settings of individual user weekdays is shown in figures 3, 4, 5, 6, 7 and 8. The heat load profiles are illustrated by the boxplot of the hourly thermostat settings for individual user weekdays. The box contains the midspread of 50% of the temperature settings and 95% of the settings are contained within the lines.

The heat load profiles of individual user weekdays share overlapping elements while being clearly distinguishable.

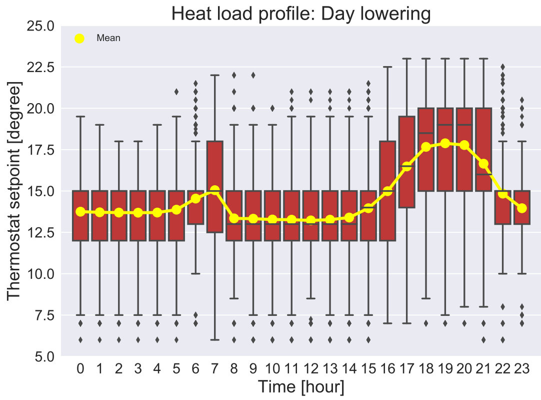

Fig. 3. Heat load profile: Day lowering

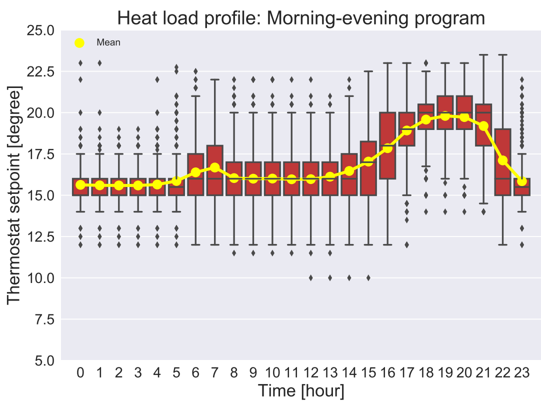

Fig. 4. Heat load profile: Morning-evening program

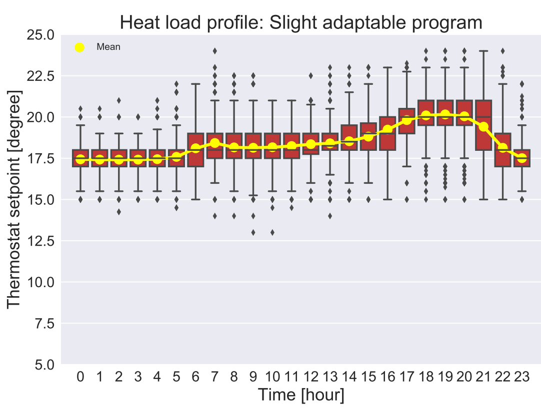

Fig. 5. Heat load profile: Slight adaptable program

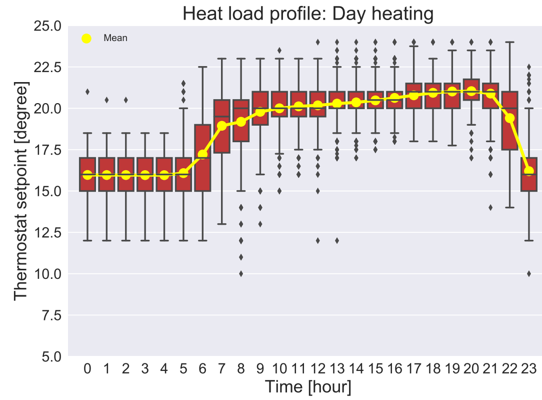

Fig. 6. Heat load profile: Day heating

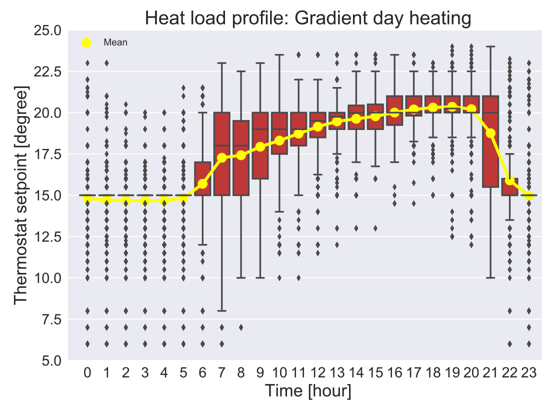

Fig. 7. Heat load profile: Gradient day heating

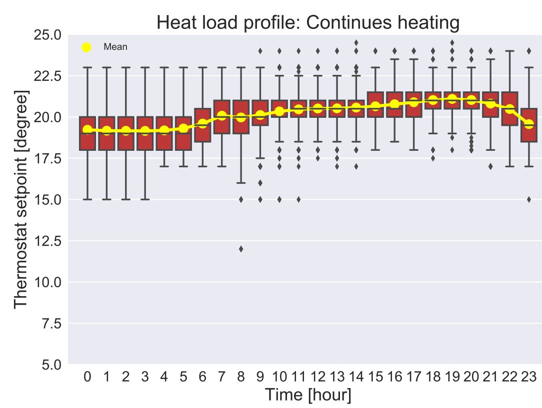

Fig. 8. Heat load profile: Continues heating

The different heat load profiles have 2 similarities in common between all the clusters. First of all, in each of the load profiles the thermostat settings are lowered overnight, compared to the day time settings. Secondly the moments when the thermostat is turned up and down. In each of the heat load profiles the thermostat is turned on in the morning and off again in the evening.
There is a clear separation between the heat load profiles during the day time in temperature settings. Figures 3, 4 and 5 represent the user weekdays with a lowered day time thermostat setting compared to figures 6, 7 and 8 with a heating daytime setting. Within the heat load profiles with a lowered thermostat setting a similar pattern can be detected. The thermostat is turned on and off again in the morning within these heat load profiles.
The exemplification of each of the heat load profiles is

shown in figure 1, in the form of percentage of households in the corresponding cluster. Two potential saving areas can be identified by analysing the different heat load profiles. Firstly in 3 of the 6 heat load profiles accounting for 51% of the user weekday population [D,E,F] have a day time heating pattern. Indicating that there is a potential to save natural gas consumption in the residential sector by lowering the thermostat during the day. The temperature can be lowered when residents are not actually at home or to a lower comfortable temperature. Secondly the majority of the user weekdays in heat load profiles [C,D,F] have an thermostat setting above 15 degrees during the night.
The clustering of heat load profiles indicates the existence of distinctive general heat load profiles. The clear difference between overall heat load profiles indicate the importance of including thermal profiles in the assessment of natural gas consumption in the residential sector. The second insight the clustering of heat load profiles generates is the possibility to target residential energy saving policy to high saving potential households. The consumption of natural gas for heating a dwelling is used to link heat load profiles to energy consumption in section 4.

4 Heat load profiles and gas consumption

The daily natural gas consumption of each of the heat load profiles is shown in a box-plot in figure 9. The box contains the midspread of the daily natural gas consumption in the collection period for 1319 households and 95% of the daily gas consumption is contained within the lines. The referencing index letter and corresponding heat load profile is shown in table 1. The heat load profiles consisting of the user weekdays without day time heating [A,B,C] clearly have a lower natural gas consumption that the heat load profiles who do [D,E,F]. Figure 9 displays the range in daily gas consumption, the natural gas consumption for each of the profiles clearly overlaps. The similarity in daily gas consumption is substantially larger in the heat load profile consisting of day time heating user weekdays.

To statistically determine the variation in daily natural gas consumption between the heat load profiles an one sided ANOVA is used. In the ANOVA test the average daily gas consumption per household in the winter period is used, shown in table 2. The daily average is taken to compare the overall heat load profile to the average daily natural gas consumption. The ANOVA results in table 2 support the findings in figure 9. There is a significant variance between all the different heat load profiles and the heat load profiles representing non day time heating. There is no significant

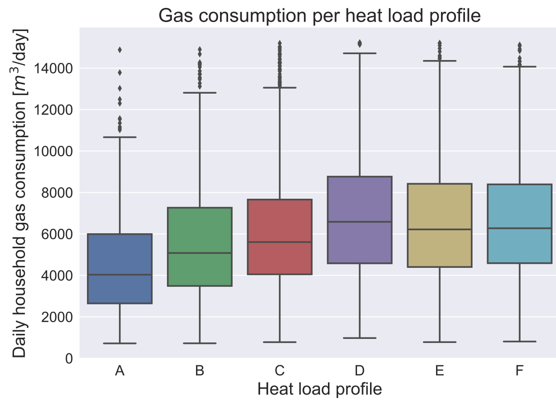

Fig. 9. Daily gas consumption for heat load profile

difference in the natural gas consumption of the heat load profiles of day time heaters.

The overlap in daily natural gas consumption is in line with the multiple factors that influence the natural gas consumption of dwellings shown in figure 1. The role of other influential factors than the thermostat settings is shown in the overlap between daily gas consumption. The considerable overlap in daily gas consumption of the day heating profiles [D,E,F], indicates that the influence of heat load profiles becomes less dominant when a dwelling is heated for longer periods during the day. The limited variance in natural gas consumption of day heating heat load profiles is expected. When a dwelling is heated for most of the day, the influence of alternative thermostat setting programs is limited.
The heat load profiles consist of dwellings with disparate physical characteristics of dwellings. Even for disparate dwellings a difference in daily natural gas consumption can be detected for separate heat profiles, indicating the impact of thermostat settings on natural gas consumption. The variance in natural gas consumption of separate heat load profiles indicate the potential to aim residential energy saving policy measures to inefficient thermostat use with relative high natural gas consumption.

5 Conclusion

With the use of hierarchal clustering of individual thermostat settings overall heat demand profiles can be detected. The clustering of individual thermostat settings results in the detection of 6 distinction heat load profiles. The heat demand profiles show clear differences in the thermostat settings in households with similarities in some aspects. The heat load profiles indicate two potential areas for reducing the residential natural gas consumption for around 50% of

TABLE 1
Heat load profiles and exemplification

Heat load profile		Exemplification heat load profile - Households in cluster [%]
A	Day lowering	11
B	Morning-evening program	19
C	Adaptable program	19
D	Day heating	21
E	Gradient day heating	18
F	Continues heating	12

TABLE 2
Variance daily gas consumption (ANOVA)

Clusters	*F value*	*p value*
All	50.9	$1.1 * 10^{-51}$
a,b,c	33.6	$4.1 * 10^{-15}$
d,e,f	2.4	0.088

the population, by lowering the thermostat overnight and during day time. To assess the extent of saving by lowering the thermostat during the day the thermal needs of residents need to be included. For example, by detecting whether residents are actually at home during the day.

The average daily gas consumption of separate thermal load profiles is dissimilar, especially in thermal load profiles without day time heating. The difference in daily gas consumption is visible for a mixture of dwellings with disparate dwelling characteristics. The difference in average daily gas consumption of separate heat load profiles displays the role of thermostat settings in the natural gas consumption of dwellings.

The clear disparate heat load profiles of individual households indicate the importance of including household characteristics residential energy policy. The heat load profiles conflict with the assumed constant inside temperature of 18 degrees in energy label determination [12]. The variation in natural gas consumption between dwellings with separate heat load profiles indicates the opportunity to aim policy measures at households with inefficient thermostat settings and relative high natural gas consumption.

5.1 Discussion

The thermostat settings of Toon users are gathered in the assessment of residential thermal load profiles. The household composition of the selected Toon users is not representative for the general population. Toon provides a preprogramed thermostat and enables users to easily adapt their thermostat programs to their needs with the use of an in-home display and mobile application. This is not the case for the general population whereby the thermostat interaction differ for users without or a different smart meter/thermostat [13]. The distribution of users over the different heat load profiles and the profiles itself might differ from the general population due to non-representativeness of the sample group. Whereby the extent of inefficient thermostat setting might not resemble the general population. However the importance of including heat load profiles in residential energy policy is present because of the distinct heat load profiles and corresponding natural gas consumption.

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