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A Heat Demand Load Curve Model of the Swiss National Territory

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Abstract. This paper presents a bottom up model simulating the hourly heat demand load curve for space heating and domestic hot water production for Swiss buildings listed in the national building and dwelling register. The model was calibrated on the actual heat demand load curves of several building types and predicts the demand as function of external temperature and solar irradiation. In addition, it includes stochastic deviations to accurately reproduce the aggregated load of large building groups. Using a climatic database covering the whole Swiss territory, the model takes account of the diverse weather conditions and climate types. The aggregated simulated load curve is compared with the measurements from a large district heating network, demonstrating that key indicators such as peak load and ranked loads are very well reproduced. To disseminate the results, a GIS database was setup that estimates the aggregated heat demand load curve for any portion of the Swiss national territory. The proposed approach addresses the challenge of large territorial scale simulation using only limited information available on its building stock. The model can be easily adapted to generate load curves for other EU regions provided the required information is available for the building stock.

1. Introduction

In most EU countries [1] and Switzerland [2] [3] the final energy for space heating (SH) and domestic hot water (DWH) production contributes to a large share of greenhouse gas emissions. The Swiss 2050 energy strategy [4] has ambitious greenhouse gas emission reduction targets that will require, among other measures, a decarbonisation of our domestic heat production system, today still mostly based on fossil energy resources.

Planning large-scale integration of renewables requires investments in capital intense infrastructures. To convince decision makers that these investments will show long term environmental and financial benefits, simulations of possible alternatives are required, which can be done for example with an EnergyPLAN [5] model. All such models will require building a heat demand atlas, as for example the Danish one [6]. The hourly demand of final energy for heat production is a commonly required input for these models. A Swiss GIS heat demand atlas of the estimated yearly heat and electricity demand [3] was developed within the SCCER FEEB&D project. The paper presents a method to derive hourly load curves from these yearly heat demand estimations. The resulting database is shared by way of a web-service providing an hourly heat demand load curve for any hectare-sized pixel of the Swiss territory.

Models based on building physics used at building level [7] or at district level as Citysim [8] require detailed knowledge on the building components. Collecting such detailed information would not be feasible at the national scale.

The proposed alternative consists in using the actual heat demand load curves of several building types to calibrate a regression model predicting the heat demand depending on external temperature and solar irradiation. The unexplained part of the demand, as the differences between the prediction and real demand, is used to add a randomized variation to the prediction model. Adding at building level this randomization allows replicating the coincidence factor that occurs, when adding individual load curves together to estimate the total hourly demand of a district. Disregarding this effect would end up with an overestimated peak load at the coldest hour of the year.

This paper is divided into 3 sections; the methodology section that explains how the model is calibrated using the actual hourly heat demand for several types of buildings; the results section provides the setup of a GIS load curve estimation database with an example of application to a large district heating in Geneva; the conclusion summarizes the findings of this paper together with some discussion of the advantages and limits of the proposed approach.

2. Methodology

Figure 1 outlines the load curves estimation process. Starting from actual hourly heat demand of different building types, the generalized least square model defined in section 2.2. estimates the parameters required to predict the hourly heat demand depending on external temperature and solar irradiation. These parameters are stored together with the distribution of errors of the model Δq_{heat}.
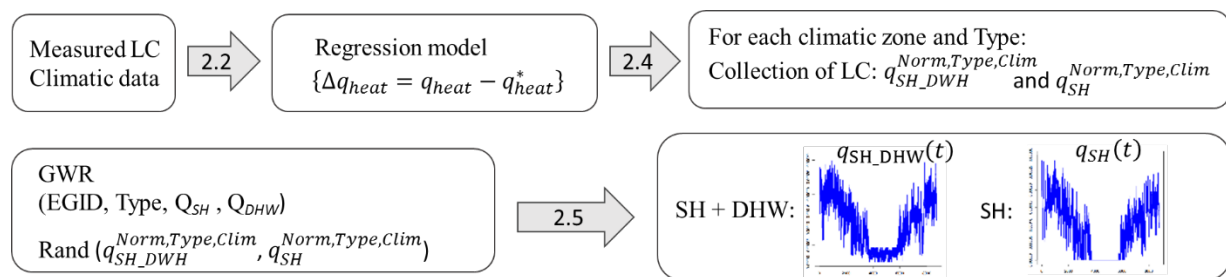
Figure 1. Overview of the load curve estimation model with corresponding sections

Using the parameters estimated by the regression model, the randomization process of section 2.4 generates for each building type and climatic zone a set of normalized hourly load curves. Each building of the Swiss national building register (GWR) [9] is linked to a random chosen normalized load curve that is picked out from its corresponding set. Since these load curves are normalized to have a total yearly consumption equal to one, it remains to upscale the associated load curve by a factor equal to the estimated yearly heat demand issued from [3] to get an estimated hourly demand. This finally allows to build the GIS heat demand load curve database described in section 2.5.

2.1. Measured load curves of different building types issued from case studies

The Energy Systems group of the University of Geneva has access to the hourly heat demand for buildings of various types. Table 1 lists the datasets used to calibrate the model. All these buildings are located in Geneva and the temperatures and solar irradiation measurements are taken from the Geneva airport meteorological station. In all cases except "Cartigny" the hourly heat demand is available separately for SH and DHW.

Table 1. List of case studies used to extract hourly measured heat demand load curves

Case study	Building type description	Measurement period	Type
Cartigny [10]	Single family, not retrofitted	2011	SF1
Laurana DC [11]	Multifamily residential, not retrofitted	2015	MF1
Laurana Chab [11]	Multifamily residential, not retrofitted	2015	MF1
Cigale [12]	Multifamily residential, retrofitted	2015	MF2
Pommier [13]	Multifamily residential, retrofitted	2006–2007	MF2
Polimmo [14]	Office, retrofitted	2011–2012	NR1

2.2. Calibration of a heat demand regression model

To predict the heat demand $q^*_{heat}(t)$ at a given date t we consider the regression model given by equation (1).

$$q^*_{heat}(t) = \begin{cases} q_{DWH} & if \; T_{ext} > T_0 \\ (T_0 - T_{ext})a_{i(h(t))} + bG_{irr} + q_{DHW} & if \; T_{ext} \leq T_0 \end{cases} \tag{1}$$

For a given date t, $h(t)$ denotes the hour of the day and q_{DHW} is the average heat demand for DHW.

Table 2 defines the index i as function of $h(t)$. This allows the regression model to use four different slopes a_i (i=1,...,4) depending on the hour of the day, to replicate the different regulation modes a heating system may have.

Table 2. Relation between the hour of the day and the slope used by the regression model

	night mode				morning reload	day mode			evening release	night mode		
Hour of the day	0	1	2	…	h_{nd}	$h_{nd}+1$	…	$h_{dn}-1$	h_{dn}	$h_{dn}+1$	…	23
Used index for a_i	1	1	1	1	2	3	3	3	4	1	1	1

In addition to these four slopes, the model will estimate the base load for DHW preparation q_{DWH}, the impact of solar gains b, the switching time from day to night mode h_{dn} and from night to day mode h_{nd}. These nine parameters are estimated solving the generalized least square problem given by equation (2) using the nlm function of R.

$$Min \; SSQ = min \sum_{t \in (1,8760)} \left(q^*_{heat}(t) - q_{heat}(t) \right)^2 = min \sum_{t \in (1,8760)} \Delta q_{heat}^2 \tag{2}$$

In case the hourly measured data is separately available for SH and DHW, the estimation procedure is applied to the SH load and q_{DHW} is set to 0. If the effect of global solar irradiation is disregarded, b is set to 0. For each case study listed in Table 1, the parameters of the regression model are estimated considering the following four cases: SH and DWH separately or not and taking account of solar gains or not. Table 3 contains for each case study these estimated parameters for the one of the four cases that has the smallest SSQ value.

When measurements are available separately for SH and DHW we compute an average demand $q_{DWH}(h(t))$ representing the load profile of a typical day for DHW production. For later use, we store also the 8760 Δq_{heat} values being the deviations between load predicted by the model and actual value.

2.3. GIS Climatic database for Switzerland

Using the climatic database IDAWeb [15] we extract the hourly external temperature and global horizontal solar irradiation of the year 2015 for 25 meteorological weather stations being at various altitudes and locations in Switzerland.

Table 3. Results of the regression model for the selected case studies

Type	Case Study	q_{SH} / q_{DHW} sep. (T/F)	Sol gains	q_{DHW}	a_3	a_2	a_1	a_4	T_0	h_{nd}	h_{dn}	b	Min SSQ
SF1	Cartigny	F	F	4.07	3.90	2.47	2.09	1.07	18.1	5	23	0.0	41'895
MF1	Laurana DC	T	T	0.00	3.61	0.92	2.50	0.93	19.2	6	21	$-2.9 \cdot 10^{-4}$	17'619
MF1	Laurana Chab	T	T	0.00	7.82	-0.05	5.76	1.02	19.1	5	21	$-6. \cdot 10^{-5}$	40'930
MF2	Cigale	T	T	0.00	5.16	0.11	4.72	0.65	16.4	1	23	$-2.4 \cdot 10^{-3}$	45'571
MF2	Pommier	T	F	0.00	1.28	0.43	0.93	0.33	17.2	5	20	0.0	8'225
NR1	Polimmo	T	T	0.00	2.36	1.12	1.54	0.91	18.0	5	21	$-5.1 \cdot 10^{-6}$	36'775

The SIA 380/1 norm [16] prescribes for each Swiss Canton a list of eligible meteorological weather stations to be used as climatic input for heat demand calculations. For Cantons having several eligible stations we select per municipality the one having the closest climate based on altitude and latitude criteria. This criteria is based on the strong correlation observed between heating degree days (HDD) and altitude plus latitude shown in [3].

2.4. Generation of a set of normalized load curves for each climatic zone and building type
For each building type and meteorological weather station we generate a set of 100 heat demand load curves such that the total yearly demand is normalized to one kWh. This is done for the total heat demand (SH + DWH) and SH only. The generation of such a load curve is done in three steps.

2.4.1. Definition of the heating season. We define the heating season using the following rules: (i) when the average temperature taken over 5 days is bigger than T_0 the heating season stops; (ii) when the average temperature taken over 5 days is below than T_0 the heating season starts. This is strongly related to the local climate of each weather station.

2.4.2. Computing non-randomized heat demand for SH and DHW. The load for SH, denoted by $q_{SH}^*(t)$, is computed using equation (1) and putting q_{DWH} to 0. Outside the heating season $q_{SH}^*(t)$ is set to 0. The total heat demand for SH and DWH $q_{SH\_DHW}^*$ is estimated by adding to $q_{SH}^*(t)$ the average demand $q_{DWH}(h(t))$ for DHW preparation.

2.4.3. Adding a random deviation to the load predicted by the regression model and normalization. The deviations observed between the measures and the model are swapped among days having a comparable demand. To do so, the daily average simulated $q_{SH\_DHW}^*(t)$ values are grouped into five classes. This gives five sub groups of days having comparable demand. For each day of the simulation year, a random day is selected within the sub group containing this day. The randomized estimated load curve is then

$$q_{SH\_DHW}^{Rand}(t) = q_{SH\_DHW}^*(t) + \Delta q_{heat}(Rand(t)) \tag{3}$$

The randomized demand for SH is obtained by subtracting $q_{DWH}(h(t))$. Negative values or hours outside the heating season are set to 0. Finally the randomized load curves are normalized using (4)

$$q_{SH\_DHW}^{Norm}(t) = q_{SH\_DHW}^{Rand}(t) / \sum_{t' \in (1,8760)} q_{SH\_DHW}^{Rand}(t') \tag{4}$$

The effect of the randomization effect is illustrated in figure 2. Without randomization, the predicted load would be very close to the yellow dotted lines and therefore not represent the true variability of the heating load. Adding the randomisation given by equation (3) leads to an hourly load prediction having a variance around the average demand for a given temperature that is comparable to the actual load shown in the right graphic of figure 2. In the next sections we denote the normalized load curves for the different climate stations and building types by using $q_{SH}^{Norm,Type,Clim}(t)$ for SH and $q_{SH\_DWH}^{Norm,Type,Clim}(t)$ for the total heat demand (SH + DHW).
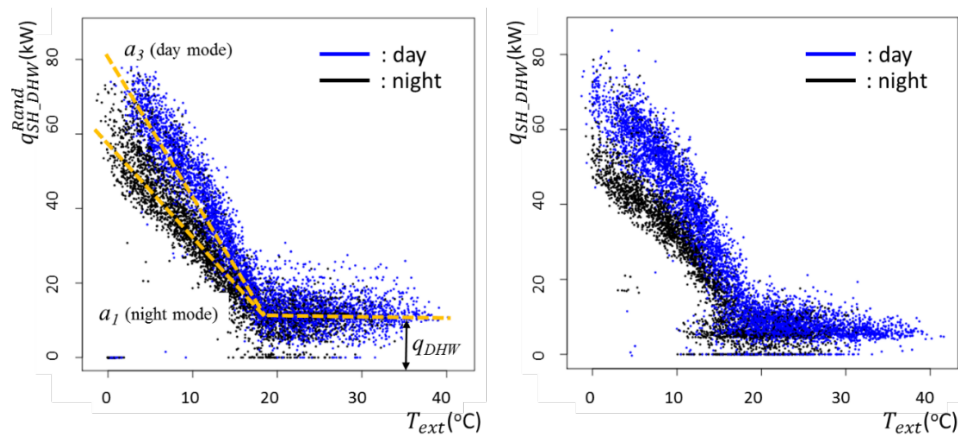
Figure 2. Hourly randomized load prediction (left) and actual load (right) depending on external temperature for the case "Laurana DC". The yellow dotted line is the load predicted by equation (1).

2.5. GIS heat demand load curve database

Each building of the GWR database is associated to a *Type* using the following mapping: (i) Single family residential buildings are associated to *Type* SF1; (ii) Multi-family residential built before 1980 to *Type* MF1; (iii) Multi-family residential built after 1980 to *Type* MF2; (iv) all remaining to *Type* NR1.

The climatic database of section 2.3 associates each building to a climate station based on the municipality where the building is located.

Finally using the mapped building type and associated climate station, we choose for each building two random heat demand load curves ($q_{SH}^{Norm,Type,Clim}$, $q_{SH\_DWH}^{Norm,Type,Clim}$) taken from the corresponding load curve set. The hourly heat demand of a building is simply obtained by multiplying the normalized load curves by the yearly heat demand for SH and the yearly heat demand for SH and DHW respectively.

3. Results

The resulting database contains 1.8 10^6 buildings having an estimated hourly heat demand load curve that can be aggregated at any territorial level. The total estimated heat demand for SH and DHW sums up to 81.6 TWh for the year 2015. This value is close to the 77 TWh estimated by [17].

3.1. Model validation

During 2014, the largest district heating of Geneva provided around 391 GWh to the 1'273 connected buildings [18]. Most buildings are multi-family residential buildings of type MF1. Figure 3 shows a comparison between actual and simulated heat demand. The model accurately predicts a peak load that is around 120 MW. The main differences are observed at the edge of the heating season. The model considers that all buildings stop and start space heating at the same date, whereas in reality there is a progressive start and stop of the heating systems. Surprisingly the actual loads have an unexplained drop during 12 cold days in December. The ranked loads are very similar showing that the simulated load curve replicates well the demand in terms of load distribution.

3.2. GIS heat demand web-service

A web-service [19] allows retrieving the estimated heat demand load curve for any portion of the Swiss territory. The hosting web-page contains the WSDL file, sample client scripts and a user manual. To get an access to this service a non-disclosure agreement must be signed.
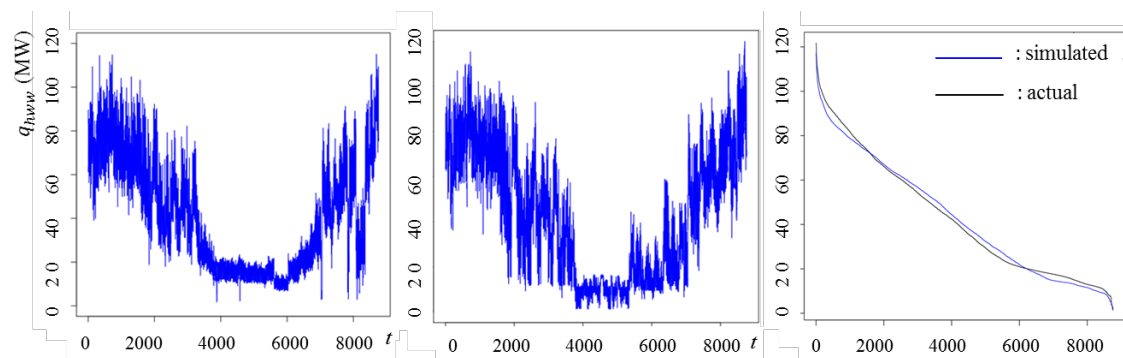
Figure 3. Actual (left) and simulated load curve (centre) of CAD SIG for the year 2014. On right graph, the actual and simulated ranked loads.

4. Conclusion

Using actual heat demand load curves issued from several case studies, a regression model is used to generate a set of 100 normalized load curves for the building types listed in table 1 and the various climate stations. As an alternative, several other regression models with increasing number of variables as well as support vector machine learning regression kernels were tested. The model of equation (1) was finally selected, because it was found to be the most effective.

The resulting set of normalized load curves permit to estimate the hourly heat demand of most of the buildings listed in the GWR database. The total heat demand of these 1.8×10^6 load curves is close to the yearly estimations of alternate studies.

Although temperature and solar radiation are the main variables that explain the heat demand, other factors as the thermal inertia, the regulation system and the user behaviour have an influence as well. For this reason not all buildings increase their heat demand exactly at the same moment when outside temperature drops. The randomization process added to the regression model allows to reproduce the coincidence factor observed when the heat demand load is aggregated over several buildings.

Larger improvement is possible for non-residential buildings, provided that more actual load curves are available, covering various building types and ages. The R scripts that estimate the regression coefficients and generate the normalized load curves can be used without changes. Extending the association of section 2.5 to the refined categorisation would improve the approach.

The accuracy of the model is tested by comparing the real load curve with the simulation output for the largest DH network of Geneva. Besides 12 days with surprisingly low real consumptions, being probably measurement errors, the model shows good accordance. Indicators such as maximum demand, ranked loads and the relation power/energy are well reproduced. This indicates that the outcome of a model simulating a multi-energy DH network would not be much affected when the real load curve is replaced be the simulated one. This reason speaks in favour to the conclusion that this model is good enough to serve as input for a multi-energy hub simulation for a residential district.

Finally the resulting database containing all results issued from this model is shared by way of a web-service to allow other research groups of the SCCER FEEB&D project doing simulations of district multi-energy grids on any portion of the Swiss territory.

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