Estimation of load curves for large-scale district heating networks

Kai Nino Streicher¹*, Stefan Schneider¹, Martin K. Patel¹

¹ Chair for Energy Efficiency, Department F.-A. Forel for environmental and aquatic sciences (DEFSE), University of Geneva, Switzerland

* Corresponding author: kai.streicher@unige.ch

Abstract. Decarbonisation and a transition towards sustainable energy systems in cities are key elements of the United Nations sustainability goal. Large-scale district heating networks sourced by excess heat or renewable energy allow to effectively transform building-related energy systems. This study proposes two different approaches for modelling load curves in large-scale district heating networks: 1) physics-based static energy balance model 2) data-driven regression model trained and adjusted on measured load curves. The load curves generated by application of these two approaches are compared with the actual load of an urban district heating network in Geneva, Switzerland. Both models allow to recreate the actual load curve of the district heating network, however with lower accuracy for higher time resolution in the case of the physics-based model. The physics-based static model can be used to simulate the demand and generate load curves of sufficient quality at monthly and daily resolution. For an hourly load curve, it is recommended to use the data-driven regression model if consumption data of the network is available.

1. Introduction

Decarbonisation represents a major challenge across all sectors including the built environment with its share of 40% of the total final energy demand [1]. This is reflected in the Sustainability Development Goals (SDG) set by the United Nations which, among others, concern the transition to sustainable cities (SDG 11) while ensuring access to affordable and clean energy (SDG 7) as well as an overall reduction of greenhouse gas (GHG) emissions (SDG 13) [2]. For developed countries this implies an increased share of renewable energy and an improvements in energy efficiency. In urban centres, large-scale district heating networks sourced by excess heat or renewable energy allow to effectively transform building-related energy systems and achieve cost-effective GHG reductions [3,4]. However, the installation of district heating systems requires labour intensive work as well as very high upfront investment cost. When designing these networks, it is therefore crucial to ensure a comprehensive energy planning which entails an estimation of the expected heat load during operation. Given this load curve estimation, the availability of the different sources feeding the network can be temporally aligned with the demand. This is in particular important if renewable and/or fluctuating sources are used or in the case of hybrid systems. Depending on the source and the availability of (thermal) storage the heating load might need to be estimated on a daily or even hourly scale.
2. Methods
This study proposes two different approaches for modelling hourly load curves in large-scale district heating networks: 1) physics-based static energy balance model 2) data-driven regression model trained and adjusted on measured load curves (see Table 1). Both models are based on archetypes buildings which represent the entire building stock. More details about the models are provided in section 2.2 and 2.3.

Table 1 Overview on the characteristics and specifications of the different load curve models

| Description                  | SwissRes          | FEEBD              |
|------------------------------|-------------------|--------------------|
| Model basis                  | physics           | data-driven        |
| Building archetypes          | 54                | 5                  |
| Energy demand                | yes               | no                 |
| Model complexity             | moderate          | very simple        |

The models are tested in relation to an existing large-scale heating network in Geneva, Switzerland (see section 2.1). For each model and archetype up to 50 variations of normalized load curves for monthly, daily and hourly resolution are created using the climate data of the year 2015 [5]. Based on the archetype categories, these load curves are then randomly assigned to each building which is identified as connected to the district heating network. This load is then scaled up by the annual demand for each building and summed up for the total network.

In order to assess the accuracy of the models a visual comparison with the measured load as well as with the ranked load is performed. In addition, the goodness-of-fit is evaluated with three commonly used indicators: Mean Bias Error (MBE), Root Mean Square Error (RMSE) and the Coefficient of Variation of Root Mean Square Error (CV RMSE) [6]. These indicators are calculated with the following equations:

\[
MBE = \frac{\sum_{i=1}^{N_p} (m_i - s_i)}{\sum_{i=1}^{N_p} (m_i)}
\]

\[
CV \ RMSE = \frac{RMSE}{\sqrt{\frac{\sum_{i=1}^{N_p} (m_i - s_i)^2}{N_p}}}
\]

Here \(N_p\) is the number of data points for the different time scales, \(m\) is the measured and \(s\) is the simulated load.

2.1. District heating network and annual heat demand of connected buildings
The CADIOM district heating network in Geneva is mainly fed by waste heat from the local waste incineration plant. The local utility SIG provided the actual hourly load curve of the heat distributed via the district heating network during the year 2015, with a total provided heat amounting to 159 GWh. A GIS analysis identifies 481 buildings connected to that network. According to the data available on the SITG IDC platform [7] the annual heat consumption in 2015 amounted to 147 GWh for those 481 buildings. The difference of 7% compared to the total delivered heat (159 GWh/year) can be explained by: (i) single family houses are not referenced in Geneva’s heat demand database SITG and are thus not included in our simulation, (ii) the heat load curve provided by SIG is itself subject to some uncertainty since it was corrected for losses and for the heat exchanged with another district heat network "CAD Lignon".
2.2. Energy balance model: SwissRes

Based on the Swiss standards on energy use in buildings [8] the Swiss Residential Building Stock (SwissRes) model calculates the energy balance of losses and gains in a certain period and hence allows to estimate the specific and total energy demand for representative archetype buildings. The model is mainly based on statistical analysis of the Cantonal Building Energy Performance Certificate (CECB) [9]. The archetype data from the CECB (e.g. average surfaces and U-values of building elements) together with external data (e.g. heating degree days by Canton) allows the energy model to calculate the standardized space heating and domestic hot water demand for each archetype [10]. Due to the archetype approach, the model allows then to identify for the techno-economic potential of energy retrofit measures.

Since the SwissRes model can only provide the energy demand for residential buildings, the non-residential buildings in the network are roughly approximated using Multifamily-house archetypes.

2.3. Regression model: FEEDB

Using measured load curves from case studies, a bi-linear regression model to predict the hourly heat demand as function of the external air temperature and the solar irradiation was developed [11]. These case studies cover several building types, i.e. single family residential, multifamily residential (retrofitted or not) and non-residential. The regression model permits for any of these types and for any given climate to build an estimated normalized heat demand load curve separately for domestic heating and domestic hot water preparation. Given that the annual demand of each building connected to the network is known, the normalized load curves can be scaled up to the yearly heat demand profile (hourly).

In the context of the FEEBD project, these load curves were combined with the yearly heat demand estimation per building, to develop a database [11] containing the estimated heat demand load curve of each building listed in the Swiss national building register [12].

3. Results & Discussion

Figure 1 shows that both models represent well the overall trend of the actual (measured) load curve of the district heating network. The visual comparison shows that the regression model (FEEDB) is following better the measured load curves for all cases. Additionally, we identify a general trend of decreasing accuracy for the simulated load curves from lower to higher time resolutions. In particular the hourly load curve of the SwissRes model features a high fluctuation around the measured values. Both models are less accurate in the summer and in the transition period. The goodness-of-fit indicator results in Table 2 show that the MBE is basically equal for all models and time resolutions whereas the RSME and CV RSME values indicate a decrease in accuracy for higher time resolution in the case of the SwissRes model.

| Time span | Source   | MBE [%] | RMSE [MW] | CV RMSE |
|-----------|----------|---------|-----------|---------|
| Month     | SwissRes | 7.1%    | 2.9       | 16.1%   |
|           | FEEDB    | 7.2%    | 2.0       | 10.9%   |
| Day       | SwissRes | 7.2%    | 3.9       | 21.7%   |
|           | FEEDB    | 7.2%    | 2.4       | 13.3%   |
| Hour      | SwissRes | 7.2%    | 8.6       | 47.3%   |
|           | FEEDB    | 7.2%    | 4.0       | 22.1%   |

Table 2 Goodness-of-fit parameter results for the three load curve models (MBE = Mean Biased Error, RMSE = Root Mean Square Error, CV RSME = Coefficient of Variation of RSME).

Table 2 shows that for all time resolutions the regression model (FEEBD) is significantly more accurate (CV RMSE 11% - 22%) than the physic-based model (CV RMSE 16% - 47%). This implies in particular for the simulation of an hourly load curve, where a CV RMSE above 30% disqualifies the SwissRes model [6], while the FEEBD model yields clearly more accurate results (22% CV RSME).

However, the main limitation of the regression-based model is that the energy demand cannot be estimated and instead the model requires an external estimation of the annual load of the network as...
input. If this estimate is not available, the physic-based model can be used to create monthly and daily load curves. For the first planning phase and if the district heating system includes a sufficient thermal storage option (e.g., hot water tank) a daily load curve estimate might be sufficient. Another advantage of the physic-based model is the possibility to study the impact of specific retrofit measures on the network [13]. This would allow to estimate if the reduction of the maximum load and subsequently the reduction of the heat source capacity through retrofit measures leads to overall reduced cost [14].

The major limitations of both models used in this study is that they do not consider dynamic effects such as the thermal inertia of the building structure [6]. Future research could therefore assess the accurateness of a full dynamic model for district heating load curve estimations.

4. Conclusion
This analysis showed that the actual load curve of a large district heating network can either be represented with a physics-based steady-state energy balance model or with a regression model trained and adjusted on measured load curves. According to the goodness-of-fit indicators the accuracy of both models decrease with higher time resolutions, with the regression model providing a better fit for the load curve on all levels. However, if the annual energy demand of the heating network is not known or the influence of energy efficiency improvements in the buildings needs to be estimated, the physic-based model can provide an accurate load curve down to a daily time resolution.

Figure 1 Comparison of load curves models with measured load curve for monthly, daily and hourly time scale.
Acknowledgments
This research project is financially supported by the Swiss Innovation Agency Innosuisse and is part of the Swiss Competence Center for Energy Research SCCER FEEB&D and SCCER CREST.

References
[1] IEA, Energy Efficiency. Market Report 2016, OECD/IEA, Paris, France, 2016. https://www.iea.org/eemr16/files/medium-term-energy-efficiency-2016_WEB.PDF (accessed January 23, 2018).
[2] United Nations, Sustainable Development Goals, (2020). https://sustainabledevelopment.un.org/sdgs (accessed January 7, 2020).
[3] A. David, B.V. Mathiesen, H. Averfalk, S. Werner, H. Lund, Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems, Energies. 10 (2017) 578. https://doi.org/10.3390/en10040578.
[4] D. Connolly, H. Lund, B.V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P.A. Ostergaard, S. Nielsen, Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system, Energy Policy. 65 (2014) 475–489. https://doi.org/10.1016/j.enpol.2013.10.035.
[5] Federal Office of Metrology and Climatology MeteoSwiss, MeteoSwiss, (2020). https://www.meteoswiss.admin.ch/home.html?tab=overview (accessed January 7, 2020).
[6] D. Coakley, P. Raftery, M. Keane, A review of methods to match building energy simulation models to measured data, Renew. Sustain. Energy Rev. 37 (2014) 123–141. https://doi.org/10.1016/j.rser.2014.05.007.
[7] SITG, Catalogue | SITG, Catalogue. (2015). https://ge.ch/sitg/sitg_catalog/sitg_donnees/i?keyword=IDC (accessed January 8, 2020).
[8] Swiss Society of Engineers and Architects, Heizwärmebedarf, SIA 380/1:2016, Swiss Society of Engineers and Architects, Zürich, Switzerland, 2016.
[9] K.N. Streicher, P. Padey, D. Parra, M.C. Bürer, M.K. Patel, Assessment of the current thermal performance level of the Swiss residential building stock: Statistical analysis of energy performance certificates, Energy Build. 178 (2018) 360–378. https://doi.org/10.1016/j.enbuild.2018.08.032.
[10] K.N. Streicher, P. Padey, D. Parra, M.C. Bürer, S. Schneider, M.K. Patel, Analysis of space heating demand in the Swiss residential building stock: Element-based bottom-up model of archetype buildings, Energy Build. 184 (2019) 300–322. https://doi.org/10.1016/j.enbuild.2018.12.011.
[11] S. Schneider, P. Hollmüller, J. Chambers, M.K. Patel, A Heat Demand Load Curve Model of the Swiss National Territory, in: Cent. Eur. Sustain. Build. CEBib9, IOP Publishing, 2019: pp. 1–7. https://doi.org/10.1088/1755-1315/290/1/012107.
[12] Federal Statistical Office, Swiss Federal Statistical Office, (2019). https://www.bfs.admin.ch/bfs/en/home/statistics.html (accessed May 3, 2019).
[13] J. Chambers, K. Narula, M. Sulzer, M.K. Patel, Mapping district heating potential under evolving thermal demand scenarios and technologies: A case study for Switzerland, Energy. 176 (2019) 682–692. https://doi.org/10.1016/j.energy.2019.04.044.
[14] K.N. Streicher, S. Mennel, J. Chambers, D. Parra, M.K. Patel, Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches, Energy Build. 215 (2020) 109870. https://doi.org/10.1016/j.enbuild.2020.109870.