Electricity Consumption Analysis of Customer Connections with Ground Source Heat Pumps

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SUMMARY

Energy saving policies of EU and national governments have set pressure to save energy, to improve energy efficiency and to increase the use of renewable energies. When in Finnish households the heating of spaces and hot water represents a considerable share of the energy use, the modern heat pump technology is one appealing option in achieving the energy saving objectives. The growth of heat pumps has been astonishing. The development has also influence on the sphere of operation of the local distribution system operator (DSO). New load models are needed. In addition, based on automated reading measurements (AMR) DSOs should identify major changes in the electricity use (change of the heating type) and further update the basic customer data in various data bases and analyses. The increase in heat pump installations will affect the use of electricity. Both the level and the load curve profile will change and thus the penetration will influence the network rating and the business environment. This paper presents electricity consumption analysis of household customer connections with ground source heat pumps (GSHP). The data included electricity usage data of households that had changed their heating system to GSHPs. The identification of the change of the heating system succeeded applying data of annual energies. The profile of the GSHPs resembles the profile of households heated by direct electricity. The level of electricity use of a single GSHP household increased or decreased depending on the original heating system of the house. Spatial analysis of how in residential areas the invasion of heat pumps could affect the power system on the primary substation level resulted to scenario of having minor increase of the spatial energy and decrease of maximum loads on the substation level.

KEYWORDS

annual energy, electricity heating system, ground source heat pump, heating, hourly model, indexed curve

1. INTRODUCTION

Heat pumps have become modern and trend option in heating. [1]-[4] The popularity is based on savings in heating energy and costs, increased energy efficiency, and decreased emissions of greenhouse gases. In Finnish climate, space heating is vital. The heating energy consumed in buildings was 81 TWh in 2012. In household and service buildings, the share of heating energy produced by heat pumps was 12 % in 2012. In addition to heat, heat pumps can produce cooling. However, in Finnish households cooling is not widely applied. On the opposite, in office buildings cooling has been a standard characteristic for a longer time.

This paper focuses on electricity consumption analysis of household customer connections with ground source heat pumps in Finland. Typically, if a household is heated by electricity, the annual electricity usage could be divided e.g. to space heating ca. 50 %, to domestic hot water heat ca. 20 % and to the appliance consumption ca. 30%. When the heating represents a notable share, major changes in that part also affect the power system. In Finnish households, the most popular types of heat pumps are air to air heat pumps and ground source heat pumps. GSHPs are used as primary heating systems. Meanwhile, the more popular air to air heat pumps operate as an auxiliary system and need another main heating system. In this paper, only the GSHP systems are analysed.

The invasion of heat pumps would have an effect on the power system and the DSOs area of business. Thus, there is a need to analyse the realized systems, create models and research the influence on the power system. This paper introduces results of electricity consumption analysis of household customer connections with GSHPs in Helsinki. Four main questions for the analysis were launched:

1. How to automatically detect a change in the heating system from measurement data?
2. What would be the load model (indexed curve, regression model) of a GSHP customer?
3. What will be the change in annual electricity consumption when a customer originally with/without electricity heating system changes to GSHP system?
4. How the invasion of GSHPs would affect the power system on the primary substation level in a residential area of Helsinki?

2. DATA OF THE ANALYSIS

Household customers having GSHPs for their heating systems were the core group of the research study [5]-[6]. To determine and find the locations of these customers, a starting point was a list of boreholes received from the city authorities. By linking this data further to DSOs data of connection points, various utilities data bases (measurement data base, customer data base, and network information system) were reachable. The linking of the different data sources was an important part in the beginning of the study.

In city surroundings where the land area is limited, GSHPs are typically ground coupled heat pumps with vertical borehole installations. The depths of holes are 100 – 200 m. When planning a heating system of a GSHP with vertical boreholes, a permission will have to be applied from city authorities. Thus, the data of GSHPs is found from city data bases. However on the DSOs side, especially in cases where a customer is changing the heating technology, DSOs will not automatically or typically receive the information of this change. The research started with a city authority list including data of boreholes and the corresponding data of real estates. In Helsinki, city authorities have reliable data for the date of drilling of boreholes since spring 2011. Data of older boreholes exists but the exact drilling dates of these holes are more unreliable. Further a link between real estates and connection points were needed. Real estates are geographically determined areas. On DSOs data bases, connection points have coordinates. Now, the borehole (real estate) and an electricity connection point could be linked via the geographical area of a real estate. At the starting point of the study in spring 2012, Helsinki had ca. 1100 boreholes. However for the study purposes, only those GSHP real estates having only one connection point were included. Finally, the analysed data base included 657 connection points comprising 1113 metering points. The majority of the metering points were detached houses (Table 1).

TABLE 1. The customer types of the analysed metering points in DSOs data bases.

Customer type	Amount
Detached house, direct electric for heating	174
Detached house, partly electric storage heating	101
Detached house, electric storage heating	53
Detached house, no electric heating	427
Attached houses, blocks of flats, no electric heating	250
Blocks of flats, property electricity	71
Services, private sector	29
Other	8
Sum	1113

The real estate data includes also data of the area of the buildings belonging to the real estate. In the research, this data was applied when determining the specific consumptions of GSHP customers.

By knowing the metering points, the electricity usage data and various customer data from DSOs data bases could be included to the analysis. Electricity usage data included two data sources from Helen Electricity Network:

- Annual energies from 2002 – 2012
- AMR measurements from 2008… 2011 – 2012. The time periods of available AMR varied according to the installation schedules of the meters in Helsinki

Table 2 presents the data sources introduced in this chapter 2 and in addition, the methods performed in the research. The methods and analyses are reported more detailed in chapter 3.

TABLE 2. The methods and data sources of the analyses.

		Identification of changes	Distinguishing from other customer types	Day profile and regression model
DSO Helsinki GSHP customers	AMR[1] Annual energies[2] Drilling date[3] Customer type[4]	 X X X	X	X
DSO Helsinki reference customers	AMR[1] Customer type[4]		X X	
Finnish Meteorological Institute	Temperature[5]	X	X	X

[1]AMR data base
[2]Customer data base
[3]City office of real estates
[4]Network Information System
[5]Finnish Meteorological Institute

3. MODELS AND ANALYSES

3.1 Detection, classification and models

The customer group with GSHPs in Helsinki could not be formed simply by linking borehole data from the city (Helsinki) to real estate data and further to electricity usage data, because one connection point could consist of more than one metering point. All these metering points were not necessarily GSHP customers. Generally and as a research case, DSOs should be able to automatically detect from the measurement data the major changes of electricity usage (here changes of a heating system). In this research, the aim was to identify when the customer has changed to a GSHP system and what was the original heating type. GSHP customers were tried to be identified by detecting a change in the daily electricity consumption using AMR data. However, it was noticed that daily consumptions were too irregular and there was not enough AMR data to be able to make reliable analyses for individual customers. The study approach suffered from the limited period of AMR data. Another approach was to identify the change of the heating system by detecting changes in annual electricity consumption. A predictive Chow test was applied to the linear regression model for annual consumptions. Only the annual heating degree day was applied as an explanatory variable. The method worked rather well. It was able to detect a change in the heating system when the dependence between annual consumptions and heating degree days changed significantly.

Above was reported how to detect when a customer had changed the heating system to a GSHP system. Another task was to classify customers to customer groups. An approach of a principal component analysis (PCA) and K-means clustering techniques were applied to measurement points. The principles of the PCA and K-means clustering are here only briefly explained and reported more detailed in [7]. The same methodology has been applied in the corresponding research project in [4]-[6], [8]-[9]. The PCA is one of the many dimension reduction techniques available. The aim is to reduce the dimension of the data (the number of variables) to a more manageable dimension; the aim is to find a small number of variables that still retain the most important characteristics of the original data. PCA finds linear components of the original variables from the data that explain as much of the variance in the original data as possible. These components become organised in an order where the first principal component (PC) explains most of the variance, the second PC the second most, and so on. The following analysis should thus concentrate of the first few PCs. [10]-[11]

The data matrix used in the PCA was [7]

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1p} \\ x_{21} & x_{ij} & & \vdots \\ \vdots & & \ddots & \\ x_{n1} & \cdots & & x_{np} \end{bmatrix} \quad (1)$$

where x_{ij} is the measured consumption of the i:th metering point at hourly measurement j, n is the number of metering points and p is the number of variables in the original data (the number of analysed hours). Two possible actions can be taken with the data matrix before running the PCA: annual energy and variable scaling [7]. Metering points consume different annual energies, i.e. they are of different size. This size information can either be included in the PCA or removed from the analysis. A reasonable way to remove the size information is to scale the hourly average of each metering point to one, as in [7]. The PCA does not do clustering. Thus, there is a need to form groups from the PCA results. K-means clustering was selected for the clustering, as in [7].

PCA and clustering with K-means were applied to AMR data of 261 GSHP customers and 847 randomly selected reference customers with different consumption profiles from another city district of Helsinki. The hourly measurements were taken between 1st of January 2012 and 31st of December 2012. Both annual energy and variable scaling were done to the AMR data before applying PCA. K-means clustering was done to six most significant principal components without the fourth one. The fourth PC was interpreted to explain structural changes of electricity consumption in the middle of the year, and therefore it was not relevant information for the clustering in the analysis. The number of clusters was selected to be four, as four different clusters could be interpreted as meaningful customer classes. Figure 1 shows the first and second PC scores coloured with the results from the K-means –clustering.

Customer classes were interpreted as direct electric heating, storage electric heating, district heating and property measurements. The property measurements usually measure the consumption of the devices that are common for all consumers on the property such as outdoor or staircase lighting and elevators. Out of the total 261 GSHP customers, 241 were classified to direct electric heating group. This group consisted of 407 (including 241 GSHP customers) customers that clearly had an electricity consumption profile of a direct electric heating customer type. The electricity consumption profiles of GSHP and direct electric heating customers are so similar that they could not be differentiated when using only the hourly measured data without size information. The only difference is that the direct electric heater has a very high consumption peak in the evening whereas GSHP customers do not. This peak is most probably caused by the two-time tariff where at the starting moment of the cheaper night-time electricity e.g. the domestic hot water heat is switched on. Households with heating of direct electricity have had this kind of tariff in use. Figure 2 presents the daily electricity consumption profiles of an average GSHP and direct electric heating customers. It was considered that the clustering might be able to differentiate these better if it had information about the floor area and the consumed annual energy.

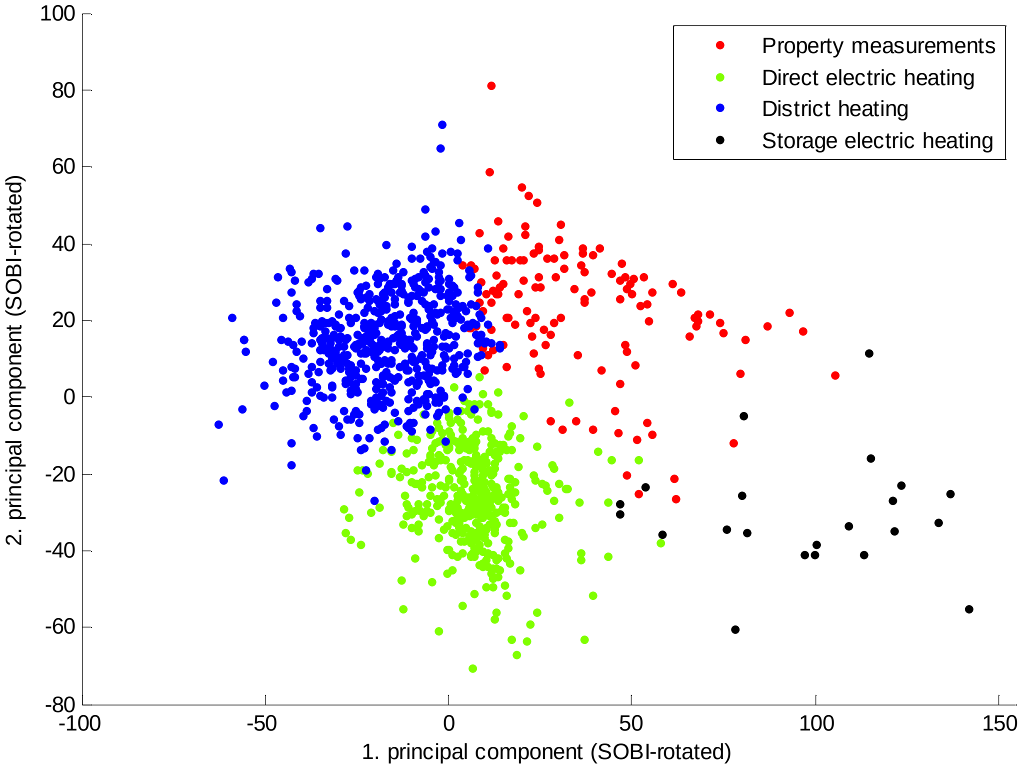

Figure 1. The scores of the first and second principal components. The clusters are a result from the K-means –clustering.

a) b)

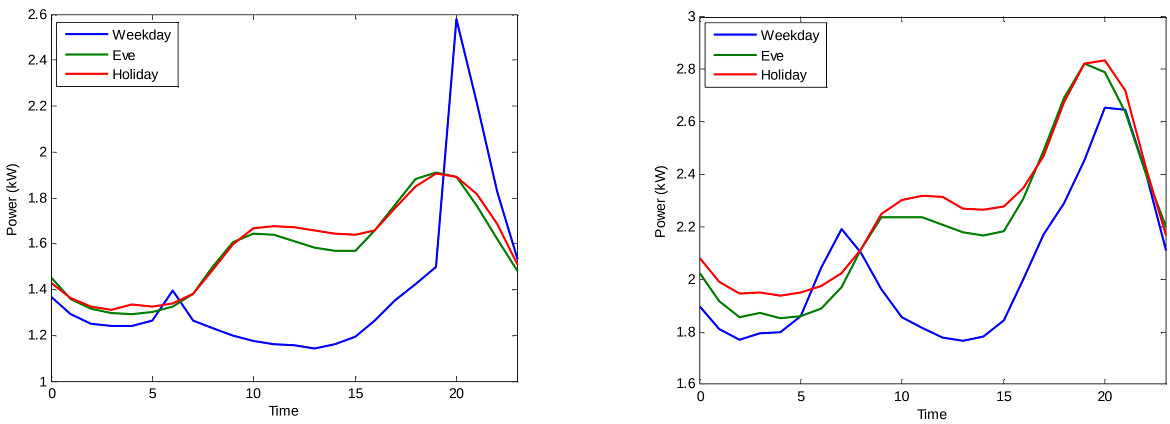

Figure 2 a). Daily profile of an average direct electric heating customer. b) Daily profile of an average ground source heat pump customer.

In the performed study, the electricity usage of GSHP customers was mainly compared to the direct electric heating customers. Although they could not be differentiated with used methods, they had some visible differences. A linear regression model for the daily energies of an average GSHP customer was created. [12] The model used in the study can be written as

$$y = b_0 + \boldsymbol{x}_{Temp}\boldsymbol{b}_{Temp} + \boldsymbol{x}_{dLen}\boldsymbol{b}_{dLen} + \boldsymbol{x}_{dType}\boldsymbol{b}_{dType} + \varepsilon \qquad (2)$$

where the dependent variable y is the average electricity consumption sum of a day, and b_0 is the constant that sets the level of consumption. Vectors $\boldsymbol{x}_*$ multiplied by the coefficient vectors $\boldsymbol{b}_*$ are the effects of different explanatory factors [7], and ε is the error term in the model. The subscript *Temp* refers to daily average outside temperature, *dLen* to the day length, and *dType* to the day type. A moving average of two days was used with the outside temperature, day length was calculated mathematically [7], and the day types were separated as working days, eves and holidays.

With the data presented in this paper, it was noticed that there is nonlinearity in the effect of outside temperature on the daily energies on warm temperatures. This was modelled with a partly-linear function using a knee-point at 12 °C, as in [7]. This method enables the different behaviour of daily energies on cold and warm temperatures while keeping the model linear.

For the direct electric heating profile, the knee-point at 12 °C was enough to model the non-linear effect of outside temperature. However, for the GSHP profile, there was a clear need for another knee-point at -5 °C. The resulting fit for an average GSHP customer profile can be seen in Figure 3. Figure 3 imply that the GSHP customer have higher temperature tendency at the colder days, which should be taken into account when modelling the GSHP profile.

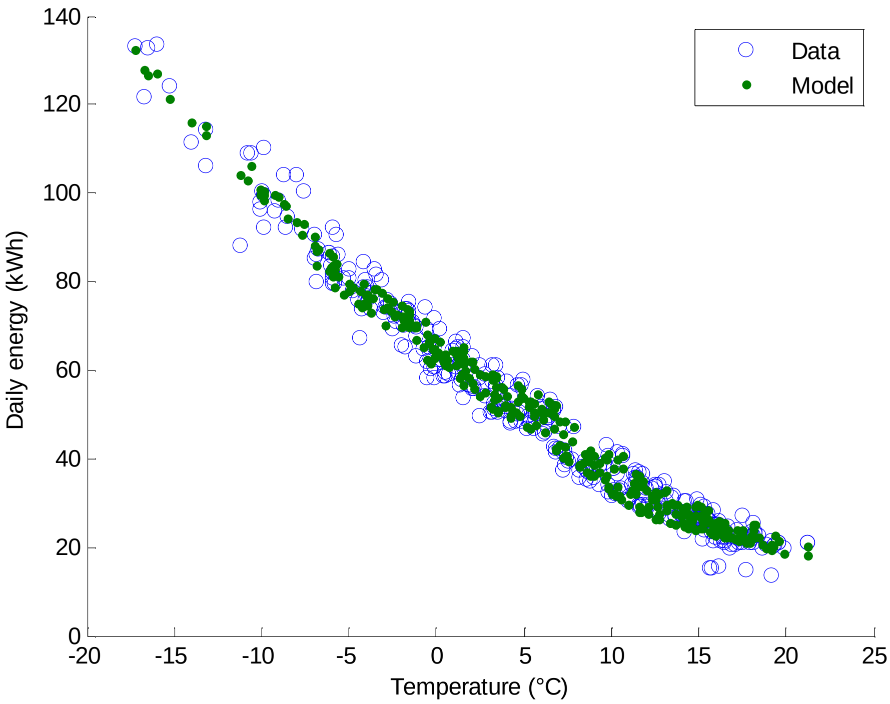

Figure 3. Daily electricity consumptions of an average GSHP customer against daily mean temperature of moving average of two days. The nonlinear effect of the outside temperature on daily energy is modelled as a partly-linear function with knee-points at -5 °C and 12 °C.

3.2 *Electricity consumption*

An interesting research task was to determine how the specific consumption or the annual energy will alter after the change in the heating type. The year of the heating system change for GSHP customers were searched and the annual electricity consumptions before and after the switching year were analysed. Customers were linked to the floor area data. With this information the mean and median annual consumption per floor area (kWh/m²) could be defined. Customers that were classified as switching from electric heating had a median consumption per floor area 222 kWh/m². The decrease in annual consumption when switching to GSHP was on median 53 %. When analysing the customers that switched from non-electric heating, the increase in annual consumption was on median 150 %. Consumption per floor area was on median 39 kWh/m² for non-electric heating. It was observed that the change in annual electricity consumption seemed to have almost no correlation with the floor area. Figure 4 shows the changes in annual consumptions as a function of the floor area. The results show that the median consumption per floor area for GSHP customers was 101 kWh/m².

The construction years of the buildings could also be obtained from the property data. It was clearly seen in this data that the buildings built in 1950s and 1960s consumed more electricity per floor area than the newer ones. This was especially clear when analysing the consumptions before switching from electric heating to GSHP.

a) b)

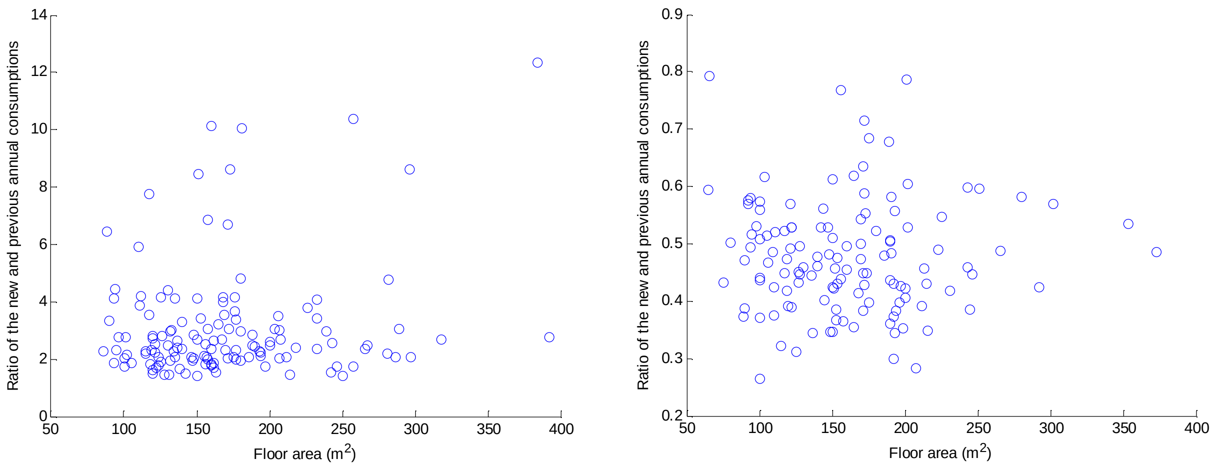

Figure 4 a). Ratio of the new and previous annual consumptions as a function of floor area when switching from non-electric heating to GHSP heating, b) Ratio of the new and previous annual consumptions as a function of floor area when switching from electric heating to GSHP heating.

3.3 *Spatial load forecasts*

A major penetration of GSHPs would affect the power system. In spatial load scenarios, the starting point is the analysed, present electricity consumption and demand and trends in the electricity usage. As above was presented, the profile of a GSHP customer resembles a profile of a customer with heating of direct electricity. In the applied data, the annual energy of a non-electric household was about 39 kWh/m^2, a GSHP customer 101 kWh/m^2 and an electric heating household 222 kWh/m^2. In this study, the customers that had changed their heating system were ca. 50 % from non-electric system (oil, district heating) to GSHP and the other half represented those households that had changed the electric heating system to a GSHP system.

In spatial long term load forecasts, the task is to model the development of the society and city into spatial future electricity usage and power demand. One of the most important aspects is to model the growth of the city. In addition, the changes in the electricity usage are included to the scenarios. Here, especially the future construction of the city, the heating solutions of new buildings and the renovations of heating systems of old buildings were modelled.

For a DSO the study of a major penetration of GSHPs is interesting and important. Considerable changes in heating practices inevitably have an effect on the power system. In this research, spatial, long term scenarios were performed to four Helsinki city sub-districts to demonstrate what would be the spatial annual energy and maximum load in 2030 when a certain share of the present (old) houses will change their heating system to GSHP and partly the new houses will choose GSHP for their heating system. These city sub-districts mainly consist of households with detached and attached houses. During the becoming decades, the city will develop and future construction is expected to take place. The city authorities make scenarios of the future construction of the city. Table 3 presents the present building areas and future construction plans of the studied city sub-districts.

TABLE 3. Present and planned building areas.

	2010		New 2011 - 2030	
	Housing (m^2)	Offices (m^2)	Housing (m^2)	Offices (m^2)
City sub-district A	115 093	14 774	34 900	7 400
City sub-district B	123 860	13 797	26 600	0
City sub-district C	296 256	32 570	13 300	0
City sub-district D	276 426	56 399	34 100	400

Housing in these city sub-districts includes detached houses, attached houses and blocks of flats according to the Table 4.

TABLE 4. Present types of houses.

	Detached houses	Attached houses, blocks of flats
City sub-district A	86 %	14 %
City sub-district B	79 %	21 %
City sub-district C	62 %	38 %
City sub-district D	66 %	34 %

Two scenarios were built where the heating type of new detached houses were varied (Table 5).

TABLE 5. Heating types of new detached houses in the normal and fast scenario.

	Scenario	
Heating type	Normal	Fast
GSHP	50 %	80 %
Electric heating	25 %	10 %
District heating	25 %	10 %

In addition, it was assumed that a part of the old detached houses will change their heating system to GSHPs: in normal scenario 40 % of households of present storage electric and district heating, in fast scenario the percentage was 80 %.

Modelling was done applying hourly indexed curve models for various customer types. The scenarios with GSHPs show that the invasion of GSHPs would mean that the spatial annual energies will increase and the maximum demands decrease compared to the scenario without GSHPs (Table 6). The profile of GSHPs is smoother than profiles of e.g. electric storage heating (Figure 5). Thus, the maximum demand will be lower, the day time usage of energy will increase and the difference between night time and day time maximum demands will be smaller. The spatial profile will change and the hour of the maximum demand will alter.

TABLE 6. Spatial energies and maximum demands in 2030 compared to the year 2010 with future city construction and various heating solutions.

			Scenarios		
		Year 2010	Without GSHP	Normal	Fast
City sub-district A	Energy	14,3 GWh	133 %	133 %	137 %
	Max demand	5,1 MW	131 %	120 %	120 %
City sub-district B	Energy	39,9 GWh	107 %	107 %	109 %
	Max demand	7,5 MW	112 %	108 %	112 %
City sub-district C	Energy	33,9 GWh	104 %	104 %	105 %
	Max demand	12,2 MW	104 %	100 %	98 %
City sub-district D	Energy	29,3 GWh	111 %	114 %	119 %
	Max demand	9,1 MW	112 %	109 %	113 %

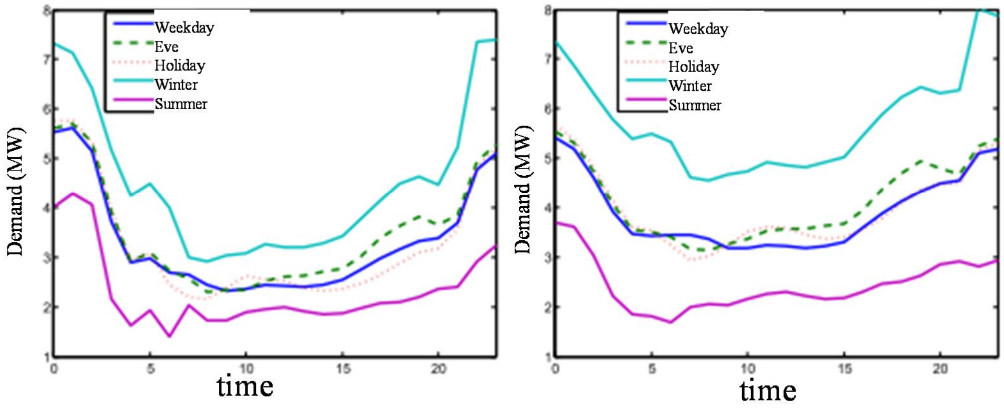

Figure 5. The spatial load profiles for the city sub-district D from 2010 (on the left) and in fast scenario in 2030 (on the right).

It was also studied how the electricity usage will develop caused by only the changes of the present heating systems without future construction. In the analysed city sub-districts without future construction the normal and fast scenarios would result to a minor increase of electricity usage. The maximum demand would decrease in the normal scenario and increase in the fast scenario. In city sub-district C, the max demand decreased also with the fast scenario.

4. CONCLUSIONS

The popularity of heat pumps has considerably increased during the past years. Heat pumps are attracting when aiming in decreasing the use and cost of energy. This paper presented results of analyses of electricity consumption of household customer connections with GSHPs. In the analysed cases, the annual electrical energy was halved when a customer primarily having an electric storage heating system changed to a GSHP system. On the contrary, the annual energy of a household of non-electric heating increased by 150 % after installation of GSHPs. A high penetration of GSHPs would influence the power system and DSOs business area. GSHPs represent a new customer type and in general, DSOs should detect from measurements the changes of the customer type (changes in heating systems). In the performed studied, this was automatically done analysing annual energies. The detection from AMR measurements needs more research. From AMR data, new profiles and regression models can be created to GSHPs and were presented in this paper. Spatial analyses of high penetration of GSHPs are also an interesting topic. The heating changes and solutions as well of present buildings and future construction should be modelled. The presented GSHP scenarios of spatial areas of currently mainly detached houses showed typically increase in the annual energy but decrease in maximum demands. The spatial profile became smoother. When in city power systems, the network is rated based mainly on power demand, this development would mean possibilities to reschedule the future investments and/or consider lower rating of network components.

5. ACKNOWLEDGEMENT

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