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GEO-DEPENDENT HEAT DEMAND MODEL OF THE SWISS BUILDING STOCK

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Abstract

One of the strategies for decarbonizing the energy mix is to increase the use of district heat networks, for distribution of waste heat or heat produced by renewable energy sources. However, planning such networks needs a geo-dependent energy database concerning demand and supply, incorporating their dependency on space and time.

The present paper concerns the development of a bottom up statistical extrapolation model for estimating the heat demand of the Swiss building stock.

The database is constructed on top of the Swiss building register, which contains basic data on building category, age, ground area and number of floors, as well as area devoted to dwellings. The model itself concerns: (i) estimation of the heated area of each building; (ii) estimation of the heat demand of each building, with disaggregation in terms of space heating (SH) and domestic hot water (DHW).

The model is calibrated by way of recorded data concerning actual yearly energy consumption of around 27'000 buildings, with a classification by building category and age. The disaggregation in terms of SH and DHW allows for climatic correction of the observed data within a common climate basis. In a second step this calibration data is used for extrapolation of the demand on the entire Swiss building stock, for which the SH component is corrected by taking into account local climate characteristics.

Finally, statistical methods tend to quantify the uncertainty inherent to the use of average demand values by age and category, in relation to the level of spatial aggregation.

Keywords:

Geo-depended energy demand; domestic hot water and space heating; bottom up model; building classification

1 INTRODUCTION

During the year 2013, the Swiss final energy consumption for space heating of buildings and domestic hot water production is estimated to 330 (PJ/Year) by [1]. According to the national energy statistics, this represents approximately 40% of the total final energy demand. Within the Swiss Energy Strategy 2050, it is foreseen to reduce this demand by 63%, while increasing the share of renewable energy. Local renewable resources are numerous, however characterized by specific spatial availability, as well as temporal dynamics and quality (e.g. temperature), which limit their compatibility with demand. Hence, for assessing the potential of these resources and designing adequate infrastructure like district heating systems, geo-dependent energy databases concerning demand and supply are needed. We focus here on the development of a geo-dependent heat demand model of the Swiss building stock.

Previous work in this direction was done by [2], where hectare raster statistics on dwelling surface and number of working places serves to estimate the heat demand of the Swiss building stock. However, a later model supposes that all building categories have the same specific heat demand of 120 (kWh/m^2 year). At European level, [3] uses population density for estimating the heat demand on a 1x1 km raster. As an alternative to such statistical extrapolation methods, other authors try to simulate the energy demand of buildings in urban area by way of models based on building physics [4, 5].

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However, such an approach requires detailed information on the building's geometries as well as on the envelope components and associated U and g values. This turns out prohibitive at national level in terms of access to such data as well as in terms of computational time.

As a response to preceding questions and state of the art, this paper outlines the development of a statistical bottom up extrapolation model, which is based on measured heat demand and heated surfaces values of a representative set of about 27'000 individual buildings. As a result, and as an improvement to previous work such as [2, 6], we estimate the heat demand of each building of the Swiss national building register (GWR) as a function of its category, age and location, and its heated surface as a function of its category, gross surface and/or dwelling surface. Furthermore, a bootstrap resampling algorithm allows to quantify the uncertainty inherent to the use of average demand values by age and category, in relation to the level of spatial aggregation. This kind of approach could be applied to other countries or communities having a GIS database containing basic information of their building stock as for example the Austrian address and building register (AGWR) [7].

2 GEO-DEPENDENT HEAT ESTIMATION MODEL

The general structure of the model is shown in Fig. 1. The combination of basic information for each building from the GWR with average statistic indicators from the calibration sets allows to estimate the heated surface A_E (m^2) and the specific heat demand E (MJ/m^2 year), from which we derive the final energy demand E_B (MJ/year).

For each pixel of territory, the estimated heat demand is summed over all buildings, and a bootstrap algorithm allows to estimate the confidence interval around the average value given by the model.

2.1 Datasets

The model uses the following datasets:

(i) The Swiss national building register (GWR) maintained by the Swiss Federal Statistical Office [8] contains basic building information such as: geographical coordinates, category, age, ground and dwelling surface as well as the main energy carrier for around two millions of buildings. This database is not exhaustive for buildings without residential purpose. A comparison with the Swiss building footprint data layer [9] shows that around 400'000 buildings are missing. A unique federal building identification number (EGID) identifies each building, allowing to link this data with other databases.

(ii) The Geneva SITG database contains measured energy consumption as well as heated surface A_E defined according to norm SIA 416/1, for residential buildings and buildings used for nonresidential purposes. This declaration is mandatory and is updated each year by a network of trained agents.

(iii) The CECB database contains energy consumption averaged over three years. This is a certification covering buildings spread over the whole Swiss territory.

2.2 Estimation of heated surface

For each building of the GWR database, the heated surface A_E is estimated by way of the gross surface (number of floors x ground surface) and/or the dwelling surface.

The estimation is based on a set of linear regressions, on ten different building categories, given by 8'951 observations from the SITG database. As an example, we show the linear regression for the category of residential multi-family buildings (Fig. 2).

Note that the CECB database, which is anonymised, could not be linked to the gross and dwelling surface of the GWR, which is the reason why it is not used in this part of the process.

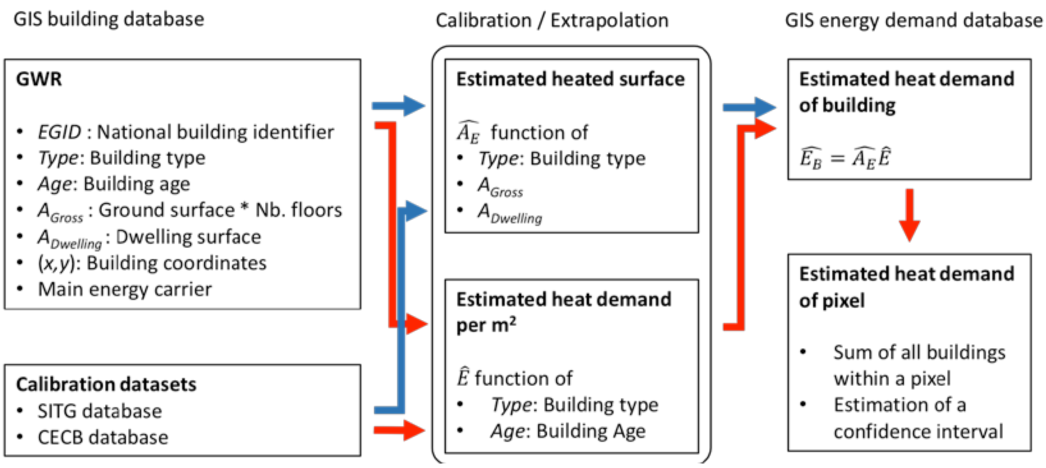

Fig. 1: Model overview.

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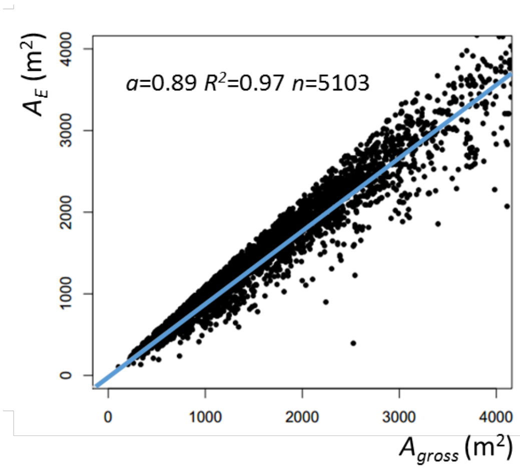

Fig. 2: A_E as a function of gross surface (multifamily buildings).

2.3 Estimation of specific heat demand

For each building of the GWR database, the specific final energy for heat demand E_B is estimated by way of its age and category, on hand of average values given by the SITG and CECB datasets, which are normalized to a common reference.

Normalization of calibration data to a common reference

Since heat demand data of CECB and SITG concern a variety of energy carriers and locations, it has first to be normalized to a common reference. Therefore, for each building of these datasets, the measured final energy demand E (MJ/m^2 year) is converted into useful heat demand for space heating:

$$Q_{SH} = \eta_{EC} E - Q_{DHW} \quad (1)$$

η_{EC} is the transformation efficiency factor estimated by [10] and Q_{DHW} the useful heat demand for DHW production according to the SIA 380/1 norm. Since some very low energy buildings may have thermal solar panels, leading to very low Q_{SH} values, we further add following constraint:

$$Q_{DHW} = \min(Q_{DHW}^{SIA}, 2/3\, \eta_{EC} E) \quad (2)$$

The space heating values are further normalized to a common climatic reference (arbitrarily Geneva):

$$Q_{SH}^{GE} := Q_{SH} \frac{DJ(GE)}{DJ(Origin\ of\ measure)}$$
(3)

DJ (Origin of measure) stands for the norm SIA 2028 heating degree days from the climatic station associated to the building.

Finally, the SITG and CECB data sets allow computing 15'588 and 11'499 Q_{SH}^{GE} values normalized to Geneva's climatic reference.

Statistical analysis by building category and age

For the sake of statistical analysis, preceding data is grouped in four building categories (multifamily residential, individual residential, nonresidential, mixed purposes). For each of these categories, the data is further divided into 12 construction periods, and analysed in terms of statistical distribution (Fig. 3). At this stage, it is worthwhile noting that the variability within each construction period is much higher than between the periods, as previously put forward by [10].

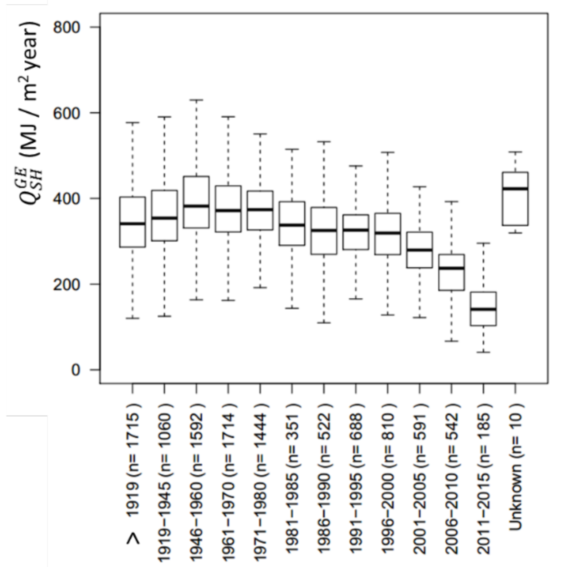

Fig. 3: Boxplot distribution of Q_{SH}^{GE} by construction period (multifamily buildings, SITG database).

Finally, for each of the building categories and construction periods, we define the average space heating demand which is used for extrapolation on the GWR database:

$$\overline{Q_{SH}^{GE}} := \frac{\sum_{\{\}} Q_{SH}^{GE} A_E}{\sum_{\{\}} A_E} \quad (4)$$

This analysis is done separately for the SITG and CECB datasets, the respective values being used for reconstruction of the entire GWR building stock located in Geneva, respectively in the rest of the Swiss territory.

2.4 Heat demand at building and pixel level

For each building of the GWR database, the specific heat demand is estimated by the average demand of its corresponding category and construction period with

$$\hat{E} = {}^{1}/_{\eta_{Agent}} \left(\overline{Q_{SH}^{GE}} \frac{DJ(b)}{DJ(GE)} + Q_{DHW}\right) \quad (5)$$

On this basis, we compute the sum of the heat demand of all buildings contained in a pixel of territory:

$$\hat{E}_{Pixel} = \sum_{B \in Pixel} \widehat{E_B} = \sum_{B \in Pixel} \widehat{A_E}\, \hat{E} \quad (6)$$

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The procedure is repeated on the entire Swiss territory, on square pixels of scalable sizes, ranging from 100 (m) to 1.6 (km).

2.5 Confidence intervals

For each of the above pixels, we compute a confidence interval around the estimated heat demand value. It is computed by way of a bootstrap resampling algorithm [11], which consists in generating a heat demand distribution, which replicates the dispersion of the calibration datasets.

Therefore, for each building of the pixel, a new $\hat{E}$ value is generated by replacing the $\overline{Q_{SH}^{GE}}$ value of (5) by a randomly picked value of the corresponding calibration dataset (same building category and construction period). Similarly, the heated surface $\widehat{A_E}$ is replaced by

$$\widehat{A_E}^* := (1 + \Delta\widehat{A_E})\widehat{A_E} \qquad (7)$$

where $\Delta\widehat{A_E}$ is a randomly picked relative error of the corresponding linear regression model, defined as:

$$\Delta\hat{A}_E := \frac{A_E - \hat{A}_E}{\hat{A}_E} \qquad (8)$$

The replicated $\hat{E}$ and $\widehat{A_E}$ values are fed into (6), generating a replicated heat demand of the entire pixel. Repeating this procedure a 1000 times per pixel generates the heat demand distribution of each pixel. Finally, the limits of the 10% level confidence interval are the 5% and 95% percentiles of this distribution.

2.6 Results

At national level

Around 90% of the 1.93 million buildings listed in the GWR have sufficient data for applying the appropriate regression model. Summing up all $\hat{A}_E$ values leads to a total heated surface estimation of 706.2 million m^2. The total aggregated final energy demand is 340 (PJ/Year) for a reference climatic year.

At pixel level

The results of the model, which cover the entire Swiss territory, are made available by way of a dedicated web service [12].

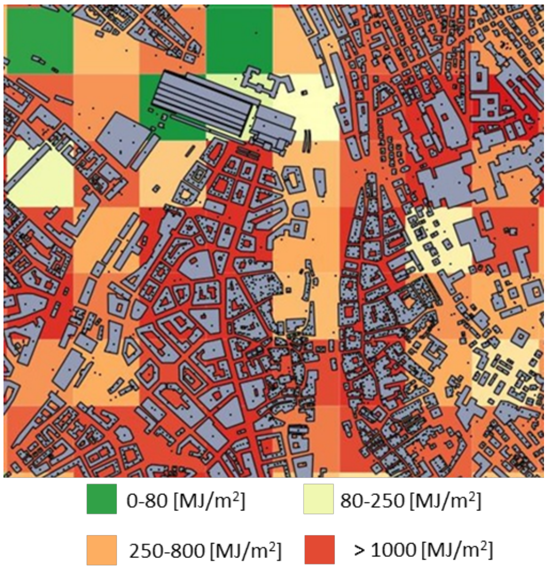

Fig. 4: Sample map of a district of Zurich.

We finally build heat demand GIS maps, with more or less aggregated information, depending on the zoom level. Fig. 4 shows an example of such a heat density map for an urban district. A colour ramp indicates the final energy consumption per square meter of territory, for each pixel of 200 (m) size.

3 DISCUSSION

Model variables

In this model, the variables used for determination of the specific heat demand have been limited to building category and age. In principle, the model could be refined with the use of additional factors, like building size or floor area ratio, which could be estimated on hand of the data contained in the GWR. However: (i) a rapid analysis of the SITG calibration dataset shows that, although statistically significant, these factors remain of secondary order; (ii) further subdivision of the calibration datasets would lead to statistically small subsets and related representativeness issues.

Due to similar representativeness issues within the calibration datasets, following finer categorizations were also abandoned (but could be introduced once more calibration data is available): (i) subdivision of the buildings in a larger number of categories, in particular for the nonresidential sector; (ii) categorization of the heat demand by Canton, for tracking and taking into account the local specificities (other than the degree day issue, which is included in the model). As seen in section 2.3, and due to the high level of information of the SITG database, Geneva is the only exception to this uniform territorial categorization.

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Comparison with national statistics

The total heated surface estimation is 6% below the estimation of 754 million m^2 given by [1]. The fact that the GWR is not complete for industrial and services buildings can explain part of this gap. When focusing on the residential sector, the model yields 580 million m^2, against 509 million m^2 in [1].

The total aggregated final energy is in line with national demand statistics as [1]. This good concordance speaks in favour of the quality of the model, which was not calibrated for this purpose.

Confidence intervals

A strong added value of the model is the generation of a confidence interval around the estimated heat demand of each pixel. Due to the high dispersion of the specific heat demand within each building category and age class (Fig. 3), the confidence interval can turn out quite large for pixels containing only few buildings, and reduces when more buildings are aggregated (the averaging of the dispersion effect). A forthcoming paper will expose the relationship between aggregation level and estimation uncertainty in more details. The main outcome is that the uncertainty decreases proportionally to $1/\sqrt{Nb.\ buildings}$ as predicted by the central limit theorem.

4 CONCLUSION

The strength of this bottom up model is to allow the estimation of geo-dependent heat demand at any aggregation level for the Swiss territory. The estimation of consumption based on the distribution of measured consumptions bears the advantage of including the variability between buildings of the same category and age. As a result, a bootstrap resampling algorithm allows to quantify the precision of the aggregated heat demand, which is an added value compared to previous approaches. Finally, the good concordance of the total aggregated final energy demand with national demand statistics speaks in favour of the quality of the model.

5 ACKNOWLEDGMENTS

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6 REFERENCES

1. Kemmler, A., et al., Analyse des schweizerischen Energieverbrauchs 2000 - 2013 nach Verwendungszwecken (2014), in BFE Report. 2014, Bundesamt für Energie: Bern.

2. Eicher and Pauli AG, Ausbau von WKK in der Schweiz WKK-Standortevaluation auf Basis einer GIS-Analyse (2011), in Verband Effiziente Energie Erzeugung Final report. 2011, Dr. Eicher+Pauli AG: Liestal.

3. Connolly, D., et al., Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy, 2014. 65(0): p. 475–489.

4. Perez, D., A framework to model and simulate the disaggregated energy flows supplying buildings in urban area (2014), in PhD thesis Report No 6102. 2014, EPFL: Lausanne.

5. Perez, D., et al., CitySim simulation: the case study of Alt-Wiedikon, a neighbourhood of Zürich City, in CISBAT 2011 - CleanTech for Sustainable Buildings. 2011: Lausanne, Switzerland. p. 937–940.

6. Eicher and Pauli AG, Weissbuch Fernwärme Schweiz – VFS Strategie, Langfristperspektiven für erneuerbare und energieeffiziente Nah- und Fernwärme in der Schweiz (2014), in Final report phase 2. 2014, Dr. Eicher+Pauli AG: Liestal.

7. The Austrian address and building register (AGWR). Information available online at: http://www.statistik.at/web_de/services/adress_gwr_online/index.html. Accessed: 12-April-2016.

8. OFS, Registre fédéral des bâtiments et des logements: Catalogue des caractères (2012), in user manual 2012, Office fédéral de la statistique (OFS): Bern.

9. Swisstopo, Swisstopo Topographic Landscape Model TLM (2015). Available online at: http://www.swisstopo.admin.ch/internet/swisstopo/en/home/topics/geodata/TLM.html. Accessed: 25-Feb-2015.

10. Khoury, J., Rénovation énergétique des bâtiments résidentiels collectifs: état des lieux, retours d'expérience et potentiels du pargenevois (2014), in PhD thesis Report No 4752. 2014, University of Geneva.

11. Efron, B. and R. Tibshirani, An introduction to the bootstrap. 1993, New York: Chapman & Hall.

12. Schneider, S., et al., SCCER FEEB&D Geo-dependent energy supply and demand web service. http://wisesccer1.unige.ch/. Accessed: 12-April-2016.