

*Digital Comprehensive Summaries of Uppsala Dissertations
from the Faculty of Science and Technology 2286*

Urban Building Energy Modeling for Retrofit Scenarios

*Development, Calibration, Validation and
Implementation for Swedish Residential Buildings*

FATEMEH JOHARI



ACTA UNIVERSITATIS
UPSALIENSIS
2023

ISSN 1651-6214
ISBN 978-91-513-1849-3
urn:nbn:se:uu:diva-508080



UPPSALA
UNIVERSITET

Dissertation presented at Uppsala University to be publicly examined in Sonja Lyttkens, Ångströmlaboratoriet, Lägerhyddsvägen 1, Uppsala, Friday, 15 September 2023 at 13:15 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Darren Robinson (The University of Sheffield, School of Architecture).

Abstract

Johari, F. 2023. Urban Building Energy Modeling for Retrofit Scenarios. Development, Calibration, Validation and Implementation for Swedish Residential Buildings. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 2286. 105 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-1849-3.

The necessity for an accelerated transition of urban energy systems and, in particular, the building sector toward energy efficiency and carbon neutrality poses new challenges to planning and retrofitting existing buildings. To cope with these challenges, so-called urban building energy models (UBEMs) have been introduced for quantifying the energy demand in the building sector, identifying the hot spots of energy use and suggesting scenarios for retrofitting the buildings. Methods for developing an UBEM vary. In this thesis, based on a comprehensive review of the state of the art, an approach to the development of an automated simplified UBEM using open-access data from Swedish residential buildings was taken. The developed model makes use of building-level geo-referenced energy performance certificate (EPC) data to automatically form simplified single-zone models of buildings which are one-by-one simulated by the building energy simulation software EnergyPlus. The UBEM also includes energy retrofit scenarios for improving the energy efficiency of energy-intensive buildings based on the latest Swedish building codes, the Passive House standards as well as net zero energy buildings.

The choice of simulation software and modeling complexity was made based on the results of this thesis proving that EnergyPlus was the most suitable software for handling large-scale building energy models efficiently. The results also showed that the mean absolute percentage error (MAPE) of a simplified single-zone model from a detailed multi-zone model is only 6 %. This error becomes marginal when the spatial aggregation of the results increases. With the calibration of the model using the EPCs, the accuracy of the model improved considerably. The MAPE of the simulated annual energy demand from the actual energy performance of the buildings was reduced from 78 % to 26 %, for the case study city of Borlänge. The validation of the model for independent sources of hourly, and monthly energy measurement data as well as EPCs proved the reliability and applicability of the model for being used for other cities or other temporal resolutions than those that it was calibrated for. Implementation of the UBEM and the energy retrofit scenarios in the city of Varberg, Sweden, resulted in improved energy efficiency of the city, i.e., the residential building sector, to the extent that the minimum requirements for net zero energy were met for several city districts.

Keywords: Urban building energy modeling, Urban building energy retrofit, Urban energy system, Urban energy planning, Energy performance certificate, Energy efficiency, low-energy cities

Fatemeh Johari, Department of Civil and Industrial Engineering, Civil Engineering and Built Environment, Box 534, Uppsala University, SE-751 21 Uppsala, Sweden.

© Fatemeh Johari 2023

ISSN 1651-6214

ISBN 978-91-513-1849-3

URN urn:nbn:se:uu:diva-508080 (<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-508080>)

*"Everything should be made as simple as possible,
but not simpler."*
Albert Einstein

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I **Johari, F.**, Peronato, G., Sadeghian, P., Zhao, X., Widén, J. (2020) Urban Building Energy Modeling: State of the Art and Future Prospects. *Renewable and Sustainable Energy Reviews*, Vol. 128, article id 109902.
- II **Johari, F.**, Nilsson, A., Åberg, M., Widén, J. (2019) Towards Urban Building Energy Modelling: A Comparison of Available Tools. in *Proceedings of eceee 2019 Summer Study on energy efficiency*, Presqu'île de Giens, Hyères, France, 1515-1524.
- III **Johari, F.**, Munkhammar, J., Shadram, F., Widén, J. (2022) Evaluation of simplified building energy models for urban-scale energy analysis of buildings. *Building and Environment*, Vol. 211, article id 108684.
- IV **Johari, F.**, Shadram, F., Widén, J. (2023) Urban building energy modeling from geo-referenced energy performance certificate data: Development, calibration, and validation. *Sustainable Cities and Society*, Vol. 96, article id 104664.
- V **Johari, F.**, Lindberg, O., Ramadhani, U.H., Shadram, F., Munkhammar, J., Widén, J. (2023) Analysis of large-scale energy retrofit of residential buildings and their impact on the electricity grid using a validated UBEM. Manuscript.

Reprints were made with permission from the publishers.

Publications not included in the thesis

- VII Psimopoulos, E., **Johari, F.**, Bales, C., Widén, J. (2020) Impact of boundary conditions on the performance enhancement of advanced control strategies for a residential building with a heat pump and PV system with energy storage. *Energies*, Vol. 13, no 6, article id 1413.
- VIII **Johari, F.** (2021) Urban building energy modeling: A systematic evaluation of modeling and simulation approaches. Licentiate thesis, Uppsala University.
- IX Han, M., **Johari, F.**, Huang, P., Zhang, X. (2022) Generating hourly electricity demand data for large-scale single-family buildings by a decomposition-recombination method. *Energy and Built Environment*, Vol. 4, article id 101016.
- X **Johari, F.**, Widén, J. (2022) A simplified urban building energy model to support early-stage energy plans. in *Proceedings of BuildSim Nordic 2022*, Copenhagen, Denmark, p.8.
- XI Dahlström, L., **Johari, F.**, Broström, T. Widén, J. (2023) Optimising the identification of representative building archetypes: A novel approach using multi-parameter cluster analysis and publicly available databases. *Energy and Buildings*, Under review.
- XII Israelsson, K., Kayayan, V.A., **Johari, F.**, Gustafsson, M., Åberg, M. (2023) Building heat demand characteristics in a planned city district with low-temperature district heating supply. Manuscript.
- XIII Ramadhani, U.H., **Johari, F.**, Lindberg, O., Munkhammar, J., Widén, J. (2023) A city-level assessment of PV hosting capacity on low-voltage distribution systems considering rooftop azimuth and tilt uncertainties. Manuscript.

Notes on my contribution

I contributed the following to the appended papers:

Paper I, I did the literature survey and wrote the whole paper except for Section 2.1.1, Section 2.2.1.2, Section 2.3, Section 3.3 and Section 3.4.

Paper II, I developed the building models in IDA ICE, TRNSYS and EnergyPlus, analyzed the results and wrote the whole paper.

Paper III, I developed all the building models and wrote the whole paper.

Paper IV, I developed the automated UBEM tool and except for Section 3.3, wrote almost the whole paper.

Paper V, I extended the developed UBEM tool and implemented the renovation scenarios, I wrote the major part of the paper except for Section 1.1, Section 2.3, Section 2.4, Section 3.2, Section 3.4, Section 4.2, and Section 4.4.

This is also to mention that this thesis is an extended version of my licentiate thesis entitled "Urban building energy modeling: A systematic evaluation of modeling and simulation approaches", which was defended and published in Jan 2021. Other than alterations and additions to the previous contents, new sections are presented in this thesis. This includes Section 2.1.3, Section 2.1.4, Section 2.1.5, Section 2.2.5, Section 2.2.8, Section 3.1, Section 3.2, Section 3.5, Section 3.6, Section 3.7, Section 3.8, Section 4.2.3, Section 4.2.4, Section 4.3, Section 4.4, Section 5 and Section 6.

Contents

1	Introduction	1
1.1	Aim of this thesis	2
1.2	Overview of thesis and appended papers	3
2	Background	7
2.1	Urban energy systems in transition to sustainability	7
2.1.1	Urban energy systems	7
2.1.2	Role of buildings in urban energy systems	8
2.1.3	Swedish regulations for energy-efficient buildings	9
2.1.4	Passive House standard	10
2.1.5	Net zero energy building	11
2.2	Urban building energy modeling	12
2.2.1	City-scale energy modeling of buildings	12
2.2.2	UBEM workflow	15
2.2.3	3D city model	17
2.2.4	Definition of building archetypes	18
2.2.5	Occupancy	19
2.2.6	UBEM simulation engine	19
2.2.7	Model calibration and validation	20
2.2.8	Applications of UBEM	21
2.2.9	Existing UBEMs	23
2.3	Research gaps	25
3	Methodology and data	27
3.1	Overview of case studies	29
3.1.1	Case study districts	30
3.1.2	Case study cities	30
3.2	Overview of data	31
3.2.1	Building drawings	31
3.2.2	GIS data	32
3.2.3	EPC data	32
3.2.4	Validation data	33
3.2.5	Weather data	34
3.3	Overview of BEM and simulation	35
3.3.1	Outside heat balance	36
3.3.2	Heat conduction through building envelope	36
3.3.3	Inside heat balance	36
3.3.4	Comparison of simulation tools	37

3.4	Model complexity and zoning configuration	41
3.5	UBEM development from open data	44
3.5.1	3D city modeling	44
3.5.2	Building archetypes	46
3.5.3	Occupancy and load	47
3.5.4	Modeling and simulation	48
3.6	UBEM calibration and validation	49
3.6.1	Calibration	49
3.6.2	Validation	50
3.7	Energy retrofit scenarios	51
3.7.1	BBR Codes	51
3.7.2	Passive House standard	52
3.7.3	Net zero energy buildings and districts	52
3.8	Performance metrics	53
4	Results	55
4.1	Comparison of simulation tools	55
4.2	Model complexity and zoning configuration	59
4.2.1	Zoning configuration	59
4.2.2	Level of detail	61
4.2.3	District level analysis	64
4.2.4	Main findings on model complexity and zoning	66
4.3	UBEM development	66
4.3.1	Model calibration	66
4.3.2	Model validation	69
4.4	Large-scale energy retrofit of buildings	72
5	Discussion and future work	77
5.1	Discussion	77
5.1.1	UBEM using BEM tools	77
5.1.2	Model complexity vs computation cost	78
5.1.3	Availability and quality of data	78
5.1.4	Definition and calibration of building archetypes	79
5.1.5	Level of aggregation and validity of the results	79
5.2	Future work	80
6	Conclusion	83
6.1	Aim i	83
6.2	Aim ii	84
6.3	Aim iii	84
6.4	Aim iv	85
6.5	Aim v	86
7	Sammanfattning på svenska	89
	Acknowledgement	91
	References	92

Abbreviations

A_{temp}	Heated floor area
BBR	The Swedish building codes (in Swedish, Boverkets byggregler)
BEM	Building energy modeling
CTF	Conduction transfer function
DE	Direct electric
DH	District heating
EPC	Energy performance certificate
EUI	Energy use intensity
FEBY	The Swedish Forum for Energy-Efficient Buildings
GHG	Greenhouse gas
GIS	Geographical information system
GUI	Graphical user interface
HP	Heat pump
HVAC	Heating ventilation and air conditioning
LiDAR	Light detection and ranging
LoD	Level of detail
MAE	Mean absolute error
MAPE	Mean absolute percentage error
MFB	Multi-family building
NMBE	Normalized mean bias error
NZEB	Net zero energy building
NZED	Net zero energy district
PE	Percentage error
PV	Photovoltaic
R-C	Resistance-capacitance
RMSE	Root mean squared error
RMSPE	Root mean squared percentage error
SFB	Single-family building
STD	Standard deviation
TMY	Typical meteorological year
UBEM	Urban building energy model/modeling
WWR	Window-to-wall ratio

1. Introduction

Undoubtedly, cities are one of the main contributors to climate change. More than 75% of greenhouse gas emission in the world originates from urban activities and associated energy use. With globally increased urbanization at an unprecedented rate, from 56% in 2022 to 68% in 2050 [1], there is less chance of reducing global emissions to a safe level unless new and expanding cities prioritize sustainable and low-carbon urban development paradigms [2, 3].

Worldwide, cities adopt different approaches to the style and structure of their climate actions [2]. Many cities and municipalities undertake these actions even in the absence of national policies [4]. Interestingly, these ambitious city-level climate-conscious policies can considerably reduce carbon emissions globally while delivering enormous benefits to the cities [2, 5]. From another perspective, cities can serve as policy laboratories for actions on climate change that help national governments understand the opportunities while designing effective policies [6]. In summary, urban or local policies can contribute to the global climate agenda to a large extent.

Addressing the complexity of climate change, local governments and municipalities require a systematic approach that identifies problems, formulates possible strategies, and evaluates resulting benefits [7]. In this context, urban planning and, in particular, urban energy planning typically seems as a pivotal approach that can be moved to the forefront of the transition to sustainability and carbon neutrality [8, 9]. Urban energy planning is an inclusive concept that targets many individual components of urban energy systems contributing to the interactive process of using and supplying energy [10]. Thus, in managing the transition of urban energy systems, it is required to target these different components, from generation to transmission and consumption, individually or in unison with each other [11].

With buildings being one of the most energy-intensive components of the urban energy system, opportunities for accelerated transformation towards sustainability are significant, and can be realized if best practices in energy efficiency and integrated renewable energy technologies in buildings are efficiently used [12]. However, in order to plan for a more resource efficient built environment, understanding of flows of energy in buildings and synergies between buildings and the other components of the urban energy system is crucial. Historically, translation of physical systems into mathematical equations, i.e., mathematical models, has paved the way for an improved understanding of systems and have given precision to formulation of ideas and identification of solutions. In other words, mathematical models, if properly calibrated,

are key tools in understanding and explaining the function and dynamics of energy systems and predicting their behaviour in response to internal and external changes.

An Urban Building Energy Model (UBEM) is a bottom-up engineering-based model of energy use in large sets of buildings within a specific geographic area such as an urban district or a whole city. This is a relatively new concept that has been developing during the last two decades [13]. An UBEM is an analytical tool that simulates and visualizes spatio-temporal patterns of energy use in buildings, in both existing and planned urban areas [14]. However, using a broader definition, the UBEM not only illustrates the current status of the urban energy system but also foresees the results of any changes in the components of the system, e.g., buildings and renewable energy systems.

In brief, UBEMs aid in designing and investigating both new and existing urban areas and systems, identifying energy saving potentials, incorporating large-scale energy retrofits, and improving the energy efficiency of cities, as well as evaluating the stability and reliability of energy grids [15]. These qualities of UBEMs make them attractive tools for urban energy system designers, city planners and policymakers.

It is generally recognized that the development of an UBEM is a challenging task that requires handling big data, automated procedures and high computational power [13]. To overcome these challenges, choosing the right simulation core for the purpose, deciding on a suitable level of model complexity, and utilizing openly accessible national and municipal datasets, are key points in UBEM development that have not been systematically addressed and scrutinized previously, but will be so in this thesis.

Moreover, the UBEMs are multi-dimensional in terms of time and space. This is an aspect that makes UBEMs different from traditional building or city level studies. This means that to ensure the accuracy of UBEMs, they have to be validated for different spatial and temporal scales [16]. In this thesis, a systematic evaluation of the accuracy of the UBEM at different spatio-temporal resolutions and the effect of aggregation will be discussed in detail.

1.1 Aim of this thesis

The principal aim of this thesis is to improve the field of urban building energy modeling and its contribution to future low energy cities. More precisely, the intention is to develop a method for a simplified and yet accurate UBEM of the residential building stock from open source data, that can be utilized for evaluating the energy use and energy efficiency potential in cities. The following precise goals of the thesis were formulated in order to reach this aim:

- i Undertake an extensive survey of the existing scientific literature on UBEMs in order to identify the state of the art and best practices in the field.
- ii Evaluate the applicability and accuracy of existing building energy modeling (BEM) software to be potentially used as simulation core in the UBEM.
- iii Determine a suitable level of complexity for the thermal building models in the UBEM.
- iv Analyse the possibility of using available national datasets for geographical and property information as well as building energy performance.
- v Based on the results for the goals i-iv, develop, calibrate and validate an UBEM for residential buildings using available and completely open datasets.
- vi Apply the developed UBEM in scenario planning for large-scale energy efficiency improvements.

1.2 Overview of thesis and appended papers

This thesis is structured as follows: In Chapter 2, theoretical background and overview of important aspects of the field of urban building energy modeling are provided. A review of previous research and identified research gaps are also presented in this chapter. Chapter 3 is a summary of the data and methods for the development and implementation of an UBEM. In Chapter 4, the main results from carrying out the developed methods are presented. Chapter 5 includes further discussion on the findings and an outlook towards further work. Finally, Chapter 6 draws the final conclusions. Overall, this thesis summarizes the work that has been done in the following appended papers:

I *Paper I* provides a comprehensive state-of-the-art literature review of multi-scale bottom-up engineering-based UBEMs. This paper aims to highlight the main approaches, persistent challenges and possible opportunities for the current research. Additionally, it suggests a new perspective on integrated modeling that includes different elements of urban energy systems, more specifically buildings and their energy systems, urban microclimate, district energy systems and, most importantly, urban human mobility, in one interactive model.

II *Paper II* is a systematic comparison of four BEM tools that could potentially work as UBEM simulation cores, namely, the indoor and climate

energy simulation software IDA ICE, the transient system simulation software TRNSYS, and the two building energy simulation tools EnergyPlus and VIP-Energy. This paper compares the modeling procedures, inputs, and outputs these tools. The main focus of this paper is to investigate the accuracy and suitability of these tools for large-scale application in UBEM simulation.

III *Paper III* investigates the trade-off between the complexity and accuracy of the intended building models for UBEM. By evaluating the most common zoning configurations and levels of detail at the building and district levels, this paper aims at finding a suitable level of complexity for the building models, which should be simplified but still accurate enough for the scope of UBEM.

IV *Paper IV* delves into open-source national data in Sweden that could be used for the development, calibration and validation of an UBEM and estimation of spatio-temporal patterns of energy use in Swedish cities. This paper, firstly, proposes a method for extraction of geometrical and non-geometrical information of buildings from the national GIS-based and energy performance certificate (EPC) data. Then, it discusses the construction and simulation of building-by-building energy models in an automated procedure in a tool based on Python and EnergyPlus. This paper also highlights the importance of the available data, in particular EPCs, in the calibration and validation of the developed UBEM.

V *Paper V* evaluates the applicability of the of the developed UBEM in *Paper IV* in improving the energy efficiency of a Swedish city. In this paper, a set of energy retrofit scenarios according to the Swedish building codes, i.e., BBR29, the Passive House standards and the net zero energy buildings are disused and evaluated on the city scale. The subsequent influence of these scenarios on the low-voltage electricity grid is also another point that is investigated in this paper. In addition, due to the availability of hourly energy use data, the credibility of the UBEM is established further.

A visual presentation of the thesis overview and appended papers is shown in Figure 1.1.

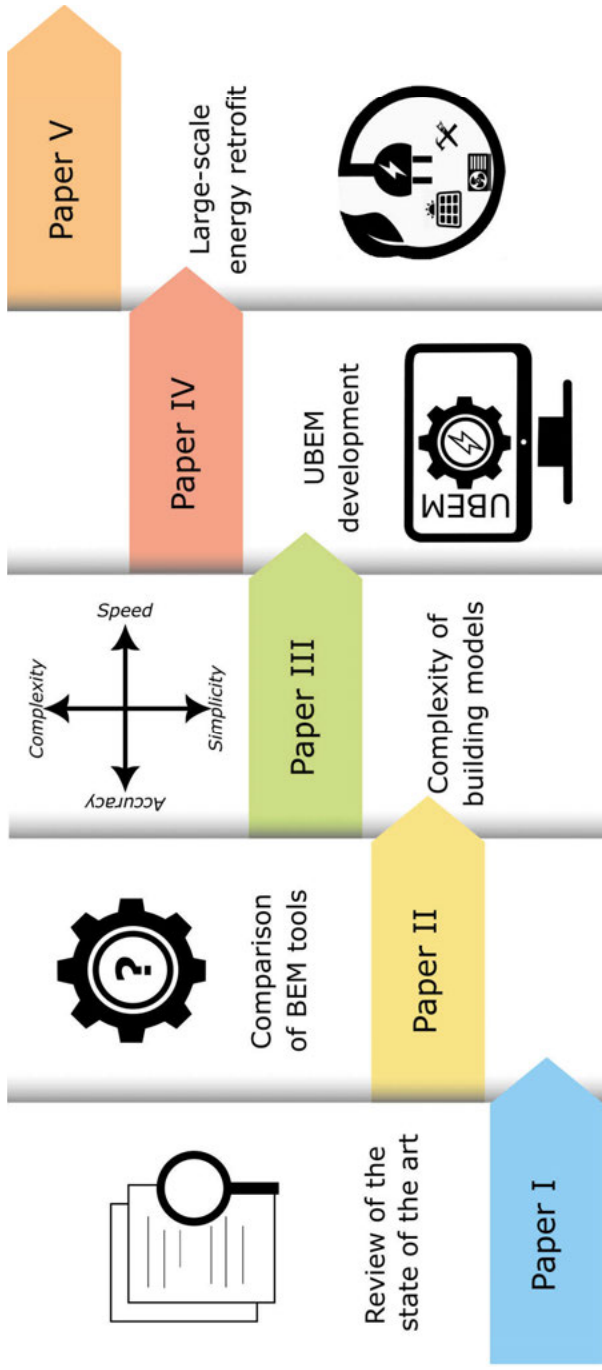


Figure 1.1. Overview of the thesis and appended papers.

2. Background

In this chapter, the background of this thesis and the state-of-the-art of urban building energy modeling are presented as follows. In Section 2.1, urban energy systems and the necessity of their transition towards sustainability are discussed. The aim of this section is mainly to shed light on the role of buildings and urban building energy models in sustainable urban development. Section 2.2 presents an introduction to the field of urban building energy modeling and discusses possible opportunities and persistent challenges during the development of a reliable model. Finally, in Section 2.3 a number of research gaps are identified and it is explained how these gaps are intended to be filled by the thesis and its appended papers.

2.1 Urban energy systems in transition to sustainability

The transition to a sustainable urban energy system is an integral part of local or municipal climate actions. The urban energy system is a broad concept that includes many components that interactively contribute to the process of supplying and using energy. Understanding the urban energy system may provide a useful perspective for well-informed and inclusive policies that are customized to the cities' specific conditions. This section draws boundaries on the definition of the urban energy system and discusses one of the most important components of the system, buildings, and their role in transitioning to sustainability.

2.1.1 Urban energy systems

There is no doubt that the future of sustainable urban development and climate change mitigation is linked with urban energy systems and their characterization [17, 18]. In the literature, the urban energy system is given different definitions encompassing the processes and infrastructure involved in supplying, managing, and utilizing energy resources in cities. For instance, Grubler et al. [19] define the urban energy system as

"a composition of all components related to the use and provision of energy services associated with a functional urban system, irrespective where the associated energy use and conversion are located in space".

Unlike this, Castán Broto [17] emphasizes the spatial organization of urban energy systems and describes them as

"an organization of multiple energy services depending on how people use energy (for lighting, thermal comfort, communications, cooking, transportation), and how energy services are provided (whether this is for the generation of electricity, gas provision or for the direct use of fuels for heat or mechanical power)".

However, the most inclusive definition of urban energy systems is provided by Keirstead et al. [20, 21] who define the urban energy system as

"a formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area".

According to the definition given by Keirstead et al. [10], it can be concluded that the transition towards more sustainable urban energy systems requires coordinated energy planning including the whole chain from primary energy extraction, through energy conversion, transmission, distribution and use [22].

Given the importance of urban and regional energy planning, Asarpota and Nadin [23] highlight the components (or the areas) of urban energy systems that can be instrumental in urban energy transitions into sustainability and carbon neutrality. Transport and accessibility are two the main components of urban energy systems that show a potential role in spatial planning and low-emission energy strategies, as argued in [24], for example. Energy infrastructure is the other key component of the urban energy systems which includes the technologies in district energy systems such as district heating and cooling networks, multi-energy systems and energy hubs, and renewable energy generation at district scale [25] as well as electricity network and smart grids [26]. The other energy-related component which plays an important role both in the supply and use of energy is the building stock [23]. From design to systems, buildings suggest a wide range of opportunities for energy efficiency and integrated renewable energy strategies [10].

2.1.2 Role of buildings in urban energy systems

Among the different components of the urban energy systems, the building stock has the greatest contribution to energy use and, thus, greenhouse gas (GHG) emissions. It is estimated that buildings account for 40% of energy use in the EU [27] and similarly in Sweden (cf., Figure 2.1). At the same time, the building stock provides a great opportunity for renewable energy integration, such as solar systems [28]. In this respect, to cope with future impacts of climate change and to move towards a more sustainable future, national, regional, and local authorities deploy a wide range of building-oriented policies

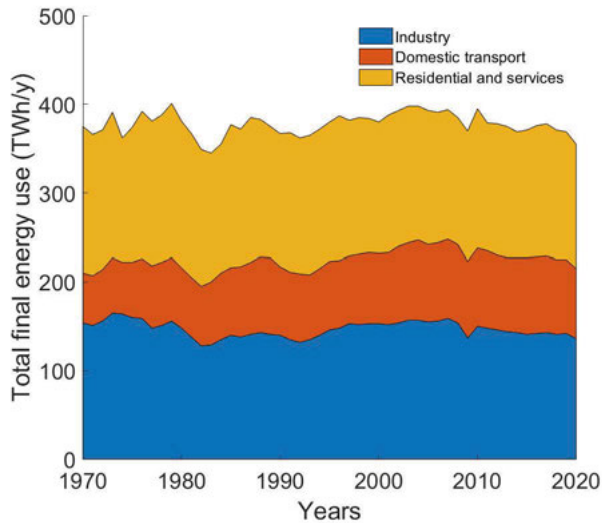


Figure 2.1. Total final energy use by sector over a period of 50 years in Sweden.

and building codes which mainly aim at the following:

- Improved energy efficiency in buildings through design, construction, and renovation of buildings and their heating ventilation and air conditioning (HVAC) systems.
- Increase the share of renewable energy resources through on-site and decentralized energy systems, such as building-integrated or building-applied solar technologies.

Building codes are general rules and regulations for the construction, operation and maintenance of buildings. The building codes are tailored to the local conditions and can vary from country to country or even city to city. The obligation on following the codes is also dependent on the local policymakers who decide to adopt these codes into law or keep them as a set of recommendations without imposing any legal obligation. In Sweden, the national building codes and regulations are the primary means for increasing energy efficiency in buildings [29]. These building codes which are mandatory to follow for new constructions, sometimes are complemented by more ambitious voluntary standards such as Passive House and net zero energy building. The following sections discuss these regulations and standards in more detail.

2.1.3 Swedish regulations for energy-efficient buildings

In Sweden, the National Board of Housing, Building and Planning, Boverket, is a central government authority for optimizing and issuing building codes

and regulations that are customized to the country's climate policy framework. The building codes are referred to as "BBR" which is an abbreviation for "Boverket's building codes", in Swedish "Boverkets Byggregler". The BBR includes both mandatory rules and general recommendations associated with construction and material, noise and fire protection, health and comfort, energy and environment, etc.

Focusing on the energy efficiency in buildings, the BBR advise that all new buildings must meet the minimum requirements for primary energy use, installed power for space heating, overall heat transfer coefficient, and air tightness. According to the latest version of the codes, BBR29, in a normal year [29], the maximum allowed use of primary energy is set to 90-100 kWh/m²y for single-family and 75 kWh/m²y for multi-family buildings. In addition, the installed power for space heating is limited. For example, for a building located in Uppsala, the installed power must stay below 4.5 kW. The overall heat transfer coefficient, i.e., U-value, of the building envelope is estimated to be 0.3 W/m²K for single-family and 0.4 W/m²K for multi-family buildings. The air leakage from buildings should also be kept as low as possible. Table 2.1 presents the requirements in brief.

2.1.4 Passive House standard

The Passive House is one of the most well-known standards for the construction and design of low-energy buildings. The concept, which originated from the idea of ultra-low-energy buildings, was later refined to a more inclusive definition for an energy-efficient, comfortable, and affordable building [30]. According to the International Passive House Institute [31], the main criteria for a building to be certified as a Passive House are: an energy demand for space heating (and cooling) that is less than 15 kWh/m²y, a primary energy use that does not exceed 120 kWh/m²y, an infiltration of maximum 0.6 air change per hour (ACH), and in a year, a room temperature that stays below 25 °C for 90% of the time.

In the Swedish Passive House standard, established by the Swedish Forum for Energy-Efficient Buildings (FEBY) [32], the specifications of a Pas-

Table 2.1. *The BBR29 requirements for new single-family and multi-family buildings.*

Building	Heated area (m ²)	Primary energy (kWh/m ² y)	Installed power (kW)	Overall U-value (W/m ² K)
SFB	>130	90		
	90-130	95	4.5 + 1.7	0.3
	50-90	100	$\times (F_{geo}^1 - 1)$	
MFB	-	75		0.4

¹ The geographical adjustment factor.

sive House are more customized to the country's specific conditions. The main goal of this standard is to limit the heat losses and therefore, minimize the space heating and, accordingly, the energy demand of a building. The heat losses from the building basically include the thermal transmission losses through the building envelope as well as infiltration and ventilation losses, when the indoor temperature is set to 21°C. Therefore, a Swedish Passive House is a low-energy building that is air-tight, well-insulated and has an optimized ventilation system. In addition, it has a very low primary energy use. The main specifications of the Swedish Passive House standard are summarized in Table 2.2.

As seen in Table 2.2, the Passive House standard in Sweden is categorized into three levels, namely, gold, silver and bronze. For buildings with larger heated areas (A_{temp}), the maximum allowed heat losses from the building range from 14 to 22 kWh/m²y. For smaller buildings, with a heated area of less than 600 m², a correction factor is added to the set values. It is also noticeable that if a building is heated by an electric heating system, an additional criterion for limiting the primary energy use has to be met. For buildings with other types or mixes of heating systems, however, no limit other than what is recommended by BBR is imposed.

2.1.5 Net zero energy building

A net zero energy building (NZEB) is a relatively new concept referring to a low-energy building that over a certain period of time, e.g., a year, uses as much energy as is available on-site [33]. This means that the total energy used by the building offsets the energy that is supplied by an on-site renewable energy system, such as solar photovoltaic (PV) systems. According to this definition, a NZEB is not necessarily an energy-autonomous or off-grid building but rather a building that stays connected to the energy grid. A NZEB imports energy from the energy grid when the demand exceeds on-site energy generation and exports excess energy back to the energy grid when it generates more than it needs.

According to these definitions, the first and one of the most important principles for a NZEB revolves around reduced energy demand and improved en-

Table 2.2. *The Passive House criteria in Sweden.*

	Heat losses (kWh/m ² y)		Primary energy (kWh/m ² y)	
	$A_{temp} > 600 \text{ m}^2$	$A_{temp} < 600 \text{ m}^2$	Electric-heated	All others
Gold	14	$14 + \frac{600 - A_{temp}}{110}$	26	BBR
Silver	19	$19 + \frac{600 - A_{temp}}{110}$	32	BBR
Bronze	22	$22 + \frac{600 - A_{temp}}{110}$	38	BBR

ergy efficiency of the building. Although no criterion for the maximum energy use or the minimum energy efficiency of the building is set, in [34], the Passive House and the EPC standards are introduced as bases for designing a NZEB. The second primary principle highlights the necessity for on-site or nearby renewable energy for covering the building load. A solar PV system is the most common example of on-site renewable generation. Additionally, solar thermal, geothermal and biomass systems as well as wind turbines are other renewable solutions that contribute to the balance of energy in NZEBs [35].

To trigger the effectiveness of the NZEBs in tackling the energy and climate crisis, the European Commission advocates for a shift from individual NZEBs to net zero energy districts and cities [36]. A net zero energy district (NZED) is expanded around the main principles of NZEB where the energy demand is low and the share of renewable energy is high. Additionally, in the concept of NZED, energy grid optimization and sharing of energy is the third principle.

2.2 Urban building energy modeling

For years, dynamic building energy modeling was widely used in the planning, demonstration, and evaluation of energy conservation measures and thermal comfort improvement in individual buildings. However, considering the interaction between buildings and the urban environment, their role in renewable resource envelope solutions, and the dynamic influences of buildings' energy use on district energy systems, the focus has begun to shift from individual building energy studies to district and city-level solutions.

This section summarizes the approaches to city-wide energy modeling and more specifically, bottom-up engineering-based energy modeling of buildings, referred to as urban building energy modeling (UBEM). This section in most parts is a short summary of the most important findings from the review of the field in Paper I.

2.2.1 City-scale energy modeling of buildings

City-scale dynamic energy modeling of buildings is highly dependent on the availability and granularity of input data and can vary from top-down to bottom-up models [37, 38]. Top-down models approach the aggregated energy use data and tend to find its interconnections with end-use-related variables. Based on this terminology, top-down models determine the long-term transitions in urban energy data and do not focus on individual end-users [39]. As regards the emphasis on socio-econometric and socio-technical factors, most top-down models are primarily based on the correlations between energy and variables such as income, employment rate, energy price, population, household size, and appliance ownership [38]. However, despite being a straightforward method for analyzing overall urban energy use, top-down models are

inherently unable to capture the dynamics in individual-level data. They also lack any technological and physical details. Thus, they are less suitable for the identification of improvement areas in existing buildings and scenario planning of future buildings [38, 40].

Bottom-up models, on the other hand, are developed based on disaggregated data which are then used for aggregation or extrapolation to the district or city level. In bottom-up models, the description of individual buildings is based on the type of input data, i.e., dwelling properties, building physics and energy use [37]. Accordingly, bottom-up models can be categorized into three distinct methods: statistical, engineering (or physical) and hybrid models [41]. Statistical or data-driven bottom-up models rely on the analysis of time-series or cross-sectional actual energy use data with respect to end-use information and give an estimation of energy demand. This means that similar to top-down models, statistical models are also capable of capturing consumption patterns based on end-use-related variables. However, the dependency of statistical models on historical measurement data makes them less useful for studying technological changes and future developments [42, 43].

In engineering (or physical) models, however, the approach is to establish a close-to-reality description of a building and its HVAC system using mathematical modeling. This means that in engineering techniques, individual building-level energy use is solely estimated from the physical and technological characteristics of buildings and, thus, no previous knowledge of consumption patterns or demographic factors is necessary. However, the required level of detail in the data on the physical properties of the building and its systems is quite extensive [13, 40].

Although these engineering models are practical representations of buildings, they cannot be reflective of the uncertain variables of the building models, such as occupants' behavior. In addition, they are unable to handle the systematic uncertainty of the simplified modeling techniques. Thus, the third type of models, the so-called hybrid models, has gained increasing popularity among model developers. A hybrid model is a collection of both statistical and engineering models with all their respective advantages. In the hybrid models, while the building is modeled using engineering methods, the uncertain parameters of the model are approached by statistics and statistical models [13]. Table 2.3 summarizes the strengths and weaknesses of these three modeling techniques in brief.

Table 2.3. *Comparison of bottom-up city-scale energy models of buildings: statistical, engineering and hybrid models.*

Models	Strengths	Weaknesses	References
Statistical models	<ul style="list-style-type: none"> • End-user information and variability in occupant behavior are covered. • No detailed technological information is needed. • Demographic factors can be considered. 	<ul style="list-style-type: none"> • Extensive data and a large number of samples are required. • Highly dependant on historical data. • Not applicable for development studies. 	Torabi Moghadam et al. [12], Nutkiewicz et al. [44], Yang et al. [45], Lo et al. [46]
Engineering models	<ul style="list-style-type: none"> • Estimation of energy use for different spatio-temporal resolutions is possible. • Detailed technical information and systems are considered. • Development studies, e.g., efficiency measures and urban development, are possible. 	<ul style="list-style-type: none"> • Detailed technical information on buildings and systems is required. • Extensive computational effort is required. • No information on end-users as well as demographic information is included. 	Nageler et al. [47], Cerezo Davila et al. [48]
Hybrid models	<ul style="list-style-type: none"> • Estimation of energy use for different spatio-temporal resolutions is possible. • End-user information and variability in occupant behavior are covered. • Detailed technical information and systems are considered. • Results in the more accurate urban energy development tool. 	<ul style="list-style-type: none"> • Detailed technical information on buildings and systems is required. • Extensive data is required. • Extensive computational effort is required. 	Nouvel et al. [49], Ghiassi et al. [50]

Referring to Reinhart and Cerezo Davila [13], bottom-up models that benefit from engineering models of buildings are referred to as "urban building energy models (UBEMs)". This means that depending on the approach to excluding/including statistical analysis in the model, an UBEM can be categorized under engineering or hybrid models. However, in the existing literature, the term "UBEM" has been used not only for engineering and hybrid models but also for statistical models.

2.2.2 UBEM workflow

As in individual building energy modeling (BEM), in UBEMs every part of the model is shaped around geometrical and non-geometrical information, i.e., construction, materials, systems and occupancy, which are then imported to a simulation engine where the energy performance of buildings is calculated under specific weather conditions and then analyzed. Nonetheless, considering the scope of urban building energy modeling, following the same procedure as for BEM is impractical. Successive modeling of hundreds or thousands of buildings with the same level of detail and model complexity as for BEM requires endless effort and large sources of information that are not available [13, 14]. To overcome these issues, UBEM developers rely on a multi-step procedure, as illustrated in Figure 2.2, with steps that are conducted in sequence or simultaneously.

In UBEM, the geometry of buildings is extracted from simplified shoebox models of buildings, known as 3D city models (Section 2.2.3). For outlining non-geometrical properties of buildings, conventional building archetypes are adopted to UBEM (Section 2.2.4). In addition, occupancy and related energy use are other non-geometric parameters that are defined for buildings, or archetypes (Section 2.2.5). Once the 3D city model and the building archetypes are available, they, together with occupancy and the prevalent weather data, are imported into an UBEM simulation engine where the building models are implemented and the energy demand is calculated in the output (Section 2.2.6). To increase the accuracy and reliability of the results, as in BEM, the UBEMs also need to be calibrated and validated against actual energy use data (2.2.7). A validated UBEM is later can contribute to the improvement of energy efficiency in cities (Section 2.2.8).

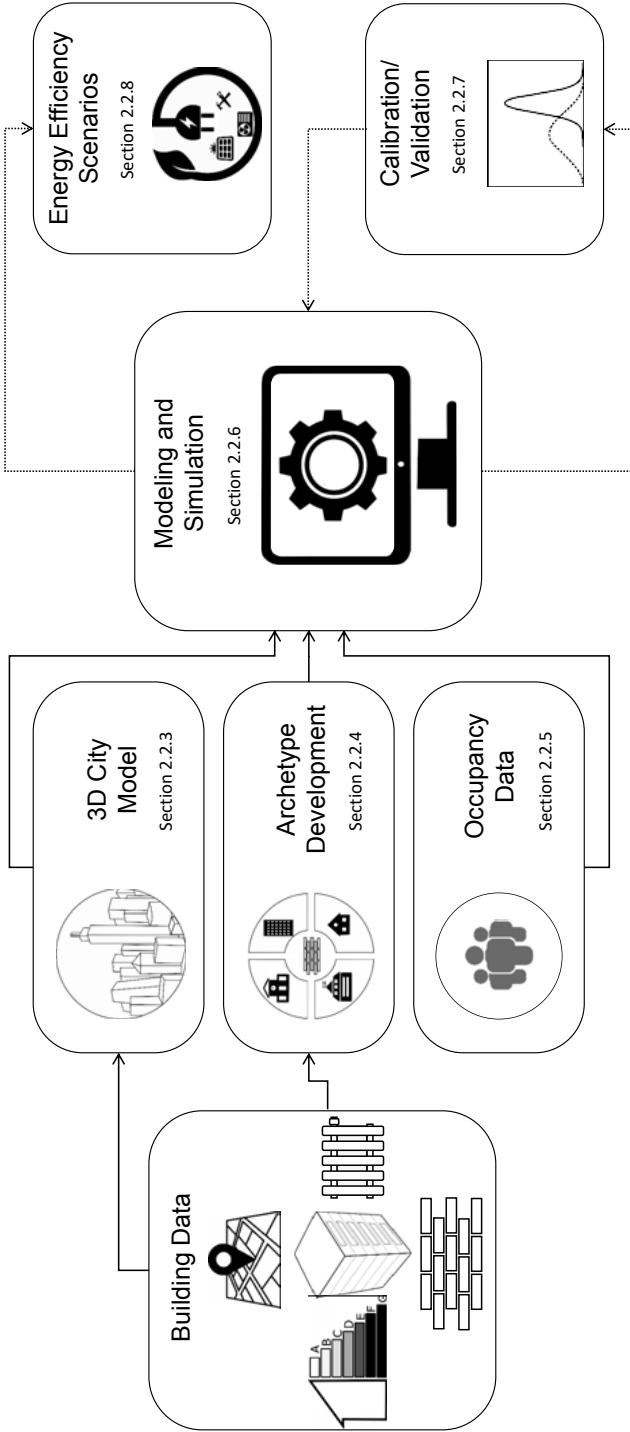


Figure 2.2. Illustration of the overall urban building energy modeling workflow.

2.2.3 3D city model

A description of the geometries of buildings and their surrounding objects is first obtained from a pre-processing step for generating 3D models of buildings in a city, referred to, in the following, as a 3D city model [51]. In the 3D city model, building footprints (2D polygons) are extruded from buildings' height and elevation information acquired from national geo-datasets, photogrammetry or laser scanning, i.e., light detection and ranging (LiDAR) data [52]. This virtual extrusion of buildings based on their height (2.5D massing) results in shoebox models of buildings corresponding to what is called Level of Detail 1 (LoD1) [14], as seen in Fig 2.3. However, to give an accurate estimation of the thermal energy performance of buildings and to investigate the solar potential on rooftops, a higher level of detail, e.g., LoD2, was used in some studies [49, 52, 53].

In addition to building geometries, the other advantage of a 3D city model is that it can be used to identify adjacent buildings, which generally escapes the attention of model developers in the absence of any 3D city model. Adjacencies of buildings can impact the thermal energy balance of buildings to a large extent [54]; adjacent walls of buildings influence the heat transmission and adjacent buildings can be used in shading analysis and calculation of solar irradiance availability on buildings.

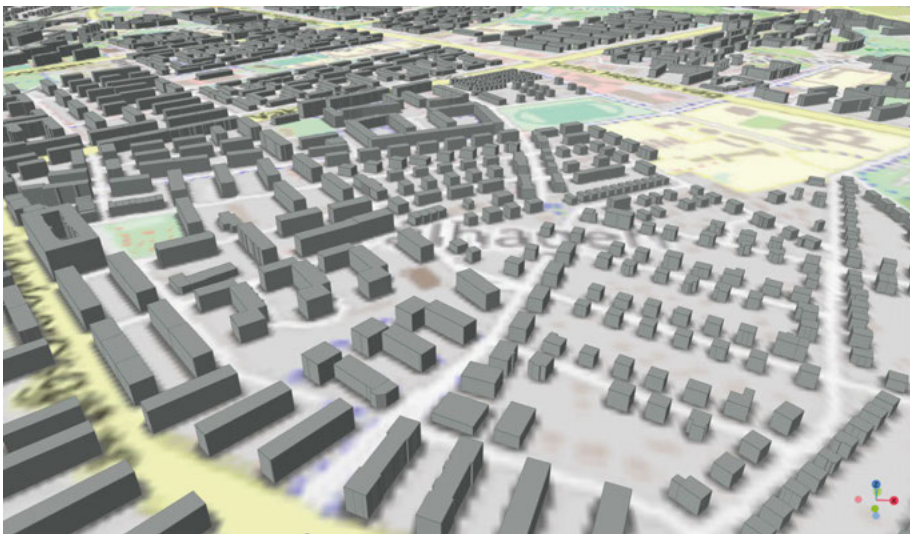


Figure 2.3. 3D city model with LoD1 for a district in Uppsala generated from extrusion of building footprints based on estimated height from LiDAR data.

2.2.4 Definition of building archetypes

Acquisition of non-geometrical information about buildings, e.g., material and construction, HVAC systems, and in some cases even occupancy, is a challenging task, specially when accessible sources of information are limited [55]. As an alternative, model developers commonly focus on reference or representative buildings instead. These representative buildings, known as building archetypes, are commonly used in the field of construction to generalize the building stock into a lower number of buildings while maintaining their diversity. By adopting the archetype approach to the field of UBEM, it is expected to moderate modeling complexities to some extent.

To define building archetypes, the building stock is first classified based on common characteristics that are likely to affect the energy performance of buildings. With a deterministic approach, it suffices to classify the buildings based on a collection of features such as their use, type, year of construction, HVAC system, or heated floor area [56, 57]. However, the simplified deterministic approach may lead to a misconceived classification of buildings. More precisely, by systematic classification of buildings based on generalized features and unrelated to energy use values, distinguishing between variations or similarities in the energy performance of buildings could be hard, especially when the building performance does not follow its characterizations such as type of use and year of construction [48]. This stresses the need for the second method of building classification in which adopting influential features and classifying buildings are conducted with respect to their energy use [58]. Applications of probability classification using the probability distribution of a set of building's common features and supervised learning have been proven to be successful [59, 60]. Recently, attention has moved to a third classification method using unsupervised learning and cluster analysis. The advantage of clustering over the other methods is its approach in not only classifying but also finding the most representative buildings, to be the building archetype, from each class or cluster of buildings [50, 61].

After the classification of buildings and identification of building archetypes are completed, non-geometrical characteristics are collected either for a real or a virtual building. Using this information, building models can be developed not only for the building archetypes but also for all similar buildings in every class. Nevertheless, due to the diversity of buildings and their characteristics, calibration of the models for building archetypes is often necessary [56, 62], in particular when the archetypes are chosen from the deterministic classification methods. Methods for calibration and validation of models and archetypes are presented in Section 2.2.7.

2.2.5 Occupancy

Given the uncertainties of occupants' behavior, at the building level, a variety of occupancy models, from deterministic to stochastic have been developed that can generate a close to reality occupancy profiles, as found in Widén et al. [63], Fisher et al. [64, 65] and McKenna et al. [66]. For urban level studies, however, the urban occupancy modeling is still uncertain. Based on a review article by Happle et al. [67], clearly in almost all existing UBEMs, the urban building occupancy is assumed to be similar to that of individual building archetypes. Besides, due to the complexity of stochastic models, it can be seen that the deterministic models are dominant.

To solve the uncertainties of simplified treatments on urban building occupancy, a new generation of studies started to evolve from urban mobility models. At the time when the review article was written by the author, except [10, 20], and [68] in which the utilization of agent-based transport models in capturing the diversity of individual activities was conceptualized, no remarkable example has been found in this area. However, since then, several studies are taking the approach to integrate transportation and human mobility models into UBEMs. Barbour et al. [69] and Wu et al. [70] estimate the absence or presence of building occupants from cellphones and mobile positioning data. Based on overall information about individuals, e.g., students and teachers, Mosteiro-Romero [71] suggests a population-based model and assigns a daily schedule to individuals in order to reach occupants' presence. Happle et al. [72] make use of web mapping services, i.e., Google Maps and Facebook, to statistically prepare a schedule for occupancy in commercial buildings, e.g., retail and restaurants, at their locations. There is no doubt that integrating mobility models into UBEMs can solve the question of urban building occupancy, yet, all these studies still struggle to approach the stochastic nature of human activities at buildings. As suggested in Paper I, it is still a research gap in addressing occupancy profiles in UBEMs.

2.2.6 UBEM simulation engine

In BEM, the simulation engine is where energy models of buildings are constructed and simulated [73]. In UBEM, the primary approach is to model and simulate buildings as done in BEM. However, considering the scale of a city, the procedure needs to be extended over hundreds or thousands of buildings. For this purpose, traditional methods and step-by-step modeling techniques, as in BEM, seem not to be working efficiently.

Many model developers rely on the validity of BEM software and intend to upscale its capability for UBEM. In this case, a BEM software is placed in the main core of the simulation engine while a set of algorithms handle the automated procedure for the whole city. The approach to BEM-based simulations is found in many studies such as [48], [74], [47] and [75]. Although these

types of models deploy the resources and capabilities of BEM simulation software to accurately estimate the energy use in buildings, their use comes with increased complexity and computation cost of the model.

Describing buildings through the resistance-capacitance (R-C) analogy is not a novel approach. It has been around since the early 1970s when the very first energy models of buildings came into being. BEM simulation tools also use this approach in their internal calculations, although the level of complexity might be different. Developing tailor-made algorithms based on the R-C analogy and on simplified heat balance equations helps modelers to considerably reduce the computation time as well as the complexity and level of detail in UBEMs. The models developed by Robinson et al. [68] and Fonseca et al. [76], are some well known examples of this modeling approach.

In addition to the type of simulation core, i.e., BEM software or tailor-made algorithms, the UBEMs may differ in considering single or multi-zone building models. Traditionally, depending on the boundary conditions and variations in the internal heating, ventilating and air conditioning of a building, the thermal model is designed to have one zone or multiple zones. However, in UBEM, in the absence of detailed building-level information, it is assumed that all buildings can be defined through similar zoning configurations. Thus, the UBEM simulation engine is also responsible for the implementation of the predefined zoning configuration.

Overall, the UBEM simulation engine is capable of executing simple to complex models of buildings and their energy systems. In some cases, it can also handle interconnections of buildings with their urban environment directly [77], or through co-simulation with other tools [47]. Nevertheless, not every UBEM simulation engine is comprehensive enough to include different models of not just buildings but also energy systems and their components such as district heating and electricity distribution. In this respect, co-simulation [47] and modular [49] approaches seem to open new opportunities for more advanced UBEMs.

2.2.7 Model calibration and validation

UBEMs rely heavily on the physical and operational characteristics of buildings. However, access to such data is often restricted, and the existing generalized methods add to the uncertainties of the model [78]. Furthermore, some of the model parameters, such as occupancy, are inherently uncertain and no model is able to fully capture their variations in time [79]. On the other hand, to reduce the associated complexities of UBEMs, simplification is a common method that also increases the performance gap between the model and reality. To reduce the input data uncertainty and optimize the performance gaps, model calibration becomes an important part of the UBEMs [78, 80, 81].

The approach to calibrating and refining the model varies in existing research, but two common methods can be distinguished. An iterative process of adjusting the model parameters and comparing the results with energy use data is commonly used in many studies. Due to the simplicity of the method and its flexibility in adapting data with various spatial and temporal resolutions, it seems a straightforward approach to use. This method can be found in the studies conducted by Heiple and Sailor [82], and Leroy et al. [80]. The second approach applies statistical methods, in particular, Bayesian statistics and Bayes' theorem to predict the uncertain parameters and calibrate the model accordingly [81, 56, 83, 57]. In an attempt to infer the parameter values from the posterior distributions of uncertain parameters, Nagpal et al. [84] suggest an auto-calibrated model to reduce the manual effort in calibrating the UBEMs, while Kristensen et al. [62] implement a hierarchical setting to propose a multi-level parameter assessment which forms an optimal solution. However, all the methods of calibrating UBEMs cannot fit into these two categories; other different methods can be found in [85] and [86].

Nevertheless, complementary model calibration methods do not suffice for judging the reliability of an UBEM. In general, the calibration is done to improve the performance and accuracy of a model compared to a reference, e.g., a building, archetype, etc. To assess the performance and reliability of a model, it has to be compared with real-world data, e.g., measurements for energy use in buildings. Validation of the model against actual energy use data may confirm the validity and superiority of a model. However, in many cases, UBEMs are not validated at any spatial or temporal level at all. Except for a few examples, limited information on model validation is provided in existing studies. An example of a validated model is found in Cerezo Davila et al. [48] in which they reported a 5-20% error when comparing the average simulated energy use of each building archetype with the reported average energy from the U.S. Commercial Building Energy Consumption Survey 2003. Other examples of validated models are found in [87, 88].

2.2.8 Applications of UBEM

The key application of UBEMs is to assess the energy performance of buildings at both the building as well as district and city levels. As an example, Cerezo Davilla et al. [48] addressed the estimation of energy use intensity (EUI) in buildings using an UBEM for the city of Boston, US. In addition to the calculation of energy demand in buildings, some studies provide insight into other performance indicators, such as thermal comfort and carbon emissions. In [89], the authors made use of a district-level UBEM to not only evaluate the energy use but also study the indoor thermal comfort in residential building blocks, in Spain. An example of the use of UBEM, and in this

Table 2.4. *Applications of UBEMs.*

Application	Comment	Example studies
Assessment of energy performance of buildings	Evaluation of energy performance, thermal comfort, and carbon emissions in buildings/districts/cities.	[48, 89, 90]
Energy retrofit scenario planning	Defining baselines and energy efficiency measured for energy and carbon reduction in buildings/districts/cities.	[91, 92, 97]
Renewable energy integration	Reducing the energy demand of buildings/districts/cities using building-integrated renewable energy, i.e., PV and battery systems.	[48, 94, 95, 96]
Urban energy planning	Estimation of energy demand in new and planned city districts.	[47]

case, a web-based UBEM framework, for the calculation of carbon emissions and accordingly carbon reduction strategies are also found in [90].

The UBEMs also support scenario planning and energy retrofit of buildings. The engineering-based approach used in the development of UBEMs makes it possible to test the effects of different energy retrofit scenarios on improving the energy performance of buildings. The examples of energy measures for improving the properties of the building envelope, and HVAC systems are found in [91, 92]. In these studies, by defining a baseline, the energy-intensive buildings are identified and retrofitted. Later, the effect of different retrofit scenarios on buildings is evaluated from different perspectives, e.g., carbon emissions or cost. However, not every UBEM is capable of these building-level analyses, and instead lower spatial resolutions are used. For instance, Pasichnyi et al. [93] studied the effect of retrofit scenarios on the archetype level which has been generalized to all the buildings categorized under the archetype class.

The UBEMs can be also used for the integration of renewable energy, in particular, on-site solar PV, and battery systems into buildings. In [48], the possibility of mitigating the energy demand of the city was tested for a scenario when 50% of the rooftops were covered by PV panels. A similar analysis of the integration of PV systems to the buildings' energy systems is found in [94, 95]. In Ref. [96], in addition to PV, applications of the battery systems in increasing self-consumption and self-sufficiency at the community level are discussed.

The application of UBEM in urban energy planning and estimation of the energy demand in the planned city districts is a topic of discussion in the existing research. In a study conducted by Nageler et al. [47] the energy demand of two planned city districts in Graz, Austria was calculated from UBEM methods. In this study, where the building designs were unknown to the authors, instead of shoebox models, the buildings were replaced by cross-shaped cubatures.

In addition, other examples of the applicability of UBEMs are found climate adaptation [98], energy forecasting [88] and demand response control [99]. Table 2.4 summarizes the domain applications of UBEMs in brief.

2.2.9 Existing UBEMs

The very first studies on building energy models and dynamic simulation of buildings emerged during the 70s and early 80s, such as Clarke [100]. Nonetheless, by doing a systematic review it is noted that the modern urban-scale building energy studies based on engineering methods can not be found until the early 21st century. Some of the examples of these early-stage engineering models were published by Huang and Broderick [101] in which dynamic energy simulation of prototype buildings (or building archetypes) was conducted by DOE [102] and extrapolated over the whole stock, and Parekh [103] that specifically focused on establishing certain criteria in defining building archetypes. However, it was only after the development of SUNtool [104] and its successor CitySIM [68] that the attention moved to the usability of urban models of buildings as a tool to support the increasing demand for sustainable urban planning. In this respect, SUNtool and CitySIM [104] can be regarded as pioneering models (or tools) in the field of urban building energy modeling.

Developed at the Swiss Federal Institute of Technology of Lausanne (EPFL), CitySIM is a simulation tool for the analysis of energy demand in buildings with respect to occupants' behavior, HVAC systems and urban microclimate and at different scales, from building to district and city. By receiving benefits from the graphical user interface (GUI) in Java, CitySIM calculates the building-related energy flows using a C++ solver in the background. Thermal models of buildings in CitySIM originated from the R-C network analogy where the conducting walls transfer the heat between temperature nodes. On external surfaces, the temperature nodes are affected by microclimatic conditions, in particular solar radiation, and the internal nodes, are designed to be reflective of the occupants' behavior and its stochastic nature. Based on the availability of geometrical information and individual building characterization, CitySIM seems to produce reasonable results [68, 105, 106].

Generally speaking, CitySIM can be regarded as a simulation platform that only handles dynamic simulations of buildings when the required information

is given as input. Yet, this data is not always available. To round this problem, SimStadt [49], developed at the University of Applied Science Stuttgart, proposes a new modular workflow based on third-party software, e.g., CitySIM, for conducting a multi-scale urban energy and environmental (CO₂ emission) analysis. To solve the complexities of handling data, using its pre-processing modules, the missing data is deduced from available information on typology and usage (archetype) or from probabilistic methods of interpolating from aggregated level data. In other words, it utilizes CitySIM while suggesting new methods to overcome its shortcomings. Furthermore, SimStadt makes use of the other already established tools to consider not only the buildings but also the energy systems. For instance, it makes use of the network analysis tool, Stenet [107] to evaluate the district heating and cooling networks and associated distribution losses. With the same approach, PV potential and renewable system integration are also considered in the tool. However, the main novelty of SimStadt, as compared to similar studies of the time, is its approach to using a modern GUI for conducting fast and parallel calculations when computation power and power limitation were a big issue for many model developers.

However, SimStadt is not the only successful example of UBEMs that have been developed based on modular workflows. The integrated framework for analysis and optimization of buildings, developed by [76, 77], known as City Energy Analyst (CEA) is another example of such terminology that incorporates six different modules for building demand forecasting, resource availability assessment, simulation of conversion, storage and distribution technologies, bi-level optimization, and multi-criteria assessment. In terms of building-specific calculations, CEA takes an analytical approach to the physical description of dynamic heat and mass transfer along with buildings, systems, users, and the surrounding environment which is then corrected through statistical analysis with annual specific values for consumption in buildings, and classified using k-means clustering and illustrated in the output. This tool utilizes an innovative 4D interface in ArcGIS to facilitate visualization and dissemination of the results. Unlike SimStadt, CEA is developed in a single interface and a series of tailor-made models in Python.

Not every UBEM is based on simplified mathematical models. Some UBEMs take full advantage of the validity and reliability of building simulation software in calculating energy demand in buildings. With a similar approach as SUNtool, the urban modeling design platform called umi [108] is an UBEM with capabilities to evaluate operational building energy use, sustainable transportation choices, day-lighting and outdoor comfort at the neighborhood and city level. In this tool, Rhinoceros 3D CAD environment and its integrated visual programming environment, Grasshopper, are used as the modeling platform while EnergyPlus handles the subsequent dynamic simulation of buildings in the background. umi forms the basis for the UBEM for the city of Boston [48]. The Boston UBEM is a city-wide model that captures the energy flows of more than 83000 buildings in the city of Boston. Due to the spa-

tial scale of the model, it is not comparable with other similar models. Using available datasets on building information and specific definitions of building archetypes, the building stock is modeled from characteristics of 52 use/age archetypes. As mentioned, umi [108] handles building-by-building modeling and simulation of thousands of buildings in 60 hours.

These are some of the examples of the developed UBEMs, more are presented in Paper I as well as in [109].

2.3 Research gaps

In an attempt to achieve a close-to-reality estimation of spatio-temporal energy use in cities, and to improve the energy efficiency of the building stock, the field of urban building energy modeling has experienced considerable improvements, during the last decade. Despite this, there is still a great deal of uncertainty about the choice of building simulation tools to be used for large-scale studies, the level of complexity of the models, and the availability of good quality data on which to build the model. The validity and reliability of the model in estimating the demand and later its applicability in urban energy system analysis is also a topic of discussion. For these reasons, the existing research gaps in the field have been identified as follows:

- Relying on the maturity of individual building energy models and the reliability of established building energy simulation tools, a large number of UBEM studies make use of one of the common BEM tools in their models. Although these BEM tools should be possible to use in large-scale studies, there is no comprehensive study that investigates their advantages and disadvantages as UBEM simulators. Paper II, therefore, aims to present a clear response to these questions by comparing some of the most common simulation tools with each other, all of them applied to the same case, and validating them against measured data.
- Due to the large number of buildings included in UBEMs, traditional multi-zone building models that are used in BEM studies are not applicable in UBEMs. While some model developers considerably reduce the complexity of the models to simplified single-zone models, others follow the ASHRAE guidelines in multi-zoning configuration, i.e., one core zone and several perimeter zones for each floor. Yet, there is no clear prescription on the proper level of complexity of the building models in an UBEM. This issue is the basis for Paper III, in which different zoning configurations and levels of model complexity are simulated and their effect on the resulting energy use is analyzed and compared between the most common simulation tools.

- Data collection is one of the biggest challenges in UBEM. In the absence of detailed information on buildings, the UBEMs are developed from a series of assumptions and simplifications that are made based on limited data. These data are mainly extracted from different sources and are not necessarily available for any districts or cities. This makes the accuracy and applicability of the models questionable. In Sweden, the national datasets for building-related information are largely open. The availability of these data is expected to decrease the uncertainties and facilitate the modeling procedure considerably. For this reason, Paper IV aims at analyzing the possibility of developing an UBEM using available national databases for geographical and property information together with energy performance certifications.
- It is commonly accepted that the accuracy and reliability of UBEMs are associated with the calibration and validation of the model. The calibration/validation procedure is dependent on measurement data which are not available in many cases. The Swedish energy performance certificates contain the annual delivered energy for space heating and domestic hot water, ventilation, and comfort cooling. For some buildings, it also includes annual data for household electricity use. In Papers IV and V, the annual energy data reported in the EPCs are used as the basis for the calibration of the model and validation of the results at different spatial resolutions. In the case where monthly and hourly energy use data is available, the validation procedure is done using independent sources of measurement data and for higher temporal resolutions.
- UBEMs not only estimate the energy demand in buildings/districts/cities at their existing conditions but also determine how different energy efficiency measures can affect the magnitude of demand at different spatial and temporal scales. Despite this capability of UBEMs, not many of the developed models have been used for further energy efficiency analysis. A number of studies elaborating on large-scale energy retrofit of buildings also overlooked the possibility of setting baselines for comparison and prioritizing buildings for efficiency measures. In these papers, the assumptions are generic and applied to either all the buildings (in case the model is run on buildings) or just archetypes. In Paper V, the main objective is to prove the applicability of the model in identifying the hotspots of energy use in the city and implementing energy efficiency measures where it is necessary. The possibility of achieving net-zero energy districts when solar PV systems are installed on the rooftops is also investigated.

3. Methodology and data

The methodology in this thesis is comprised of a series of interconnected steps that draws upon the findings in Papers I, II, III, IV, and V. An illustration of the methods and achieved outcomes are presented in Figure 3.1. The first step in this thesis was to conduct a review of the state of the art. The choice of the modeling approach, i.e., hybrid UBEM based on available BEM tools, was made from the findings of this review. The major part of this review was presented in the background of this thesis (cf., Section 2).

After choosing the general modeling method, an evaluation of some of the commonly-used BEM tools enabled the identification of the most suitable tool for the development of the UBEM. Section 3.3 describes the fundamentals of BEM and a method for the comparison between the BEM simulation tools. In addition, using a systematic comparison of the tools, the proper level of complexity of the building model in terms of zoning configuration and level of detail was chosen. Section 3.4 presents the method for analysis of model complexity in brief.

With knowledge about the modeling approach, the choice of tool and the level of complexity, an UBEM customized to the Swedish residential building stock was developed. In Section 3.5, the suggested method for developing this UBEM from open data in Sweden is outlined. To improve the performance of the model, it was calibrated with available EPC data in Sweden. The calibration was done for two case study cities located in the middle and southern parts of Sweden. The method for the calibration of the UBEM is found in Section 3.6.1.

The calibration step improved the accuracy of the UBEM considerably. The subsequent step was to test its validity when applied to other cities and time resolutions than calibrated for. Therefore, the calibrated UBEM was validated against independent sources of measured energy data at different spatial and temporal scales and for different cities. The validation of the UBEM is detailed in Section 3.6.2.

Finally, the calibrated and validated model was adopted for analysis of large-scale energy retrofit of buildings and their effects on the district energy systems. Section 3.7 discusses the application of UBEM for scenario planning and energy retrofit of buildings.

Considering the importance of data to proceed with the methodology of this thesis, this chapter begins with an overview of different datasets used for the development of the UBEM (Section 3.2) and continues with the method.

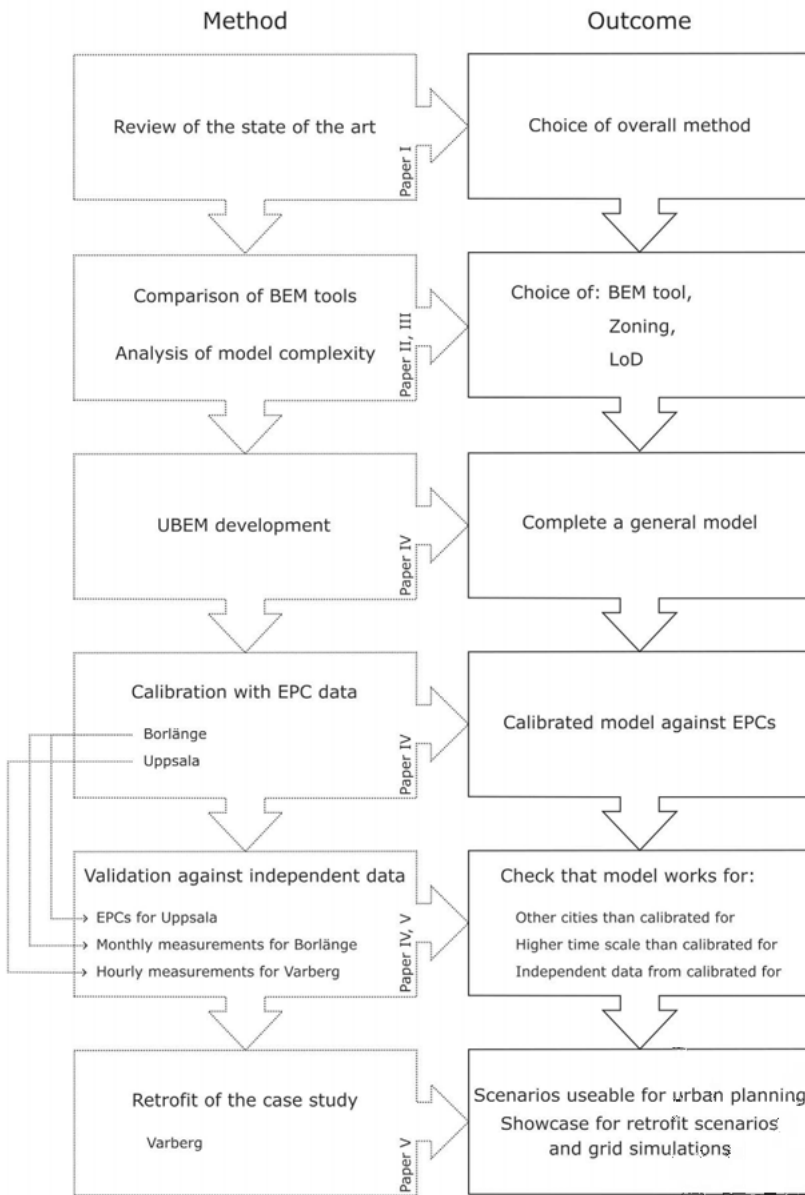


Figure 3.1. Overview of the methods and their outcomes for this thesis and the appended papers.

3.1 Overview of case studies

To implement the developed methodology of this thesis several case study cities and districts located in Sweden were chosen. Figure 3.2 shows where in the country they are located. More information about these case studies is found in the following subsections.



Figure 3.2. Location of the case study cities of Borlänge, Uppsala and Varberg in Sweden. The case study districts of Gräslöken and Gottsunda located in the city of Uppsala are also labeled in the map.

3.1.1 Case study districts

In Paper II, a district in Uppsala, Sweden, called "Gräsöken", with 32 buildings of two different types (defined as types A and B) was chosen for modeling and validation of the respective BEM tools when applied to UBEM simulation. These buildings are connected to the city's district heating (DH) system through a local substation and a secondary heat distribution system, from which the thermal energy is transferred to the buildings. A detailed description of the buildings and the distribution systems is given in [110].

The buildings in this area are multifamily buildings with two heated floors and an unheated attic. However, for the sake of simplicity, in this study, the unheated attic was not considered as a part of the building model and rather merged with the external roof. The buildings of type A have an average heated floor area of 906 m² and window area of 102 m², while the buildings of type B have 1019 m² heated floor area and 109 m² window area.

In Paper III, to complete the study of the modeling complexity on the district and building levels, a district in the Southern part of Uppsala, called "Gottsunda", was chosen. This district includes the typical Swedish district-heated residential multifamily buildings constructed during the early 1970s. According to the characteristics of these buildings (found in detail in Paper III), they are divided into three main types that are presented in Table 3.1. Out of 30 buildings found in the district, 5 were categorized as type A, 20 as type B and 5 as type C.

Table 3.1. Summary of the main properties of three building types in the case study district of Gottsunda, Uppsala.

Building type	Floors	Heated area (m ²)	Energy performance (MWh/y)	(kWh/m ² y)
A	2	699	109	157
B	3	1498	235	157
C	8	5197	896	173

3.1.2 Case study cities

In Papers IV and V, three case study cities were chosen for completing the objectives of the study. The choice of these cities was made based on the availability of the data for calibration and validation of the model. In Paper IV, the cities of Borlänge and Uppsala, located in mid-Sweden and with more than 240 000 and 50 000 inhabitants and approximately 40 000 and 21 000 residential building blocks were chosen for implementing the model. In these two cities, the majority of the buildings ($\approx 60\%$), in particular MFBs, are district heated and the rest are mainly supplied by electricity and the electric-heating systems.

Table 3.2. *General information about the case study cities.*

City	Population	Building stock	Residential share
Uppsala	240 000	46 700	86%
Borlänge	50 000	23 700	89%
Varberg	35 000	25 600	89%

In Paper V, the case study city of Varberg, located on the West coast of Sweden, was selected. This city, similar to Borlänge, is a mid-size city with around 35 000 inhabitants residing in 22 000 residential building blocks. Unlike Borlänge and Uppsala, the coverage of district heating is not that high (only 25%) and most buildings are dependant on electric-based heating systems.

3.2 Overview of data

UBEMs rely heavily on building-specific data. In the appended papers to this thesis, to proceed with the development of the UBEM, various sources of data were explored. An overview of these datasets is presented in Table 3.3 and briefly described in the following sections.

3.2.1 Building drawings

Due to the smaller spatial scale in Papers II and III, the largest share of data on buildings was collected from the building blueprints. The data used in paper II came from a previous study by Åberg et al. [110]. These detailed building-level data were already provided by the housing association company, HSB 53 BRF Gräslöken. In Paper III, the municipality-owned housing company Uppsalahem provided the buildings' constructions and blueprints to the study.

Table 3.3. *Summary of the datasets used in each paper.*

Paper	Modeling ¹	Simulation ²	Calibration ³	Validation ⁴
II	Drawings	Historical	-	Hourly DH
III	Drawings	TMY	-	EPC
IV	GIS, EPC	TMY, Historical	EPC	EPC, Monthly DH
V	GIS, EPC	TMY, Historical	EPC	Hourly electricity

1. The data used for defining geometrical and non-geometrical information.
2. The prevailing weather data used for the simulation of the model.
3. The data used for calibration of the model.
4. The measurement data used for validation of the model.

3.2.2 GIS data

The Swedish Mapping, Cadastral and Land Registration Authority, Lantmäteriet [111], owns the real property register that provides an overview of real estate in Sweden. This real property register consists of a collection of geographical information system (GIS) data on buildings and land use. This information builds the foundation for the developed UBEM and the method elaborated in Papers IV and V.

In general, five layers out of many layers of data were found to be practical. The first layer of data, the property map for the built-up area, here referred to as the building polygon layer, includes information on building footprints, and building types. The types of buildings explicitly portray the purpose or use of buildings, e.g., residential-detached single-family, residential multi-family, heating plant, school, etc. In total, 49 different building types are identified in this data layer, six out of which are residential buildings.

The second layer informs about the real property boundaries and land parcels. This layer of data mainly contains the real property polygons and the designation names, i.e., a unique designation that is assigned to each property. However, similar to the building polygon data, in the property polygon data layer, each property is also labeled based on its type.

The other layer was specifically used for extracting the year of construction or re-construction (if any) of buildings. However, this layer presents a wide range of additional information about buildings, from their types to their share of residential or non-residential area, taxation year, etc. Here, each building is represented by a GIS data point with given XY coordinates.

The fourth layer contains comprehensive data on several properties such as address place points and designated postal addresses. The address point of a building is a GIS point with given coordinates. This address point is reported for either the exact or approximated entrance of the building/property. Similar to the previous data layers, this data also includes more than just the addresses which have not been used in this study.

The laser data, known as light detection and ranging (LiDAR) data, is another layer of data that is used in this study. The LiDAR data include a point cloud with classified points captured from airborne laser scanning of the terrain corresponding to tiles measuring a minimum 2.5×2.5 km. Coverage of the so-called low-resolution point clouds with a point density of 0.5-1 point/m² is widespread over the whole country. Each point in the low-resolution data is classified as ground, water, bridge, or unclassified. Using this dataset it is possible to get an overview of the building topography.

3.2.3 EPC data

The Swedish Energy Performance Certificate (EPC) database is open-source data that is collected by the National Board of Housing and Planning in Swe-

den, Boverket [29]. This certification system was introduced to the Swedish housing stock in 2007 in order to highlight the energy performance of buildings.

The EPC data in Sweden contain information on the heated area of the building, delivered energy use for heating, comfort cooling, and domestic hot water for actual and normal years, household and operational electricity, energy performance and energy class of the building, as well as types of heating and ventilation systems and ventilation flow rate. Further information on the solar energy systems, both PV and thermal, including system area and estimated on-site energy generation is found in the EPC data. Additionally, some of the key attributes of buildings, such as type and use, year of construction, number of heated floors above and below ground, number of apartments, and complexity of the constructional shape, are also found in the EPC data.

The requirement for establishing an EPC is not effected unless the building is sold, rented, newly built, or visited frequently by the public. This means that the coverage of the EPC data is not complete. An analysis of the data (version 2022) shows that approximately 65% of the residential building stock (30% of SFBs and 90% of MFBs) was issued an EPC.

In Paper III, the use of EPC data is limited to the validation of the model for a district where the EPC coverage was full. In Papers IV and V, however, the EPC data is the main source of data for modeling, calibration and even validation.

3.2.4 Validation data

The availability of the measurement data depends on a set of factors, such as integrity and confidentiality of the data. In this thesis, different sources of measurement data were used to accomplish the validation of the developed UBEM at different spatial and temporal resolutions.

In Paper II, with the building owner's consent, the hourly heat use on the substation level was obtained from the district heating utility company Vattenfall Heat AB [112]. This data was measured on the supply side and includes the total thermal energy used, flow rate, and inlet and outlet temperatures for the year 2015. More information about the data is found in [110].

The validation data for Paper IV consisted of monthly heat use for a group of municipality-owned distinct-heated MFBs scattered around the case study city of Borlänge, Sweden. The data were collected on the substation level and primarily included the monthly district heating data in 2018 for 105 substations. The data were made available by the housing association company, Tunabyggen, and later processed in [113]. After post-processing the data to match the EPCs, only 12 substations serving 40 buildings were left for further validation of the model.

In Paper V, the validation of the models was done using hourly electricity use data for the city of Varberg. The data was recorded at the household level and for the year 2021. After pre-processing the data to match the spatial and temporal resolution of the simulation results, the validation was done on 2955 buildings.

3.2.5 Weather data

In Papers II-V, the choice of weather data was dependent on the aims and objectives of each study. In general, the chosen weather data were historical data and/or typical meteorological year (TMY) data. Historical weather data refer to the past observations of the climatic parameters in a given location and over a specific period of time, e.g., a year [114]. On the other hand, TMY data are representations of the typical climatic conditions in a specific area. TMY data are also generated from observation data recorded over a sufficiently long period of time, e.g., 10 to 30 years, and averaged out or condensed to one year [114]. Both historical and TMY data have an hourly time resolution.

In Paper II, to make the simulation results comparable with the energy data, the historic weather data for the year 2015 was collected from the Swedish Meteorological and Hydrological Institute (SMHI) [115] for the city of Uppsala, Sweden.

In Paper III, following the recommendation from the Swedish National Board of Housing, Building and Planning [29], the energy performance of a building has to be calculated for a normal year. A normal year is defined as a year with averaged climatic conditions. This definition can be interpreted as a TMY. Therefore, TMY data for the city of Uppsala, where the case study buildings and district is located, was obtained from ASHRAE's International Weather for Energy Calculations (IWEC) [116].

Paper IV incorporated a calibration/validation procedure of the model versus EPCs. Similar to Paper III, the energy performance of a building was the basis for this procedure and hence, for the sake of comparability, the TMY data for both case study cities of Borlänge and Uppsala were collected from the PVGIS online tool [117]. Furthermore, in this paper, the method included validation of the model against measurements. The corresponding historical data for the city of Borlänge and the observation year of 2018 were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) [115].

The developed methodology in Paper V was used for calibration of the model using the EPC data and validation of the model based on energy measurement data for the case study city of Varberg. Accordingly, the TMY data were obtained from the PVGIS online tool [117]. Due to the unavailability of downloadable observation data for Varberg from SMHI [115], instead of actual data, the modeled data for the year 2021 was obtained from ERA5 (ECMWF Reanalysis version 5) weather data available on [118].

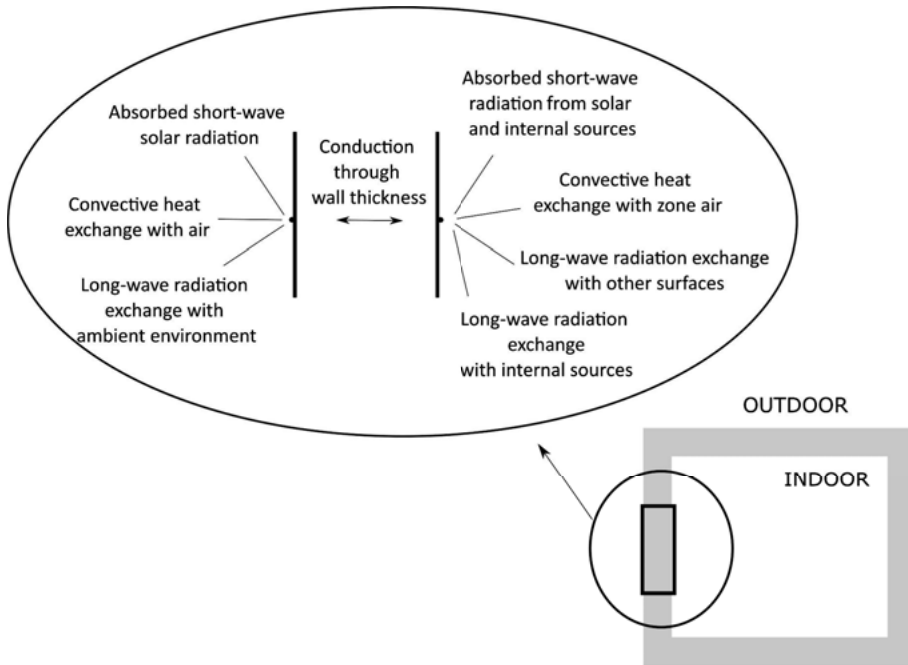


Figure 3.3. Illustration of the heat balance on building surfaces exposed to the ambient.

3.3 Overview of BEM and simulation

As already discussed in Paper I and Section 2.2, the BEM-based urban building energy modeling forms a major part of the existing UBEM research. To decide on the choice of the proper BEM tool, to be used in UBEM, in Paper II and Paper III, different tools were analyzed. A summary of this analysis is presented in the following.

Traditionally, the BEM tools such as EnergyPlus, TRNSYS, or IDA ICE, take full advantage of physical modeling and numerical simulation of heat and mass transfer throughout buildings. To be more focused on the thermal performance of a building, it can be stated that the core of these simulations is based on heat balance principles for every surface of the building. Figure 3.3 shows a simplified illustration of the components of the heat balance on an exposed surface of the building.

In general, the heat balance of the building consists of three parts, including the heat balance on the external surfaces, the heat conduction through the building envelope and the heat balance on the internal surfaces.

3.3.1 Outside heat balance

An external surface, i.e., the external surface of a wall or roof, basically incorporates the measures for heat exchange with the ambient,

$$Q_o = Q_{abs} + Q_{conv} + Q_{lw}, \quad (3.1)$$

where Q_o is the conduction heat into the surface, Q_{abs} is the absorbed solar radiation on the external surface, Q_{conv} is the representative for convective heat exchange with the air, and Q_{lw} is the long wave radiation exchanges between the external surface and the surroundings.

3.3.2 Heat conduction through building envelope

Fourier's law specifies that heat conduction is proportional to the magnitude of the temperature gradient,

$$q = -k \frac{\partial T}{\partial x}, \quad (3.2)$$

where q is the conductive heat flux, k is the conductivity of the material and $\frac{\partial T}{\partial x}$ is the temperature gradient in one-dimensional form [119]. In order to capture the heat conduction through the building envelope, e.g., walls, and solve the partial equations, the conduction transfer function (CTF) and response factor methods are the dominant methods for estimation of transient heat transfer in most BEM tools [120]. In the response factor method, the material thermal response is a linear system that is related to time series of current and past temperature and heat flux. In CTF, additionally, the current temperature and heat flux is connected to the past outputs which considerably reduces the computation time [121].

3.3.3 Inside heat balance

As for the outside, the inside heat balance is calculated on the internal surface of the walls, roofs, and floors as

$$Q_i = Q_{abs} + Q_{conv} + Q_{lw}, \quad (3.3)$$

where Q_i is the conduction through the surface. Due to the contribution of internal sources of energy, e.g., lighting, Q_{abs} is the absorbed short-wave radiation from diffused solar as well as internal sources. In this equation, Q_{lw} refers to the long-wave radiation exchange between internal surfaces of the building as well as internal sources of energy, e.g., occupants, equipment and lighting. Finally, Q_{conv} is the heat convection to the air flows in the building.

Methods for calculating each component of the heat balance in buildings differ between tools. Besides systematic differences in the way a simulation

tool conducts the energy simulation of a building, these differences in the fundamental heat balance equations contribute to variations in the results that can be obtained from each tool.

3.3.4 Comparison of simulation tools

Among various BEM software, only some are compatible with the scope of UBEM. In general, there are technical barriers to the application of some of the tools that limit them to individual building modeling and make them unable to cope with urban energy studies. An overview of BEM tools that could potentially be used for UBEMs and, their most relevant features from an UBEM point of view, is presented in [25, 122]. Nevertheless, it seems that only a few are actually capable of handling UBEMs with all their complexities. An overview of the most feasible tools, IDA ICE, TRNSYS and EnergyPlus, that have been used in Papers II and III, is given as follows.

EnergyPlus [116] is an open-source building energy simulation software that estimates the need for heating, ventilation, and air conditioning of buildings using a variety of systems and resources. TRNSYS [123] is a dynamic simulation software that enables users to study the behavior of transient and dynamic systems. Having an extensive library and an organized simulation environment makes TRNSYS a flexible tool that can be used in many applications from building energy modeling to system energy analysis and solar energy studies. IDA Indoor Climate and Energy (IDA ICE) [124] is a dynamic multi-zone simulation software that accurately models buildings, systems, and controllers in order to maintain the thermal comfort of the building occupants.

Despite the fact that these tools have many similar features, they can be very different in their fundamentals, especially when it comes to the calculation of the heat balance and its components.

Calculations of outside heat balance

Absorbed solar radiation, Q_{abs} , as a factor of incoming solar radiation, is defined as

$$Q_{abs} = \alpha A(I_b + I_d), \quad (3.4)$$

where α is the solar absorptance of the surface, A is the wall area, and I_b and I_d are beam and diffuse solar radiation, respectively, on the wall surface. In IDA ICE and EnergyPlus, direct and diffuse incident radiation are mainly assessed based on the ASHRAE guidelines [125] and Perez model [126], while TRNSYS gives the possibility of choosing between sets of common methods such as the Perez model [127] or the Hay and Davies model [127].

Convective heat transfer on external surfaces, such as a wall, is determined based on the convective heat transfer coefficient as

$$Q_{conv} = h_c A(T_{air} - T_{wall}), \quad (3.5)$$

where h_c is the convective heat transfer coefficient, A is wall area, T_{air} is the ambient air temperature and T_{wall} is the wall surface temperature. In IDA ICE, the convective heat transfer coefficient for external surfaces is calculated based on the heat transfer coefficient as a factor of local wind velocity. By default, EnergyPlus calculates the total convective heat transfer coefficient as the sum of coefficients for forced and natural convection with respect to the local wind speed and wind direction. In TRNSYS, on the other hand, the convective heat transfer coefficient is assumed as either a user-defined variable to be static or time-dependent or to be calculated internally. The internal algorithms calculate the convective coefficient with respect to the surface inclination and heat flux.

The long-wave radiation exchange with the surrounding environment can be generally written as

$$Q_{lw} = Q_{lw,sky} + Q_{lw,ground} + Q_{lw,air}, \quad (3.6)$$

with $Q_{lw,sky}$, $Q_{lw,ground}$ and $Q_{lw,air}$ being the components of radiation exchange with sky, ground and the air respectively. Generally, the radiation exchange with the surrounding is estimated using

$$Q_{lw,x} = \varepsilon \sigma F_x A (T_x^4 - T_{wall}^4), \quad (3.7)$$

where ε is the long-wave emittance of the surface, σ is the Stefan-Boltzmann constant, A is the surface area, F_x is the view factor between the sky, air or ground and T_x represents the temperature of the sky, air or ground, while T_{wall} is the surface temperature. Using Equations 3.6 and 3.7, the long-wave radiation exchange with the surrounding is calculated accurately in EnergyPlus. In IDA ICE, however, the long-wave radiation exchange with the air, $Q_{lw,air}$, is neglected in these equations. Calculation of the radiation exchange is conducted slightly differently in TRNSYS, with T_x in Equation 3.7 being the fictive sky temperature and representing not only the sky temperature but also the ground temperature and the view factor between the sky and the surface. In this method, based on the definition of the fictive sky temperature, both ground and sky long-wave radiation exchange with the surface are combined in one term.

Calculation of heat conduction through building envelope

Calculation of the heat transfer through opaque and transparent surfaces of the building envelope, e.g., walls, and windows, plays a principal role in the differences that can be seen later in the results from Paper II and III.

In IDA ICE, the calculation of the CTF function is simplified by designating fewer thermal nodes to the heat transfer surfaces. Using an optimized thermal-electrical analogy of heat conduction for a given thermal resistance-capacitance (R-C) network with only three capacitances, IDA ICE conducts an optimization method to estimate the model parameters. On the other hand,

TRNSYS and EnergyPlus take full advantage of CTF methods and response factors in calculating the heat conduction through the opaque surfaces. However, each uses a distinctive solver. TRNSYS utilizes the direct root finding methods [128] and treats the surfaces as black boxes with no need for information on temperature variations inside the surface. EnergyPlus, however, makes use of the state space methods in solving the analytical CTF models [121]. By assigning multiple temperature nodes to the heat transfer surface, in EnergyPlus the heat flux through the wall is calculated from one node to the other. Discretizing the wall into multiple nodes is expected to reduce the length of the CTF series, and thus the computation cost, to some extent. More information on differences in calculation and solving the heat conduction transfer through the building envelope is found in Paper III.

Calculation of the inside heat balance

As for the calculation of the outside heat balance, the components of the heat balance equations on internal surfaces, Equation 3.3, are estimated differently in each tool. The method for calculation of internal convective heat transfer is almost similar to the method used for estimation of outside convective heat transfer in TRNSYS and EnergyPlus. In IDA ICE, however, the convective heat transfer is estimated from the slope of the surface and the temperature gradient between the internal air and the internal surfaces.

The absorbed short-wave radiation is determined as a function of transmitted solar radiation through windows

$$Q_{abs} = XI_{dif}, \quad (3.8)$$

with X being the absorption matrix in IDA ICE, the transposed of Gebhart matrix [129] in TRNSYS and the relative absorption of the surfaces multiplied by the window area in EnergyPlus, and I_{dif} the solar radiation transmitted through windows.

In the calculation of the internal long-wave radiation exchange, EnergyPlus assumes the inside air to be completely transparent to long-wave radiation, the internal surfaces of the buildings to be grey-bodies and all the radiation to be diffuse. Then relying on a unique coefficient for all reflections, absorptions and re-emissions from other surfaces in the zone, EnergyPlus calculates the radiative exchange in the building. In TRNSYS, and based on its standard-level calculation methods, the radiation exchange is approximated from the star method [121], for a hypothetical temperature node in the middle of the room. In this method, not only the radiative exchange but also the convective heat contributes to the temperature node. In IDA ICE, the long-wave radiation is proportional to the radiosity and the properties of the black-body surfaces.

In addition to these differences in the principal methods of calculating heat transfer, there are systematic differences in how the modeling procedure is conducted.

Ground coupling

To model the heat transfer from the building to the ground below the slab or the basement in IDA ICE, it is sufficient to determine the average annual ground temperature as well as slab and soil properties. According to ISO 13370 [130], IDA ICE calculates the heat resistance of layers below the building construction and, accordingly, the heat transfer through them. If the standard weather datasets are used, the respective annual ground temperature is assumed automatically. In TRNSYS, the procedure is not as effortless as in IDA ICE. For this purpose, the external slab components from the TRNSYS library should be connected to the building. Depending on the building model and desired accuracy, ground coupling models with different levels of complexity can be used, e.g., Type 49 for approximation of the slab on grade, or Type 77 for calculation of the soil temperature. More components for calculation of both slab and basement heat transfer are found in the TESS library [123]. However, computing time is greatly influenced by choosing alternative components. In EnergyPlus, different ground coupling concepts exist. The two associated auxiliary tools for basement and slab modeling in EnergyPlus, conduct an accurate calculation of heat transfer and boundary temperatures [116].

Shading analysis

Analysis of shading from nearby buildings or surrounding obstacles and its effects on building performance is one of the sources of differences between the tools. Using the SketchUp [131] plugin for building form and external shadings, TRNSYS acquires the geometrical information of the shading obstacle. However, the implementation of shading analysis from SketchUp file generator is not feasible for TNSYS 17. In TRNSYS 18, this feature has been included, yet the building model does not consider the influences of shading obstacles on the heat performance of the building as effectively. Instead, it is suggested to add the external components for shading models provided in the TRNSYS library. With the application of a similar SketchUp Plugin for EnergyPlus, or by determination of the geometry of the shading obstacle in the site location, shading analysis in EnergyPlus is easily conducted. Due to the increase in complexity of the model, the computation time increases slightly. IDA ICE does the shadings analysis differently. By importing the site plan in 3D format or by drawing the obstacles, IDA ICE includes the shadings and performs the simulation automatically.

Occupancy and use profile

In the calculation of the metabolic heat gain of occupants, all four tools have the same methodology using ASHRAE standards [125] and taking just the convective heat into consideration. However, the main challenge is to define annual schedules for hourly-based activities and the presence of buildings' occupants. IDA ICE can accept hourly schedules for weekdays or weekends as well as months. However, while specifying the hourly or even daily profiles

seems impractical, importing any external file to its database is impossible. Thus, the only way is either to use constant or predefined schedules or just rely on low-resolution profile development. In EnergyPlus and TRNSYS, the procedure brings no difficulties for the user and it would be possible to import the schedules or load profiles by just importing a text file to the programs.

Number of buildings

In TRNSYS and EnergyPlus it is impossible to model and analyze one building at a time. However, IDA ICE as a BEM tool is capable of handling the energy modeling of buildings at larger scales e.g., district level up to a limited number of thermal zones (300 simple zones and 70 detailed zones).

Time step and simulation

In terms of accepting sub-hourly data both in input and output, IDA ICE and TRNSYS have no limitations, even for considerably small time steps, e.g., seconds. Similarly, EnergyPlus can handle minute-based time steps, although for receiving the best output from the tool hourly or at least a 10-minute resolution is suggested.

Given the importance of BEM simulation tools and their usefulness in UBEM, in Paper II, a comparative study on the validity of the dominant BEM tools, i.e., IDA ICE, TRNSYS, and EnergyPlus, for being used as the main simulation core of the UBEM is performed. In order to explore their advantages and disadvantages in large-scale studies, a district-level energy model of 32 district-heated multifamily buildings was developed in the three tools.

In this study, it was tried to make the models as similar as possible in order to be comparable. Some of the assumptions and conducted methods in Paper II are linked to this point. For instance, due to limitations of IDA ICE in handling hourly load profiles input to the model, the occupancy profile, i.e., occupant presence, household electricity and lighting as well as DHW, and its contribution to internal heat gain was calculated separately from the models and added to the final results later. In this study a stochastic occupancy load generator developed in [63] was used.

3.4 Model complexity and zoning configuration

In addition to the choice of BEM tool, the complexity of the building model is another parameter which was not chosen systematically, in the existing studies. Therefore, in Paper III the model complexity in terms of zoning configuration and level of detail was evaluated.

As mentioned, to overcome the complexity of simulating a large number of building models, in the UBEM the aim is to abstract the buildings and their systems, and estimate their performance without having to deal with all their

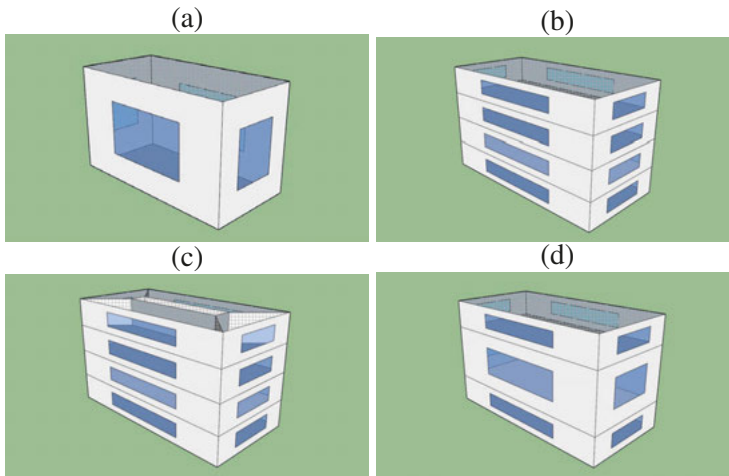


Figure 3.4. Thermal zoning configurations in UBE: (a) single-zone model (1 zone per building), (b) multi-zone model (1 zone per floor), (c) multi-zone model (5 zone per floor) and (d) multi-zone model (3 zones per building: one for bottom floor, one for top floor and one for all middle floors).

details. Some examples of such simplification are reducing the number of thermal zones or reducing the level of detail in the building models. However, the exact effectiveness of these alternative methods is not clear in existing research. The risk of defining too simple models is likely to increase the uncertainty and decrease the accuracy.

To untangle these questions about model complexity in an UBE, in Paper III, some of the most common zoning configurations and levels of detail are systematically compared. The single-zone model is traditionally one of the simplest ways of describing a building by a set of equations. Differences in heating and air conditioning as well as influences of the inner walls of the building are neglected and it is assumed that the whole building can be described as one thermal zone. The windows are also modeled based on the corresponding window-to-wall ratio (WWR) on every external wall. Figure 3.4(a) illustrates the single-zone model. Although a single-zone model (1 zone per building) cannot, in most cases, be an accurate representation of an individual building, it improves the computation cost to a large extent and might be accurate enough on an aggregated urban scale.

The second approach is to assign one thermal zone for every floor of the building, as shown in Figure 3.4(b) (1 zone per floor). Defining a simplified multi-zone model is expected to slightly capture the contribution of internal building elements, e.g., adjacent floors, but still run the simulation in an acceptable time. The third and very common method for multi-zone modeling follows the ASHRAE guidelines for envelope setting and zoning configuration. According to ASHRAE 90.1, Appendix G [125], different thermal zones

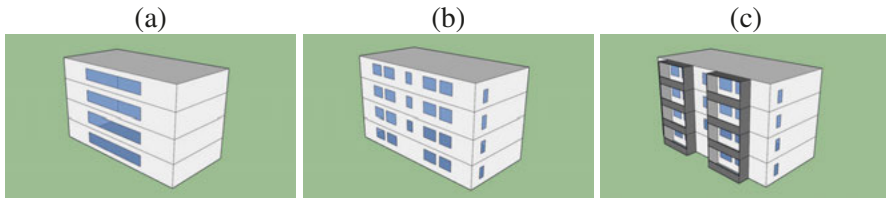


Figure 3.5. Level of detail in building modeling: (a) LoD1, Shoe-box model of the building with 25% window area on long walls, (b) LoD2*, Detailed building model excluding the shading components, (c) LoD3, Detailed building model with the precise geometry of windows and shading components

are assumed for perimeter and interior spaces that are at least 4.6 m away from the exterior or semi-exterior walls. This means, for a square base building, that at least 5 thermal zones, i.e., one core and four perimeter zones, are required for every floor of the building (5 zones per floor), as visualized in Figure 3.4(c) (5 zones per floor).

In addition to these three configurations, when tall buildings are of interest, there is another alternative in which the building is divided into three main thermal zones. One thermal zone is assigned to the ground-coupled or the bottom floor of the building while a second one represents the top floor that is adjacent to the exposed roof. All the intermediate floors are considered as one big zone (3 zones per building). Figure 3.4(d) illustrates this.

In most UBEEM studies, the description of the building geometry is relatively simplified and the building construction is defined through shoe-box models corresponding to Level of Detail 1 (LoD1). This level of simplification, however, may lead to inaccuracy of the results and, therefore, further calibration might be needed to compensate for the deviations from the measured data. Thus, in Paper III, the LoD of the building construction and its impacts on the simulated energy demand is analyzed in depth. In this study, three levels of detail, namely LoD3, LoD2*, and LoD1, are considered, as shown in Figure 3.5. Accordingly, LoD3 implies a detailed building model with precise components and geometries. In LoD2*, the geometry of windows is kept as in LoD3 but the balconies and shading components are excluded from the model. Finally, LoD1 represents a simplified shoe-box model with 25% WWR ¹.

Finding the most suitable zoning configuration depends not only on the scale of the study but also on the simulation tool that is used as a main core of the UBEEM simulation engine. In this study, to validate the already mentioned configurations, three different case study buildings are modeled and analyzed in the three simulation tools introduced previously, IDA ICE, TRNSYS and EnergyPlus.

¹The WWR varies between 20% and 25% as a typical value for the window area in buildings of similar type.

3.5 UBEM development from open data

Following the simulation evidence provided by Paper II and Paper III, a functional BEM tool for UBEM and a proper level of complexity were chosen. Relying on these, in Paper IV, a methodology for the development of an UBEM from available national data was proposed. Similar to the general UBEM structure, already presented in Figure 2.2, the developed model consists of the main components, including 3D city modeling, archetype development, occupancy, simulation and finally calibration and validation. In Figure 3.6 the exact overview of the UBEM developed in Paper IV is illustrated.

The functionality of this model is dependent on the building-level data, the building energy simulation tool EnergyPlus and the programming language Python. Further elaboration on the modeling structure and related information is provided in the following sections.

3.5.1 3D city modeling

To construct a 3D representation of the cities, a general methodology for the extrusion of the building footprints from open-access low-resolution LiDAR data was adopted in Papers IV and V. This method was performed as a pre-processing step and allowed for the creation of reasonable representations of the buildings which were later used as an input to the developed UBEM.

In Paper IV, the open-source tool, 3dfier [132], developed at the Delft University of Technology, handled the automated procedure for reading the 2D GIS and LiDAR data and translating them into shoebox models of buildings (equivalent to LoD1). However, due to the low resolution of the LiDAR data, a post-processing step was added to the method in order to modify the height of buildings that was wrongly captured from the close-by objects or faulty points. The modification was done based on the average height of similar building types in the area.

The 3D city model in Paper V, was obtained from the model developed by Lingfors et al. [133]. As in 3dfier [132], Lingfors et al. [133] made use of LiDAR data to elevate the building footprints. Additionally, they informed the model with typical roof types and improved it with a co-classing technique that enables the model to estimate the geometry of the segments of the roof. This novel approach resulted in higher levels of detail (equivalent to LoD2) where the shape, slope and azimuth of the roof were achieved from the model. With knowledge of the height and shape of the roof, more accurate shoebox models of the buildings were constructed and used for energy modeling. Again, if the estimated height of buildings was determined to be inaccurate, the modifications were done accordingly.

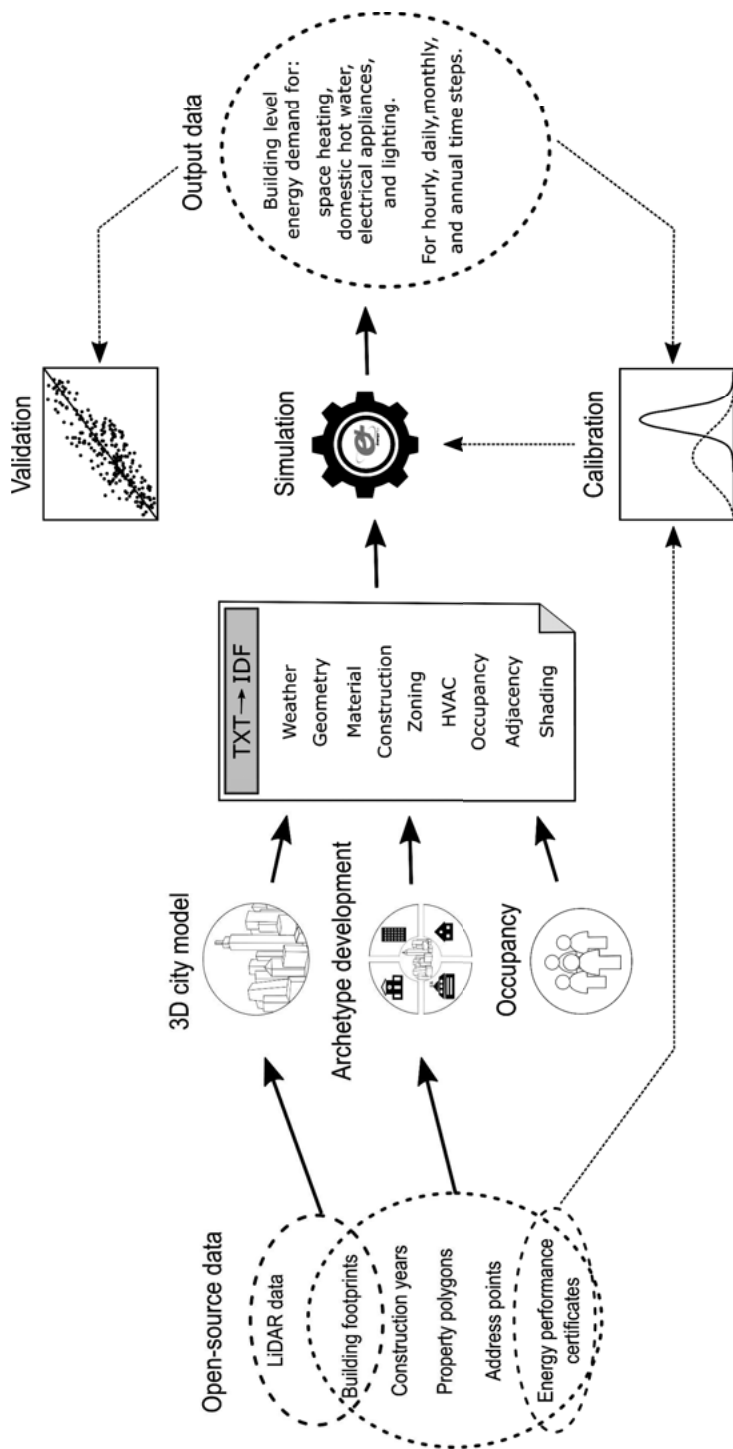


Figure 3.6. Overview of the developed UBEM from open data.

Table 3.4. *Identified building archetypes based on type and construction year of buildings. SFB and MFB refer to single-family and multi-family buildings respectively.*

Archetype	Building Type	Construction Period
1	SFB	2010-2021
2	SFB	2000-2010
3	SFB	1990-2000
4	SFB	1980-1990
5	SFB	1970-1980
6	SFB	1960-1970
7	SFB	1950-1960
8	SFB	before 1950
9	MFB	2010-2021
10	MFB	2000-2010
11	MFB	1990-2000
12	MFB	1975-1990
13	MFB	1960-1975
14	MFB	1945-1960
15	MFB	before 1945

3.5.2 Building archetypes

According to [134], building construction and design in Sweden typically have a strong correlation with the construction period of the building. Unless the building has undergone renovation or significant changes, its construction period is often a reliable indicator of its constructional characteristics. On the other hand, the availability of energy use data is limited to the EPCs, which do not have 100% coverage. Putting all this together, a simple deterministic approach to archetype classification was preferred over more advanced probabilistic classifications or unsupervised clustering (which was suggested in the Paper I).

In Paper IV and Paper V, the classification of the building archetypes was done based on the type of residential buildings, i.e., single-family and multi-family, and the construction period of buildings. The initial classification of the archetypes was primarily derived from the similar categorization found in the two reference books [134, 135]. Later, further modifications were carried out to be sure that the chosen archetype classes better represented the building stock. The chosen archetype classes are presented in Table 2.2.4. In total, 15 archetype classes were chosen, with 8 archetypes representing the single-family buildings and 7 archetypes assigned to the multi-family buildings.

Characterization of the archetypes, i.e., finding the common characteristics of the buildings of each class, was also completed based on the available literature such as [134, 135, 136]. Here, the main objective of the identification and characterization of the archetypes was to define construction assemblies and materials for buildings.

Table 3.5. *Identified building archetypes and their share of heating system, namely, DH, B, DE, and HP refer to district heating, boiler (regardless of their energy carrier), direct electric, and heat pump systems, respectively, in percentage.*

Archetype	DH	B	DE	HP
1	12	3	9	76
2	13	4	6	77
3	14	14	20	52
4	18	5	39	38
5	6	3	46	45
6	29	8	19	44
7	15	12	26	47
8	23	14	18	45
9	84	0	1	14
10	90	0	3	7
11	85	1	2	11
12	41	14	23	22
13	55	0	42	2
14	81	1	5	14
15	57	2	5	36

In Paper V, in addition to the construction and material, the heating system of the buildings also corresponded to the archetypes. In this paper, based on the EPC data, the share of different heating systems was averaged out over all the buildings of each archetype class and later assigned to the buildings with no available EPCs. The share of each heating system for each archetype is found in Table 3.5.

The air tightness and infiltration rate of a building is another archetype-related parameter. However, in the base definition of archetypes, it was set to zero. Later, in the calibration procedure, it was added to the model where it was necessary.

The window area or WWR is also another archetype-related parameter which was set to a constant ratio for all the archetypes. According to the latest building codes in Sweden, the window area should be at least 10% of the floor area. It was assumed that the later standard is valid for the older archetypes as well.

3.5.3 Occupancy and load

The occupancy and occupants' related energy use are intrinsically stochastic. However, in UBEM, the stochastic approach to the occupancy and load does not seem to be well-established [109]. There is no doubt that the complexities associated with stochastic models make them impractical for large-scale studies.

Therefore, in Papers IV and V, fixed hourly profiles for occupancy, heat gain from occupants, lighting, appliances and domestic hot water were used. These profiles were constructed from averaged daily load profiles and a stochastic model [63]. The resulting profiles distinguish between the main building type, i.e., single- or multi-family, and the weekday-weekend patterns. More information on the process of generating the profiles is found in Paper IV.

3.5.4 Modeling and simulation

In the chosen approach to UBEM (cf. Section 2), the simulation interface and the BEM tool are the main cores of the procedure. In Paper IV, followed by Paper V, the simulation interface was where the automated energy modeling and simulation of large numbers of buildings take place. The developed interface used Python and its object-oriented properties in defining a modular method for reading the building-related information, translating them into an IDF file, running the IDF file using EnergyPlus and reporting the results at desired spatio-temporal resolutions. A brief description of the process is presented in the following paragraphs.

In the model interface, the geometry and geospatial information of a building was used to define the models for the surfaces of a building, e.g., wall and window. Depending on the type of building and the construction year, the building was assigned to the relevant archetype class and the corresponding construction material from the directory of materials was extracted. The location of the building in relation to the surrounding buildings was checked for possible adjacency and shading effects. If the building had an adjacent wall, it was labeled as adiabatic and if the effect of shading was calculated to be high, the shading obstacles, i.e., buildings, were identified and added to the model.

No building model is completed without defining the thermal zones. Following what was concluded from Paper III (discussed in Section 3.4), only one thermal zone was assigned to each building. The zone was connected to an ideal heating system that maintains the zone temperature at 21°C. The zone air was also constantly ventilated at a fixed rate of 0.5 ACH per hour. In case the EPC of a building was available, the heat recovery effect of the ventilation was also considered in the model.

Finally, the occupancy and schedules were incorporated into the model. The completed model was translated into IDF and forwarded to EnergyPlus where the simulation was completed for a specific year and weather data. The simulation results were then read from the EnergyPlus output files and saved in the Python database. The procedure continued to the next building and was repeated until all the buildings were modeled and the results were saved.

In a post-processing step, the contribution of the heating system to energy use was also evaluated, in case the EPC of a building and the heating systems were known to the model. In Paper V, if the EPC was not available, the es-

timated share of different heating systems was taken from the corresponding archetype. The effects of heating systems and associated models are presented in Paper IV.

3.6 UBEM calibration and validation

After developing the UBEM, it required calibration to reach the desired level of accuracy and further validation to ensure its reliability. These were done in Papers IV and V, and are presented in the following.

3.6.1 Calibration

In BEM, sensitivity analysis of uncertain parameters and calibration of individual building models is a well-established step of the modeling procedure. In UBEM, however, the degree of uncertainty of the model parameters is high. In addition to occupancy and internal gain, the exact geometry, WWR, construction and material, HVAC and schedule usually remain uncertain. In Papers IV and V, some of the uncertain attributes of the model were identified and calibrated. The calibration was done in an iterative procedure with the goal to reduce the deviation of the simulation results from the energy use measurement data obtained from EPCs.

Calibration of geometrical parameters of buildings

It is generally recognized that building morphology has a great impact on the energy performance of a building. Previous studies show that the higher the shape factor¹ of a building, the greater the heat losses through the building envelope and therefore, the higher the heat demand in the building [137]. In Paper III, a similar trend in increasing energy demand was noticed when the building form was more complex. Therefore, the first step in the calibration of the model was to simplify the complex building polygons. The simplification algorithms aimed to unify the multi-polygons and simplify the complex polygons to the extent that the footprint area was not largely affected.

The estimated building height from the low-resolution LiDAR data brings additional uncertainty to the model [133]. Estimation of the building height from low-resolution LiDAR data and digital elevation models is associated with some problems including vegetation interference, shadowing and glaring, complex and multi-level roof structures, etc. Moreover, the estimated height of the building may not be attributed to the heated volume of buildings, in particular when the building has a plenum or unheated attic. For these reasons, a calibration of the height of the building based on the number of heated floors, found in the EPCs, was done.

¹The shape factor of a building is defined as the ratio between the envelope area, where the heat losses occur, and the heated volume of the building.

The estimation of the heated area of the building introduces more uncertainty to the model. According to Boverket [29], the heated area of a building is the sum of the internal area for each floor, attic and basement that is heated to more than 10°C. The area occupied by internal walls, openings for stairs, shafts and similar are included in the heated area. However, the area for garages, within the building, or an unheated basement, attic, or staircase, is not included. The GIS data mainly includes the footprints of buildings, including all the heated and not heated premises. Therefore, a calibration of the building area to match the heated area of the building was conducted based on EPCs.

Calibration of thermal parameters of archetypes

Although the archetype approach addresses part of the problems associated with UBEM of large sets of buildings [48], it also adds to the uncertainty of the model [57]. Using the archetype approach, the heterogeneity of buildings cannot be completely captured, in particular when the characterization of buildings is done based on conventional construction trends. Therefore, calibration of thermal properties, i.e., construction and material, of the archetypes was a necessary step in the enhancement of the model. The objective for the calibration of the thermal properties of the archetypes was to reduce the mean error within each archetype class. More information on the method for calibration of the thermal properties of building is found in Paper IV.

3.6.2 Validation

Validation of a model is an essential step towards accuracy and approval of the model. In data-driven models, the availability of data makes the model validation straightforward. In engineering models, however, a lack of measurement data makes validation more complicated, in particular, if the model belongs to more than one or a few buildings.

In Papers IV and V, the UBEM was validated mainly based on available measurement data on different spatial and temporal resolutions. The validation of the model was also determined by common validation metrics such as mean absolute percentage error (MAPE), and Pearson's linear correlation coefficient.

The validation of the aggregated annual simulation results was done against the delivered energy to the buildings as reported in the EPCs. Therefore, the spatial extent of the annual validation is limited to the buildings that are found in the EPC dataset. Furthermore, the validation targeted the simulation results for a normal year and with an average TMY weather data. This is in line with the regulations from Boverket regarding the normalization of the delivered energy data.

Due to the availability of data for monthly district heating use over 12 substations, the second level of validation was conducted on the monthly level.

These 12 substations supplied 40 multi-family buildings with district heating throughout the year. These buildings were located in 12 properties spread around the case study city of Borlänge.

The last step to validation of the model was completed on the hourly level, for more than 3000 buildings located in the case study city of Varberg. The availability of hourly electricity use data made it possible to check the validity of the model for higher temporal resolutions than are usually readily available.

3.7 Energy retrofit scenarios

The accuracy and reliability of the developed UBEM were proven through the calibration and validation procedures, presented in Papers IV and V, and the previous section. This UBEM was then ready to be used for different applications. One of the most interesting uses of an UBEM is to apply different energy retrofit scenarios and study their effects on reducing energy demand of buildings, districts and cities. This type of analysis was done in Paper V in which the large-scale energy retrofit of buildings was carried out for three scenarios based on the Swedish building codes (BBR), Passive House standards and net zero energy buildings/districts.

3.7.1 BBR Codes

Paper V adopted the BBR to establish the first renovation strategy of buildings on the city level. Therefore, the main renovation goal was to minimize the primary energy use of buildings by improving the U-value of windows, walls, roofs and floors. The rule-based decision-making algorithms evaluated the primary energy use of the buildings and compared it to the suggested baseline in BBR. In this study, the BBR29 method for the calculation of the primary energy use was followed. Accordingly, the primary energy use was calculated as,

$$PE = \frac{\sum_{i=1}^6 \left(\frac{E_{SH,i}}{F_{Geo}} + E_{SC,i} + E_{DHW,i} + E_{OE,i} \right) \times F_{C,i}}{A_{temp}} \quad (3.9)$$

where E_{SH} is the energy used for space heating, E_{SC} is the energy for comfort cooling, E_{DHW} is the energy for domestic hot water, and finally E_{OE} is the operational electricity used for running pumps, fans, etc. In this equation, the geographical adjustment factor F_{Geo} and the conversion factors for the energy carriers F_C are also proposed for the proper transformation of the energy use to the primary energy for six energy carriers, such as electricity and district heating. The exact values for each of these parameters are found in [138]. In order to present the primary energy in kWh/m²y, the heated floor area A_{temp} is also included in the equation for the calculation of the primary energy.

In Paper V, if the calculated primary energy use exceeded the baseline, the building underwent renovations that involved adding a layer of insulation to the walls, roof and floor, and replacing the windows. The estimation of the thickness of the insulation was determined by the U-value of the building envelope. According to the BBR29, the U-value of the wall, roof and floor after renovation should be lower than 0.18 W/m²K, 0.13 W/m²K, and 0.15 W/m²K, respectively. The U-value of the new windows should be also 1.2 W/m²K and lower.

3.7.2 Passive House standard

In paper V, in the second energy retrofit scenario, the Passive House standard, established by FEBY, was taken into account. By adding an extra layer of insulation to the building envelope, i.e., walls, roof and floor, the U-value of the enveloped was reduced to 0.1 W/m²K. The windows were also changed to energy-efficient windows with a U-values of 0.8 W/m²K. Finally, the ventilation system of the building was replaced with a mechanical ventilation system with heat recovery of minimum 75% efficiency. The intention with all these changes was to reduce the heat losses from the buildings to a large extent. However, similar to the BBR scenario, the Passive House renovation scenario was applied only to the buildings that do not already satisfy the minimum requirements for heat losses or primary energy use.

3.7.3 Net zero energy buildings and districts

In paper V, both NZEB and NZED were investigated for the case study city of Varberg. In this paper, the third scenario includes increasing the share of renewable PV generation in low-energy buildings to its maximum capacity. The choice of the low-energy building was limited to the already discussed scenarios based on BBR and Passive House standards. The available PV area on the rooftop was obtained from [139], where the solar potential and the available PV area on the buildings were estimated. This study also provided methods for estimating the tilt and orientation of the roofs of the buildings.

Together with the rest of the building-level input data, the information on available PV area, tilt and orientation of the roofs was imported to the developed UBEM where the generation of the energy was computed for the given simulation period. In the PV model, the power output from each module, with approximately 2 m² surface area, was assumed to be 400 W.

A building was labeled as a NZEB (or a district as NZED) if

$$\sum_{i=1}^{8760} E_{sh} + E_{hw} + E_{hel} + E_l = \sum_{i=1}^{8760} E_{pv}, \quad (3.10)$$

meaning that, over a year (8760 hours), the sum of PV generation equals the sum of energy use. In this equation, E_{sh} and E_{hw} are the space heating and hot water energy use which are covered by electricity or district heating (and for some buildings by boilers). E_{hel} , and E_l represent the electricity use for household appliances and lighting, respectively.

The share of operational electricity use in the energy balance of a building was neglected. The main reason for excluding operational electricity use was its inconsiderable share in the total energy demand of buildings. Using the latest EPC data, it was calculated that the share of operational electricity does not go higher than 2% for single-family buildings and 7% for multi-family buildings. The energy for air conditioning, i.e., cooling demand, of the building was also neglected due to the fact that normally buildings are not equipped with cooling systems in Sweden, and even if not, the cooling demand over the year is still negligible compared to the heating demand.

3.8 Performance metrics

Performance metrics are quantitative measures used for evaluating the performance of the model. In this thesis and the appended papers, to assess the performance and accuracy of the model, some of the known error metrics were used.

The mean absolute percentage error (MAPE) [140] is a performance metric that shows the average deviation between the simulated data from the actual measurements and is presented as

$$MAPE = \frac{1}{N} \sum_{i=1}^N \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (3.11)$$

where \hat{y}_i and y_i are the simulated and measured data points, respectively. N is the number of data points.

Furthermore, the root mean squared error (RMSE) [140] is another commonly used metric that is defined as

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2}. \quad (3.12)$$

In case the RMSE is represented in percentage, i.e., root mean squared percentage error (RMSPE), the equation is re-written as

$$RMSE(RMSPE) = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{y_i - \hat{y}_i}{y_i} \right)^2}. \quad (3.13)$$

The mean absolute error (MAE) [140] is another metric for presenting the absolute deviation of the simulation results from the measurements. The MAE

is

$$MAE = \frac{1}{N} \sum_{i=1}^N |y_i - \hat{y}_i|. \quad (3.14)$$

Finally, the determination or goodness of fit of the model was evaluated using R-squared which is given as

$$R^2 = 1 - \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{\sum_{i=1}^N (y_i - \bar{y})^2}. \quad (3.15)$$

In this equation, \bar{y} is the mean value of the actual data points.

4. Results

In this chapter, results from Papers II-V are presented in brief. The BEM-based method for UBEM required a proper choice of BEM tool. Section 4.1 summarizes the results from the comparison and validation of the most common BEM simulation software to be potentially used as the main simulation core of the intended UBEM. The level of complexity of the model was also another unknown parameter. Section 4.2 provides a summary of the investigation of zoning configurations and level of detail in thermal models of buildings and their impact on simulated energy demand. The results from the previous sections made the development of a simplified and yet accurate UBEM possible. Section 4.3 is an overview of the simulation results of the developed UBEM and the procedure for its calibration and validation. After calibrating the model to increase its accuracy and validating it to prove its reliability, was applied in scenario planning and reducing the energy demand of a Swedish city. Section 4.4 presents the analysis of different large-scale energy retrofit scenarios.

4.1 Comparison of simulation tools

This section summarizes the most important results from modeling and simulation of a case study area, in the BEM simulation tools IDA ICE, TRNSYS, and EnergyPlus and reflects on their validity and reliability in large-scale UBEM studies. The full results are presented in Paper II. Furthermore, the results on the performance of the BEM software VIP-Energy are excluded here. As stated in Paper II, the functionality of this tool for large-scale studies is limited and, thus, despite its strong correlation with the measurement data, it is excluded from this summary and from subsequent analyses.

Following the methodology in Section 3.3.4, the energy model of a district with 32 district-heated multifamily buildings was implemented in IDA ICE 4.8, TRNSYS 17, and EnergyPlus 8-7-0. IDA ICE is capable of handling more than one building model at once and gives the user the opportunity to easily move from individual-level to district-level studies. This is in contrast with TRNSYS and EnergyPlus, in which every building model is treated individually. This means that, for the latter simulation tools, in order to reach the district-level energy performance of buildings, the obtained results from individual buildings need to be aggregated externally.

Table 4.1. Correlation of the simulation results with measurement data for the hourly time step.

Tool	MAE (kWh)	RMSE (kWh)	R ²
IDA ICE	72	203	0.80
TRNSYS	61	130	0.83
EnergyPlus	52	117	0.83

The final results from modeling and simulation of the buildings with two heated thermal zones and an ideal heating system¹ maintaining the room temperature constantly at 22°C are presented in the following.

Figure 4.1(a) shows the annual heat use calculated in the three tools, IDA ICE, TRNSYS and EnergyPlus, as compared to the measured data for the year 2015. Overall, the simulation results from all three tools seem to be a reasonable approximation to the measurements. It is observed that IDA ICE and TRNSYS tend to overestimate the demand by 18% and 15% respectively, whereas EnergyPlus results in 13% lower energy use. To be more precise, while the actual heat use over the whole neighborhood is 3.48 GWh/y (115 kWh/m²y), it is calculated to be 4.1 GWh/y (136 kWh/m²y) for IDA ICE, 4.03 GWh/y (133 kWh/m²y) for TRNSYS, and 3.03 GWh/y (100 kWh/m²y) for EnergyPlus.

The same conclusion is drawn from the analysis of the correlations of the hourly simulated results from TRNSYS and EnergyPlus versus measured data, as seen in Figure 4.1(b) and presented in Table 4.1. Yet, IDA ICE shows a weaker correlation with measurements, in particular when the hourly heat demand is higher than 600 kWh/h. Clearly, during heating hours, IDA ICE highly overestimates the demand, while at low heating hours, it gives a scattered profile with an overall tendency of underestimating the demand. Although on an annual basis, IDA ICE and TRNSYS result in very similar numbers, on an hourly basis it can be seen that TRNSYS has a more consistent profile with lower variability as compared to IDA ICE. However, it has a positive bias in estimating heat use.

Figure 4.2 demonstrates the heat use profile that is simulated in the three tools compared to the measurements over the course of a year. Figure 4.2(a) demonstrates the deviation of the simulation results from the measurements (ϵ), at the district heating substation level.

Following the results presented in Figure 4.1(b), here, the high diurnal and seasonal variability of the simulated results in IDA ICE is also evident. On the other hand, in TRNSYS and EnergyPlus the variability is less extreme and more consistent throughout the whole year. While the deviation of the results

¹An ideal heating system provides sufficient energy to the building to maintain the room temperature at the set temperature. With the use of the ideal heating system, no system sizing and design is needed for the model.

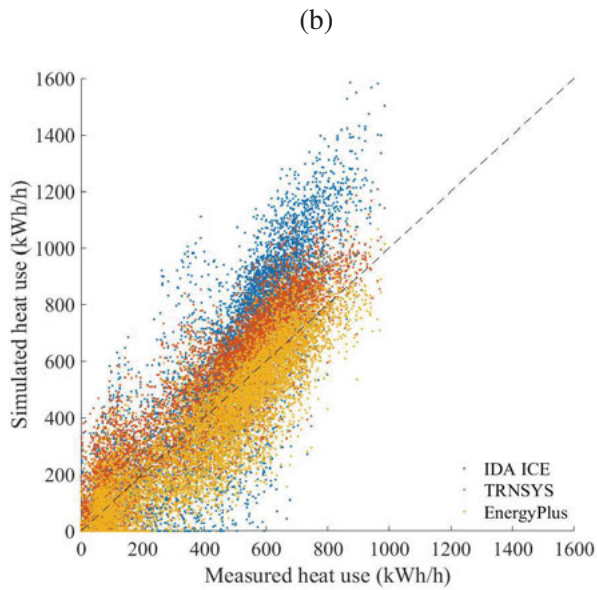
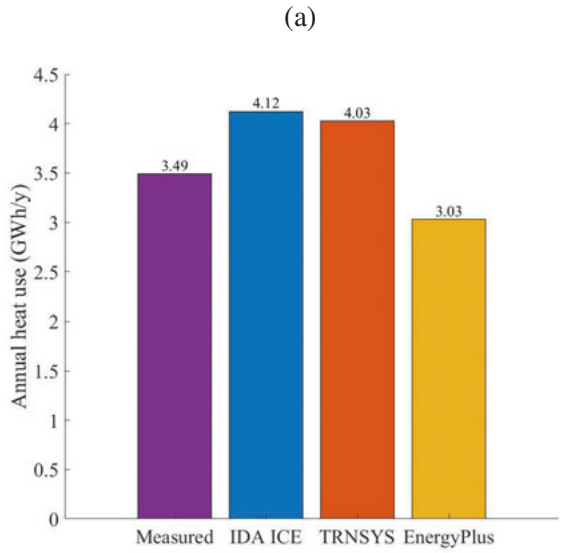


Figure 4.1. Validation of the simulation results from IDA ICE, TRNSYS and Energy-Plus against measured heat use data: (a) is the total heat used in the year 2015, and (b) shows the scatter plot that indicates the correlations between simulated and measured values for all 8760 hours of the year.

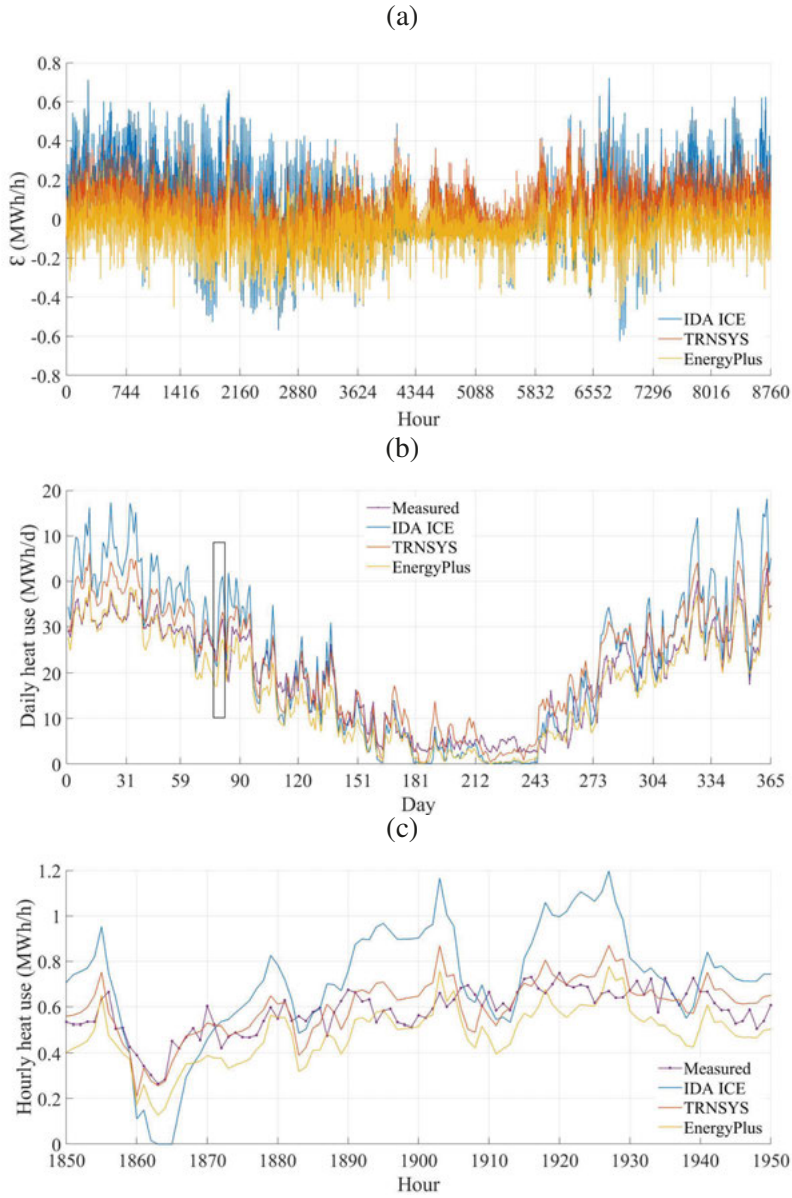


Figure 4.2. Validation of hourly heat use profile from IDA ICE, TRNSYS and EnergyPlus against hourly measurement data: (a) is the hourly deviation profile of the simulation results from measurements, and (b) is the daily heat use profiles with subplot (c) zooming in on 100 hours of the profile with higher time resolution (hourly resolution).

from measurement data (ϵ) can go beyond ± 0.5 MWh/h (± 0.016 kWh/m²h) in IDA ICE, it mainly fluctuates between ± 0.3 MWh/h (± 0.009 kWh/m²h) for TRNSYS and EnergyPlus. In Figure 4.2(b), a comparison of the daily heat demand profiles from the tools with respect to actual use per day is presented. Clearly, all three tools follow the same trend as the measurements, with EnergyPlus being closest to the actual data. Despite differences in magnitude, EnergyPlus and TRNSYS behave very similarly.

Considering the similarity between simulation tools in calculating the heat balance in the building (Section 3.3), the main reasons for the observed discrepancies between the results lie in the contribution of solar energy heat gain and thermal losses through the building envelope. As compared to TRNSYS and EnergyPlus, in IDA ICE, simplified thermal zone models result in higher sensitivity of the values to the ambient condition, particularly when there is solar radiation. The same observation is reported by Nageler et al. [141]. The second reason is related to the influence of the thermal mass of the building envelope and thermal responses to short-term variations in the ambient condition. As can be seen in the results from Paper III, reduced thermal mass of the building in IDA ICE increases the total heat use in the building and at the same time increases the variability of the hourly heat use profile in response to diurnal and hourly changes in the ambient conditions. Finally, ground coupling and limitations in the proper calculation of the heat exchange with the ground lead to higher energy use in TRNSYS and IDA ICE as compared to EnergyPlus in which the use of an auxiliary slab model improves the results.

Overall, the review of the field of UBEM includes examples of the use of all three tools in large-scale energy analysis. However, the results of this study prove that EnergyPlus is the most suitable BEM tool to be used in the UBEM that was developed and will be discussed further in the following sections.

4.2 Model complexity and zoning configuration

The second step after choosing the BEM tool was to decide on the complexity of the model. In Paper III, analysis of the different zoning configurations and model complexity was conducted using the same three BEM simulation tools IDA ICE 4.8, TRNSYS 18 and EnergyPlus 9.1. The simulations were conducted for a normal year² and with hourly time steps.

4.2.1 Zoning configuration

Figure 4.3 illustrates the results from the energy modeling of building type A, a multifamily building with two floors, with different zoning configurations in IDA ICE, TRNSYS and EnergyPlus.

²A normal year describes the average climate for a given place and time period, i.e., one year.

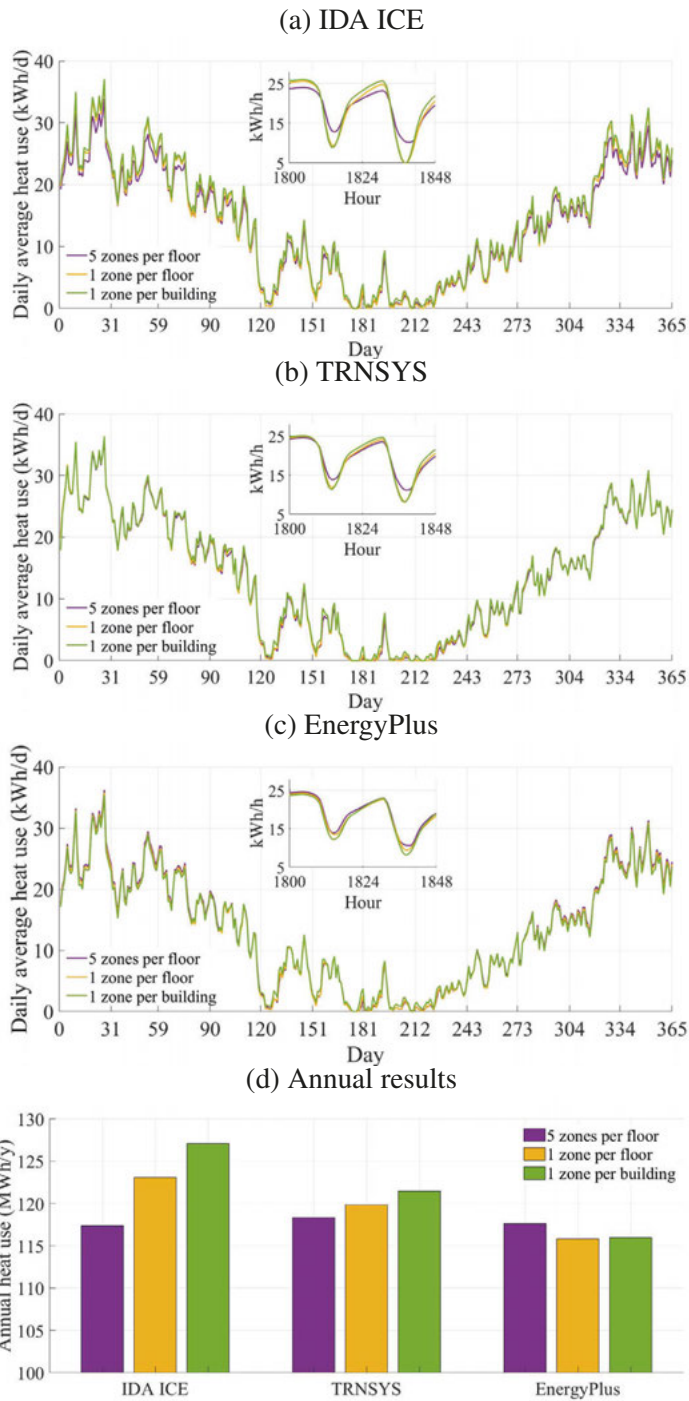


Figure 4.3. Comparison of zoning configuration of the case study building type A in different tools: subplots (a), (b), and (c) represent the results for daily average heat use over the course of a year with a zoom-in on hourly heat use for an example day in winter. Subplot (d) compares the results of annual heat use.

Considering Figure 4.3(a)-(c), it can be concluded that EnergyPlus gives no major changes in the hourly results when the zoning configuration is changed. On the contrary, IDA ICE is more influenced by the total number of thermal zones in the building. Almost the same trend can be seen in the case of TRNSYS. This means that in comparison to EnergyPlus, in IDA ICE and TRNSYS, there is a systematic tendency to overestimate the heat use when the simplest zoning configuration is applied. As seen in Figure 4.3(d), on an annual basis and with more complex zoning configuration, i.e., 5 zones per floor, all three tools tend to produce very similar results, where the deviation between the annual values from each tool is less than 1%. When reducing the number of thermal zones to 1 zone per floor and 1 zone per building, the heat use profiles start diverging from each other to the extent that in the simplest model, i.e., 1 zone per floor, IDA ICE gives 9% and 5% higher annual values as compared to EnergyPlus and TRNSYS, respectively.

For building type B, a multifamily building with three floors, the results are very similar to the ones for building type A and hence are not shown here, and the same conclusions can be drawn. EnergyPlus gives the most robust results with respect to changed zoning configuration.

Figure 4.4 shows a comparison of the simulation results for the energy model of building type C, multifamily house with 8 floors, with different zoning configurations in the three simulation tools IDA ICE, TRNSYS and EnergyPlus. Here, it can also be noticed that while thermal zoning plays a insignificant role in EnergyPlus and TRNSYS, in IDA ICE it still has a considerable impact on the results, as seen in Figures 4.4(a) and 4.4(d).

As mentioned, in high-rise buildings, zoning configuration can be different from low-rise buildings. As regards the complexity of the model and the computation time associated with a large number of thermal zones, in addition to the previous configurations, the 3 zones per building model is also evaluated for this case, which is visualized in Figure 4.4(a)-(d). It can be seen that the performance of a 3-zone per building model is quite similar to a 1 zone per building model, which suggests that even a single-zone building model could be used. A major advantage of having 3 zones per building instead of 1 zone per building is its applicability in mixed-use buildings where lower floors have a different user profile from the upper floors.

4.2.2 Level of detail

Figure 4.5 shows simulation results for a building model with three different levels of detail, i.e., LoD3, LoD2*, and LoD1, in IDA ICE, TRNSYS and EnergyPlus. The illustration of the annual heat use, Figure 4.5(d), proves that over the year, the mean absolute percentage error (MAPE) of LoD2* and LoD1 from LoD3 is 25% and 21% for IDA ICE and 25% and 20% for EnergyPlus, while for TRNSYS it is only 8% and 3% respectively.

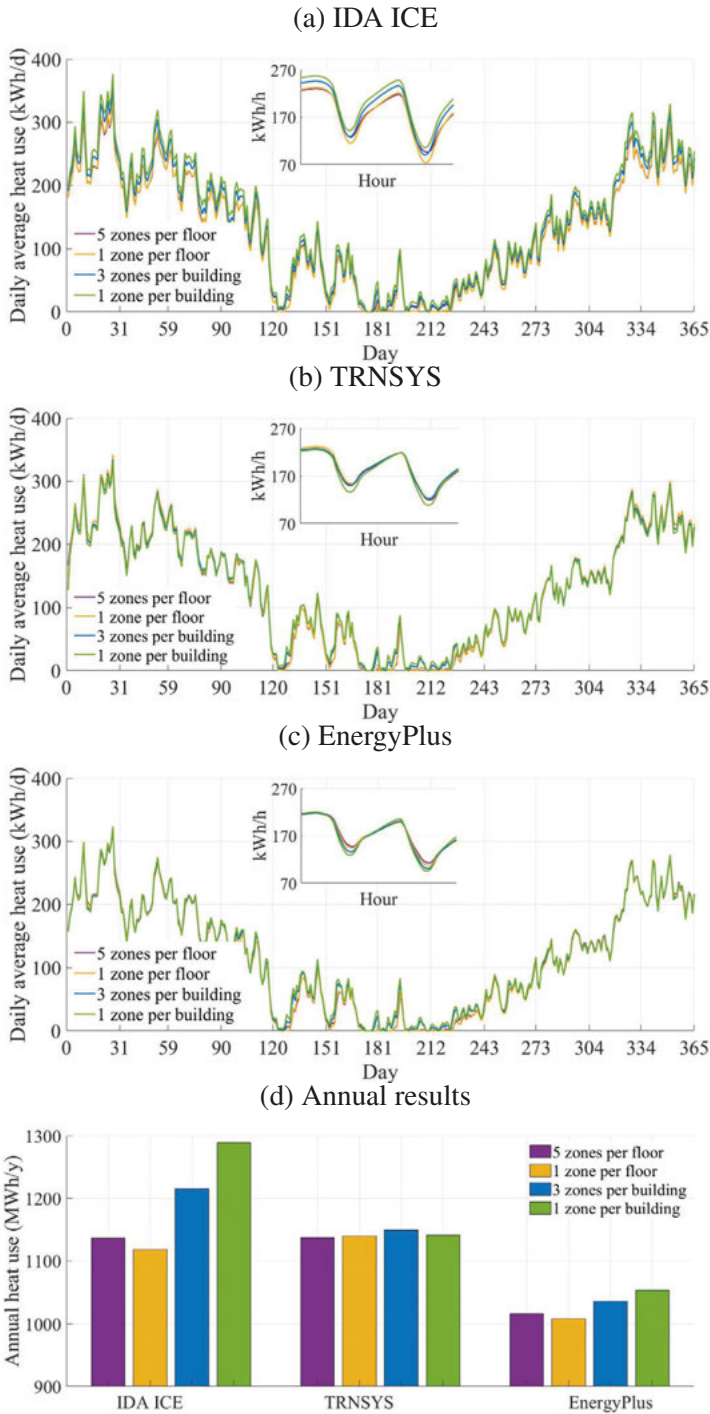


Figure 4.4. Comparison of zoning configuration of the case study building type C in different tools: subplots (a), (b), and (c) represent the results for daily average heat use over the course of a year with a zoom-in on hourly heat use for an example day in winter. Subplot (d) compares the results of annual heat use.

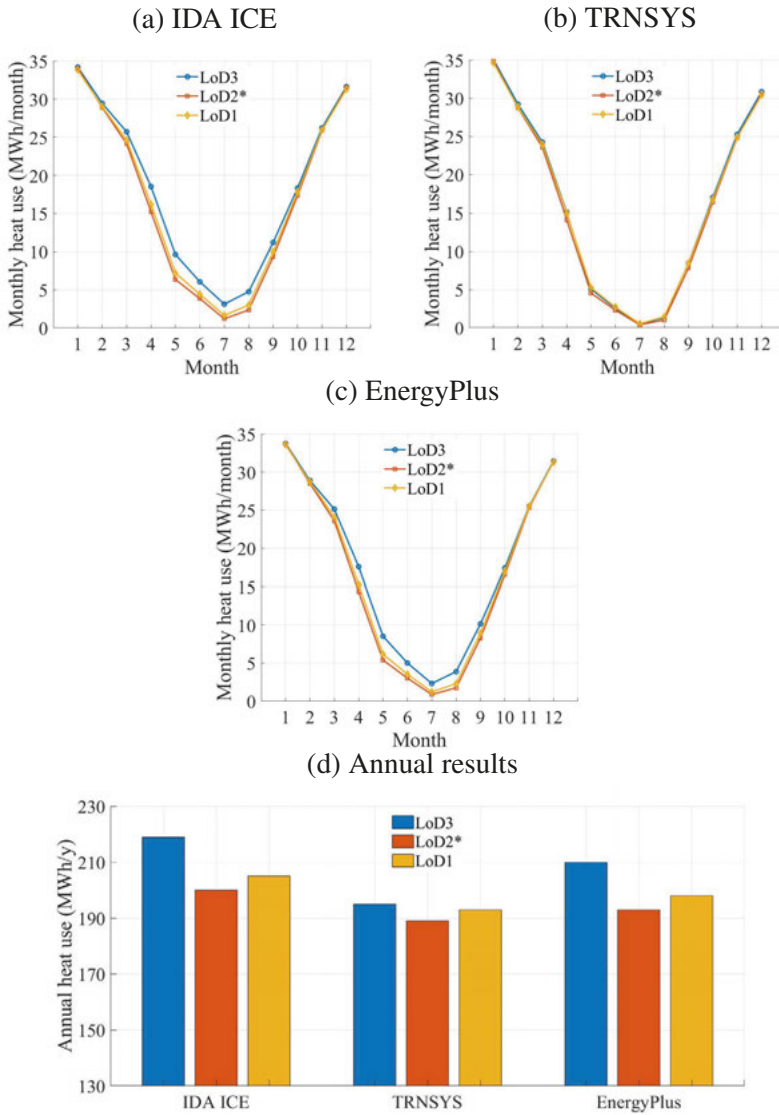


Figure 4.5. Results from comparison of the levels of detail in building energy model in different BEM tools. Subplots (a), (b) and (c) illustrate the monthly results for IDA ICE, TRNSYS and EnergyPlus. Subplot (g) shows the annual heat user for all three LoDs and simulation tools.

Figure 4.5(a)-(c) suggests that these slight deviations between the LoD2* and LoD1 with LoD3 mainly occur during the warmer periods of the year when the solar altitude is higher and the incident solar radiation through windows is considerably reduced by the shading objects. However, in the case of TRNSYS, as already mentioned in Section 3.3, the software does not consider the impact of the shading obstacles on the heat performance of the building effectively and as a result, no clear differences are seen in the result from simulation of the building with three LoDs.

Overall, based on the definition of the level of detail given in Paper III, LoD1, i.e., the shoe-box model of a building, can deviate by 25% from the detailed building models annually. However, this deviation between the results is basically seen when the heating demand is lower.

4.2.3 District level analysis

To evaluate the effect of model complexity, in particular, zoning configuration, on the performance of UBEMs, the study in Paper III was extended from the building level to the district level. With automated urban building energy modeling of the district using EnergyPlus, it was noticed that the MAPE of the simulation results from the measurement data, i.e., energy performance of buildings, was not largely affected by the choice of zoning configuration. As illustrated in Figure 4.6(a), the MAPE moves from 15.2% to 14.1% and 13.1% for 5 zones per floor, 1 zone per floor, and 1 zone per building, respectively. An evaluation of the variability of the error distribution proved a negligible difference in the standard deviation (STD) of the three cases.

Figure 4.6(b) is another illustration for the comparison of the simulations versus measurements, on both building and aggregated district levels. This figure shows that regardless of the zoning configuration, the accuracy of the results becomes higher on the aggregated level. Among the three zoning configurations, the performance of the simple single-zone model was more affected by the spatial aggregation of the results. The MAPE for this zoning method was reduced from 13.1% to 0.1%. A summary of the recorded errors on the building and district levels is found in Table 4.2

The computation time for modeling and simulation is another important factor in UBEMs. Referring to Table 4.2, the complexity of the model largely affects the computation time. While for the 1 zone per building model, it took approximately 170 s to complete the urban building energy modeling of the district with 30 buildings, it required 5 times more for the 5 zones per floor models.

In summary, the results of the district-level analysis of the model complexity specified that the single-zone model performs even better than the complex models and in a reasonably shorter time.

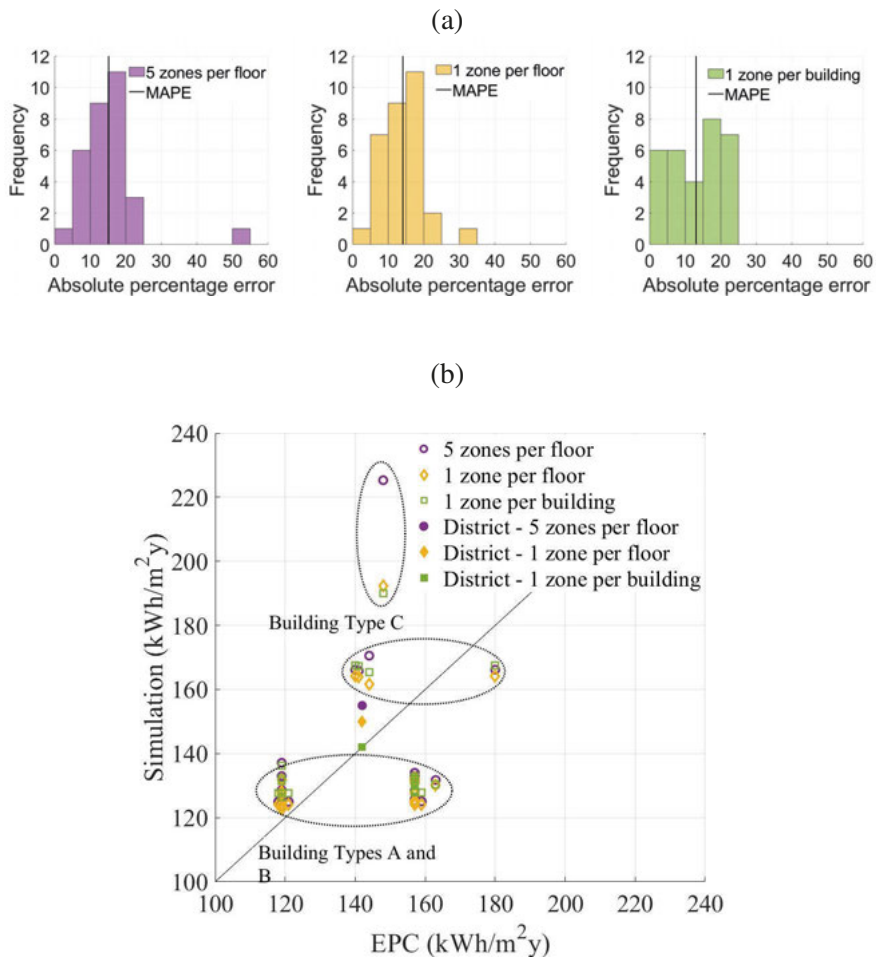


Figure 4.6. Analysis of the energy performance of buildings on the district level. In (a) the distribution of the APE of the simulated energy use vs EPC, in (b) the correlations between simulated energy use vs EPC values for the buildings as well as the district.

Table 4.2. Performance of the UBEM for various zoning configurations on building and district levels.

Zoning configuration	MAPE (%)		Time (s)	
	Building	District	Building	District
5 zones per floor	15.2	9.1	28.8	866
1 zone per floor	14.1	5.6	10.9	327
1 zone per building	13.1	0.1	5.6	170

4.2.4 Main findings on model complexity and zoning

The overarching aim of this step of the study was to not only check the level of complexity of the model but also confirm the choice of the BEM tool. The results of this study proved that the simplified shoebox single zone model, i.e., 1 zone per building model and with LoD1, reduces the computation cost of the model particularly when the number of buildings is larger. On the other hand, the deviation of this modeling strategy from more complicated models, e.g., the core/perimeter models, was inconsiderable especially when the results were analyzed on a higher aggregation level. Therefore, it is suggested to use a single-zone model if the use of the building is homogeneous. Otherwise, for mixed-use buildings, the zoning should be set according to the use.

4.3 UBEM development

Based on the method described in Section 3.5, and the findings in the previous section (Section 4.2), in Paper IV an UBEM was developed which was applied to the three case study cities of Borlänge, Uppsala and Varberg (in Paper V), Sweden. The following sections discuss the performance of the model according to Paper IV and Paper V. In Paper IV, the model was first calibrated based on EPC data and then validated for a number of buildings with available monthly measurements for district heating use on the substation level. These were done for the case study city of Borlänge. In addition, to ensure the general reliability of the model, and to check potential overfitting problems resulting from the calibration to Borlänge, it was validated for the city of Uppsala. This validation was done on the building level and based on the EPC data, i.e., annual energy delivered to the building.

In Paper V, the developed UBEM was further extended and used for the analysis of the large-scale energy retrofit of buildings. In this paper, the model was calibrated for the case study city of Varberg and validated based on building level hourly electricity use data for a large set of buildings in the city. The following sections discuss the results of the model in detail.

4.3.1 Model calibration

The calibration of the developed UBEM based on the simplification of the building polygons, modification of the building height, considering the heated area versus floor area of the buildings and finally changing the thermal properties as well as infiltration rate of the building archetypes, considerably affected the results and accuracy of the model. A comparison of the results of the UBEM before and after the calibration is presented in Table 4.3. The results present the deviation of the simulated space heating and hot water use of buildings from the EPCs in a normal year. Considering the temporal res-

olution of the EPCs, the hourly simulation results were aggregated to yearly values.

The MAPE and RMSE of the uncalibrated model were calculated to be 78% and 144% whereas for the calibrated model, they decreased to 26% and 30% respectively. A closer look at the results on the archetype level highlights the importance of the suggested calibration techniques for some of the archetypes in particular. For archetype 9, the most significant improvement was noticed where the error metrics dropped from 600% to only 10%. An analysis of the model before and after calibration proved that the preliminary estimations of the height of the buildings of this archetype class were almost fivefold compared to what is estimated from EPCs. The calibration of the model on the archetype level using EPC data and more certain numbers for the heated floors and the height of buildings solved the major issue with the performance of the model for the buildings of this archetype class. Likewise, for the rest of the archetypes and buildings, the calibration of the height as well as the heated area had the highest effect on the results.

The illustration of the distribution of the PE of the calibrated model for each archetype class is presented in Figure 4.7. The results are presented for the annual energy demand for space heating and hot water in the buildings. In general, except for a few buildings, the results for most buildings fell in an acceptable range. As seen in the figure, more than 80% of the buildings had an error of less than $\pm 40\%$ and only 18% recorded higher ($\pm 50\% < PE < \pm 100\%$). The error for approximately 2% of the results exceeded $\pm 100\%$. Due to the smaller number of these buildings and their spread over 15 archetypes, they could be hardly noticed in the figure and therefore excluded from the illustrations, but not from the calculations of the error.

The other observation from Figure 4.7 was that the distribution of the percentage error of the simulation results from EPCs was more skewed for the single-family buildings (archetypes 2 to 8). On the contrary, for multi-family buildings, except for the older ones (archetype 15), the variability became lower. The calculated STD of the distribution of the single-family buildings was 36%, while for the multi-family buildings it was estimated to be 21%. Considering the share of single-family buildings in the Swedish building stock and the wide variations in their construction and design, the later results were expected.

To assess the performance of the calibrated model on different spatial aggregation scales, similar to what has been already indicated in Paper III, a comparative analysis of the MAPE of the model for four levels of aggregation on properties, districts, zipcodes and city was conducted. Table 4.4 summarizes the results of this analysis.

The model exhibits the same trend as in Paper III when increasing the spatial aggregation of the analysis. While on the building level, it was already realized that the MAPE is 26%, on the zipcode and city levels, it was calcu-

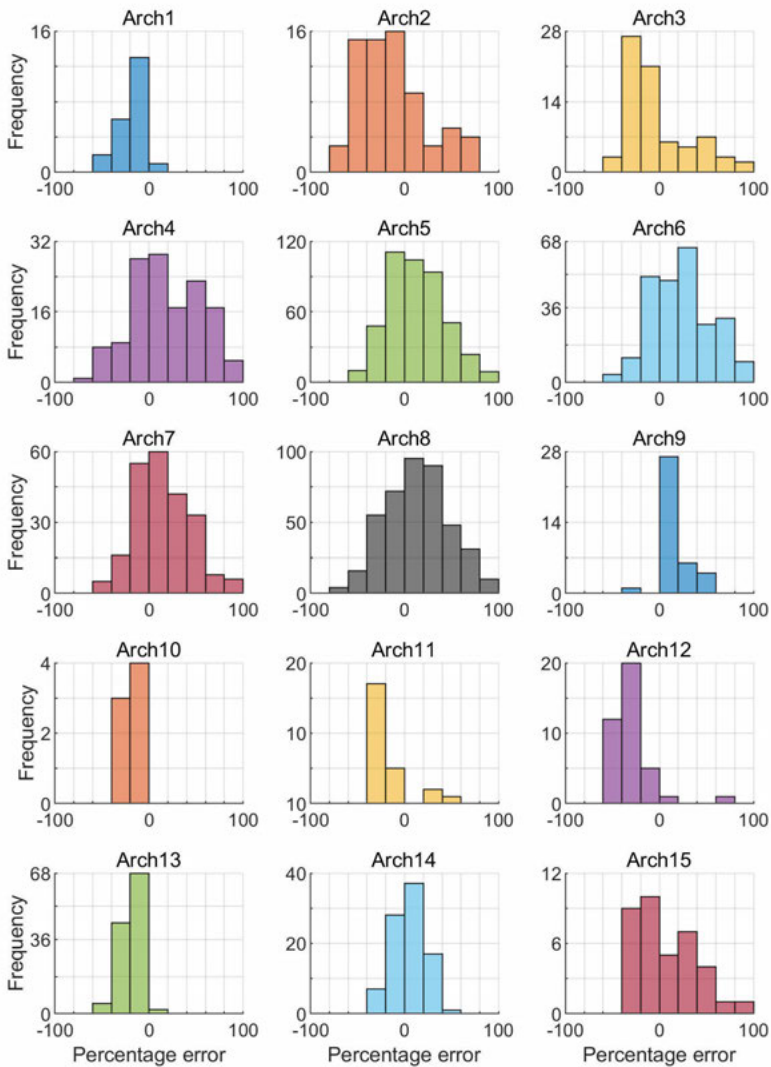


Figure 4.7. Calculated percentage error (PE) of the simulated annual energy demand for space heating and hot water of each building from the values in EPCs, presented for each archetype class. To make the distribution of the PE more visible for all the archetypes, the y-axis limits are set to the range of frequency in each archetype. The x-axis limits are also set to $\pm 100\%$ although the PE for approximately 40 buildings falls beyond this limit.

Table 4.3. Accuracy of the simulated annual energy demand for space heating and domestic hot water compared to EPCs before and after calibration for each archetype class for Borlänge.

Archetypes	Population	Uncalibrated		Calibrated	
		MAPE (%)	RMSE (%)	MAPE (%)	RMSE (%)
1	22	141	168	26	29
2	70	54	68	32	43
3	74	76	89	29	34
4	141	89	114	29	37
5	459	36	57	24	29
6	260	71	149	32	38
7	229	72	135	25	29
8	434	69	100	27	34
9	38	609	712	10	36
10	7	80	85	30	47
11	25	139	171	29	42
12	39	71	91	37	36
13	119	55	68	27	36
14	90	136	147	12	21
15	37	67	83	26	30
Overall	2044	78	144	26	30

lated to be 12% and 10%, respectively. This means that the developed model consistently performed better on the larger aggregations.

Despite reaching an accurate UBEM in Paper IV, as justified in the paper, the calibration of the thermal properties of the building archetypes is valid for the building stock in the middle part of Sweden. Therefore, in Paper V, in which the case study city was located in the southwestern part of the country, the model was re-calibrated to the case study. Similarly, the calibrated UBEM for Varberg resulted in more accurate outcomes. The MAPE for the calibrated more was calculated to be 26%. Further results from customizing and calibrating the model to the case study city of Varberg are found in Paper V.

4.3.2 Model validation

In Paper IV, the first step in the validation of the model was taken. The annual results from the model were compared to the EPC data and the reported delivered energy for a normal year. Figure 4.8 presents the building-level validation results for the case study city of Uppsala. Figure 4.8(a) illustrates the correlations between the measurements and simulations. The data points are clearly aligned in the straight ideal line and the correlation is very high. Figure

Table 4.4. Calculated mean absolute percentage error (MAPE) of the simulation results of the calibrated model compared to EPC values for different spatial aggregations in Borlänge.

Aggregation level	Counts	MAPE (%)
Property	1710	27
District	681	21
Zipcode	49	12
City	1	10

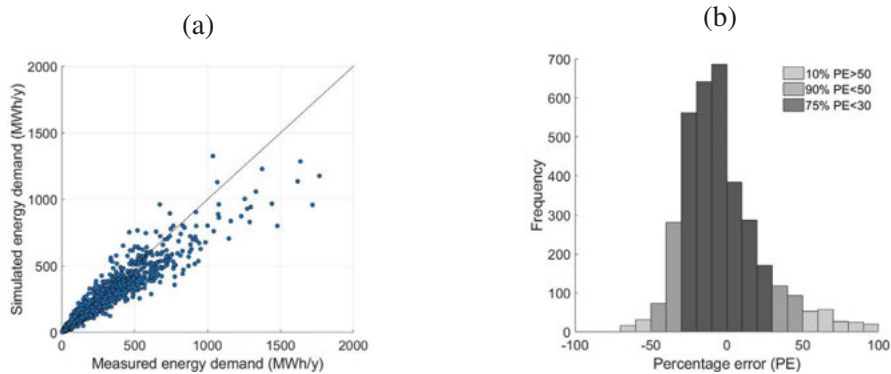


Figure 4.8. Validation of the simulated energy use for space heating and hot water with the corresponding values in the EPCs for more than 3000 buildings in Uppsala. Subfigure (a) shows the correlation between the simulation results and EPCs while subfigure (b) presents the deviation of the two using the error metric PE.

4.8(b) representing the PE of the result confirms this observation. More than 90% of the data points have a PE of less than 30% and only 10% go beyond 50%.

The validity of the UBEEM for the monthly heat demand was evaluated in Paper IV. Figure 4.9 (a) shows the correlation of the monthly simulation results for space heating and hot water demand versus the monthly district heating measurements for 12 properties consisting of 40 multi-family buildings in the case study city of Borlänge. The MAPE of the property-level monthly results was calculated to be 38%. The error ranges from 0% to a maximum of 90%. Despite the tendency for slightly underestimating the monthly demand, on the aggregated annual level, the model reached lower errors and therefore, higher accuracy. The MAPE of the aggregated annual demand for the 12 properties was 17%.

In Paper V, the validation of the developed UBEEM on the hourly resolution was conducted using hourly electricity use data in the city of Varberg. In Table 4.5, a summary of the validation results is presented based on the calculated MAPE of the simulated versus measured electricity use in the year 2021. The deviation of the model from measurements was 150% on the building level

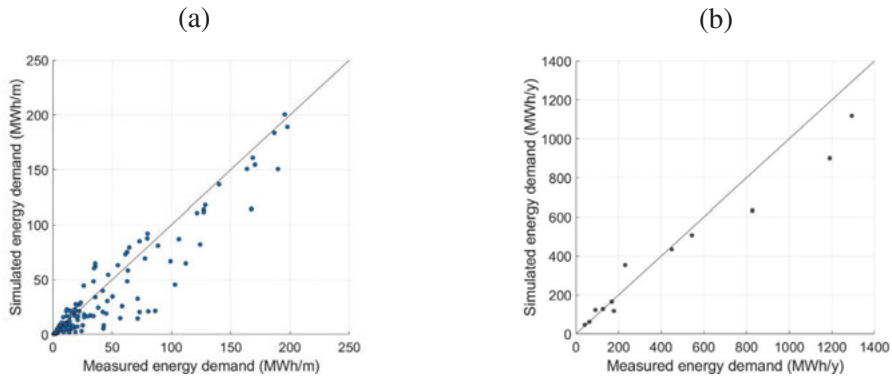


Figure 4.9. Validation of the simulated energy demand for space heating and hot water use versus measured data for 12 properties in Borlänge. Subfigure (a) presents the correlation of the monthly measured data versus the monthly simulated demand for 12 properties, and subfigure (b) presents the correlation of the annual measured versus the simulation energy demand for 12 properties.

and at the hourly time step. The highest discrepancy between the results was noticed for the buildings without an EPC. These buildings lacked enough information on the building and system properties and therefore brought more uncertainties to the model. On the other hand, for buildings with a reported EPC, the MAPE was 89%. With increasing the spatial aggregation of the results from buildings to zipcode, area and city levels, the MAPE for the hourly results was reduced to 52%, 48% and 26%, respectively. This descending trend in the MAPE with spatial aggregation agrees with what was observed in Section 4.3.1 but shows the combined impact of spatial aggregation and time averaging.

The temporal aggregation of the results to the yearly resolution introduced a similar decreasing trend for the buildings with an EPC. However, for buildings without EPC data, the error hit its maximum when aggregating the building electricity to the monthly values. Probably this is because the main deviation between the models and the real buildings is an incorrect assignment of HVAC systems. This mainly impacts the seasonal variations, due to an incorrectly modeled heating demand, which should be most visible on the monthly time scale. The main reason for this behavior can probably be explained by the incorrect assignment of heating systems. This mainly impacts the seasonal variations, due to an incorrectly modeled heating demand, which should be most visible on the monthly time scale.

The MAPE of the model on a spatio-temporal aggregated level, i.e., annual electricity for the city, was as low as 12%. This also matched findings in Paper IV, and Section 4.2.3. More observations on the validity of the UBEM on different resolutions are found in Table 4.5 and in Paper V.

Table 4.5. *MAPE in percentage for different spatial and temporal aggregation levels.*

(a) All buildings.				
	Buildings	Zip-code	Area	City
Hourly	150	52	48	26
Daily	170	39	36	17
Monthly	279	38	34	16
Yearly	106	35	35	12

(b) Buildings with EPC data.				
	Buildings	Zip-code	Area	City
Hourly	89	30	32	20
Daily	76	26	24	18
Monthly	67	26	22	18
Yearly	57	22	11	16

(c) Buildings without EPC data.				
	Buildings	Zip-code	Area	City
Hourly	166	72	52	36
Daily	195	55	39	26
Monthly	336	54	37	26
Yearly	119	56	40	28

4.4 Large-scale energy retrofit of buildings

In Paper V, after calibrating and validating the UBEM (described in Sections 4.3.2 and 4.3.1), it was applied in scenarios of large-scale energy retrofit of buildings. Figure 3.2 illustrates the effect of these renovation scenarios on the energy performance of the city of Varberg over a year. The model estimates that the energy demand for a share of the residential building stock that was modeled and simulated for a normal year was 193 GWh/y in total out of which 94 GWh/y was covered by the district heating system and 90 GWh/y was supplied by the electricity grid. There is also a low demand for wood/pellets in some of the buildings (approximately 9 GW/y), which was not illustrated in the figure. The reason for excluding this parameter from the further analysis was that the use of wood/pellet is not supplied by energy systems, e.g., the district heating and electricity grid.

When renovating the buildings with a primary energy use of more than the minimum threshold recommended in BBR29, the total energy use of the building stock is reduced to 182 GWh/y. This was roughly 6% lower than what the buildings were estimated to demand at their existing conditions. Despite the fact that more than 30% of the buildings underwent energy refurbishments, the expected outcome was not satisfactory enough.

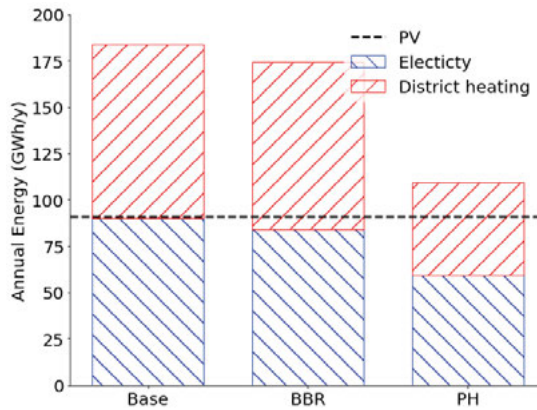


Figure 4.10. Annual energy demand, district heating and electricity, in the buildings of the case study city of Varberg at their existing condition and after renovation based on BBR and Passive House standards. Moreover, the total annual PV electricity generation is illustrated by the dashed line.

Nonetheless, renovation of the buildings according to the Passive House standard, can considerably improve the energy efficiency of the city. In this case, the overall energy demand of the city decreased to 110 GWh/y which was 43% lower than the base case. This reduction in demand was observed both for district-heated and electrically heated buildings equally. However, even after deep renovation of the buildings, not all of them could meet the requirements for receiving a Passive House certificate.

The last renovation scenario in Paper V included increasing the share of on-site renewable energy which was achieved by installing PV systems on the rooftops. In this respect, the annual generation of renewable electricity was equal to 91 GWh/y. This was approximately balanced out by the electricity use of the buildings over a year in the base case and the BBR scenario. However, a combination of the PV and Passive House scenarios could considerably reduce the energy demand of the building stock.

Figure 4.11 is a better representation of the influence of each energy retrofit scenario on the city-scale energy status of the buildings. This figure illustrates both district heating and electricity demand of the buildings with an hourly time resolution, sorted in descending order. At peak hours, when the energy demand for space heating is at its maximum, the BBR renovation scenario did not have a substantial effect on reducing the demand. On the contrary, the Passive House scenario had the highest contribution to the shaving of the peaks to one-third. However, during hours of low demand, specifically when space heating is not required, the performance of a refurbished building is roughly comparable.

Due to the low or no PV generation during the cold hours of the year, the energy status of the buildings remained unchanged when the share of renewable

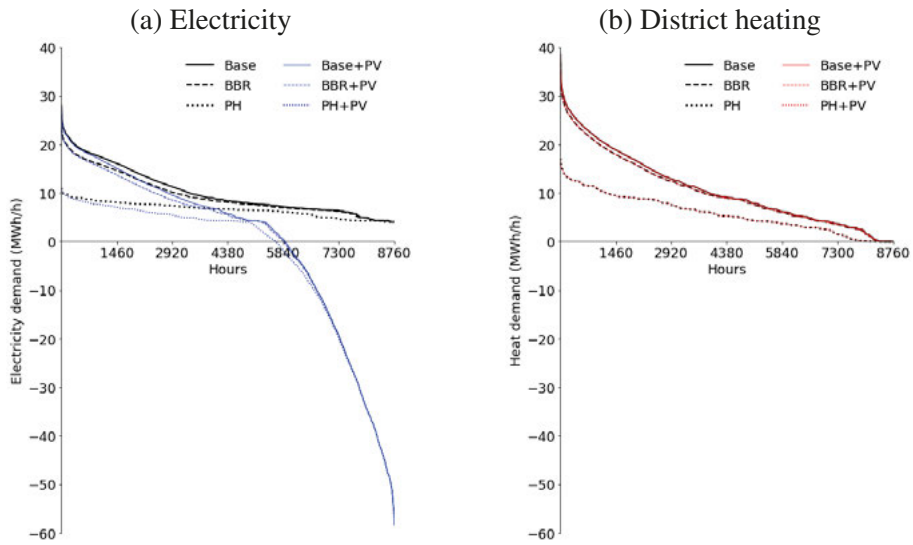


Figure 4.11. Hourly electricity (subfigure (a)) and district heating (subfigure (b)) demand, in descending order, for the city of Varberg before and after large-scale energy retrofit, based on BBR standards and based on Passive House standards, and with and without PV systems. In this figure, the negative values represent the excess PV power generation.

energy increased in the buildings. As expected the contribution of renewable electricity generation was maximal in low energy hours to the extent that in more than 2900 hours (30% of the year), the city achieved electricity autonomy. However, the demand for district heating is independent of renewable electricity generation. Therefore, as seen in the figure, the heat demand stayed the same.

In Figure 4.11, the excess PV generation leads to negative energy hours where the energy is not bought from the grid and rather sold back to the grid. At peak sun hours, the excess PV electricity could reach 60 MWh/h which is almost two times higher than the peak electricity demand. This assumption has further consequences for the electricity grid which were discussed in Paper V.

Figure 4.12 is another illustration of the energy demand of the city before and after implementing the renovation scenarios. The heat maps for electricity and district heating demand highlighted the hotspots of energy use over the city which were more accumulated in the city center where the population density is high. In certain areas of the city, i.e., suburbs, the district heating system is less likely to be present. Therefore, the electricity demand in such areas is dominant. After implementing and testing the energy renovation scenarios using the UBEM, it is noticed that the energy intensity, for both

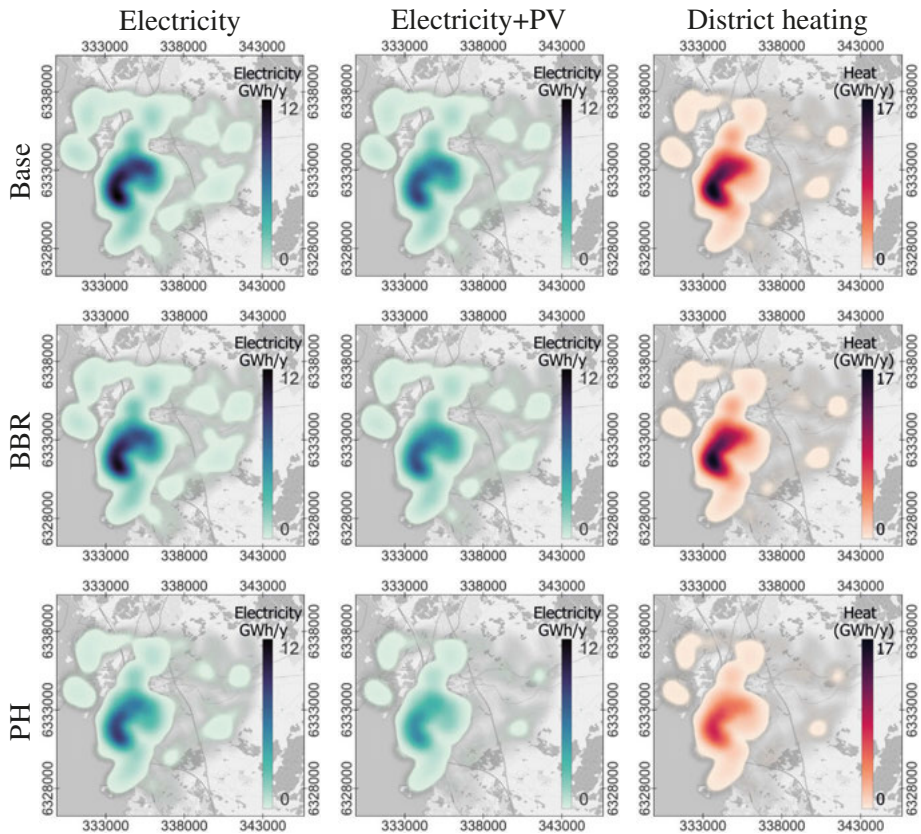


Figure 4.12. Spatial distribution of the hourly aggregated annual energy demand over the residential buildings in the city of Varberg, before and after energy retrofitting scenarios. The illustrations belong to electricity demand with and without the contribution of PV, as well as district heating for the year 2021. The x and y axes represent the coordinates of the map.

electricity and district heating use, in the city center is considerably lower for the Passive House scenarios, with or without PV systems.

Based on Section 3.7.3, if the sum of annual energy use, i.e., electricity and district heating use, in the building/district, equals the annual PV generation, the building or district is called net zero. Figure 4.13 depicts the spatial distribution of NZEDs in the city of Varberg based on this definition. As already seen in Figure 4.10, the annual energy demand over the city, i.e., the residential building sector, was reduced to a minimum of 19 GWh/y when the Passive House renovated buildings were equipped with PV systems. The heat map of the city, given in Figure 4.13, shows that the annual energy demand over some areas of the city was calculated to be very low. This figure also shows that it is possible to reach not only net zero but also positive energy in some districts of the city (highlighted in green shades). As seen in Figure 4.12, these areas

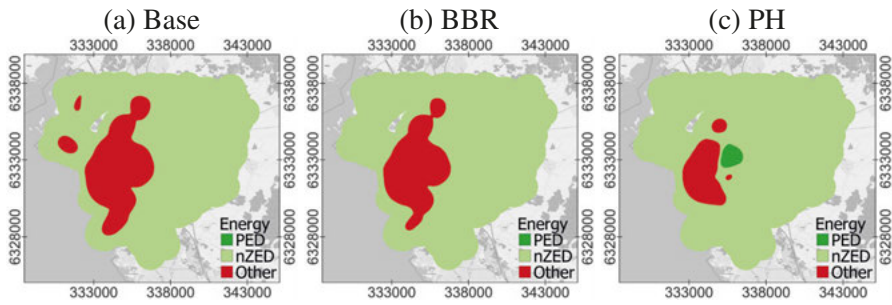


Figure 4.13. Reaching NZED in the city of Varberg with large-scale energy retrofit of buildings and increased share of PV electricity for (a) buildings at their existing condition, (b) after renovation based on BBR, and (c) after renovation based on Passive House standards. The x and y axes represent the coordinates of the map.

are still dependent on the energy grids, i.e., electricity and district heating, but the excess power from PV generation, over a course of a year, results in the positive energy.

5. Discussion and future work

This chapter further discusses some of the important findings of this thesis and appended Papers I-V. It also provides suggestions for future work and improvement in the field of UBEM.

5.1 Discussion

In this chapter, further reflection and discussion about the use of BEM tools for UBEMs, model and computational complexity, the availability and quality of data, definition and calibration of archetypes, and the accuracy of the UBEM at different levels of aggregation. Below, each of these points is discussed in turn, and a summary of best practices for UBEM is given, based on the insights from this work.

5.1.1 UBEM using BEM tools

Based on the findings from Papers II, and III, it is evident that not every BEM tool handles the complexities involved in urban building energy modeling. While most validated and commercialized BEM tools can generate accurate energy models of individual buildings, when it comes to urban building energy modeling, their capabilities become limited.

The results from Papers II and III indicated that in terms of large-scale simulations, IDA ICE offers interesting features not found in the other software. It can accept more than one building model in each simulation project, and automatically calculate the influences of surrounding buildings and shading obstacles. This means that IDA ICE captures the heat performance of a building with respect to the urban context. However, it has a limited capacity to incorporate high-resolution occupancy profiles and occupants' related use patterns, which makes it biased toward calculating one of the highly influential parameters of an UBEM. On the other hand, TRNSYS provides various opportunities in modeling district energy systems, which can be used through co-simulation with the other tools, as it has been demonstrated in Ref [47], yet, the building model type 56 and the building energy modeling tool, TRNBuilt [123], is not suggested to be used for UBEM.

Considering all the features that have been discussed in Paper II and Paper III, including the modeling approach, and calculations related to the heat

balance of a building, EnergyPlus seems the most suitable tool to be used in simplified, but rather accurate UBEMs. The short computation time in EnergyPlus is also another merit. While it only takes a few seconds to conduct a simple single-zone model simulation in EnergyPlus, it takes some minutes for IDA ICE and TRNSYS. Thus, the overall computation time for a large number of buildings increases considerably in the latter tools.

5.1.2 Model complexity vs computation cost

As presented in Paper III the deviation of single-zone building models from detailed multi-zone models can be negligible in building-level studies. This means that, on the aggregated level and for city-scale energy modeling, the simplified zoning configuration does not adversely influence the accuracy of results. This being said, it is more likely to have even more simplifications in the models and yet reach results with acceptable accuracy. In this respect, the LoD of the building model should not be an issue on the aggregated level although it is still possible to make use of correction factors and calibration methods to compensate for lower LoDs. Another important factor, here, is that the study was done for the estimation of the heating demand for a case study located in a cold climate. However, to generalize the latter conclusions, a detailed analysis of the effect of zoning and LoD at different climatic conditions and with respect to cooling demand has to be conducted.

5.1.3 Availability and quality of data

In Paper I, it was discussed that the UBEMs heavily depend on building-level data. However, in the case of the availability of data, the quality of data is also another important factor. Low-quality data lead to increased uncertainty and inaccuracy of the model. Data quality can be discussed from different perspectives including, completeness, consistency and accuracy.

Regarding the data used in Paper IV and Paper V, the Swedish GIS data could be considered as good quality data although the datasets are not free from errors. However, as compared to the extent and coverage of the data the percentage of defective records is still negligible. Nonetheless, the quality of EPC data has to be improved. The Swedish EPC data is neither complete nor consistent. The accuracy of the data is not completely ensured. As stated in Paper IV, only 30% of single-family buildings are present in the EPC dataset. Despite the importance given to EPCs, there is no mandate for having one unless the house is listed on the market. This under-representation of single-family buildings might possibly bring a bias to the data. Moreover, registered information about buildings such as heated floors and construction year, energy use and systems is found to be inconsistent and imprecise in several cases.

These problems lead to the loss of a share of data after the data pre-processing, meaning that the dataset became even smaller in size.

Therefore, due to the importance of EPC data, their quality needs to be improved. The methods of collecting the data should be consistent and precise. Moreover, a newer generation of the dataset with more parameters such as U-values and WWR could bring a better understanding of buildings and their behavior. A geo-spatially informed EPC is also a benefit to the field. In Paper IV the EPC data were converted from tabular to GIS format before being used in the model.

Finally, in Papers IV and V, the choice of low-resolution LiDAR data was made to make the method reproducible for any Swedish city. However, the accuracy of the model is improved if high-resolution LiDAR data are used instead.

5.1.4 Definition and calibration of building archetypes

In Paper I, one of the conclusions of the review of the field was to make use of a non-deterministic approach to the classification of the buildings and identification of the building archetypes. However, due to the limited coverage of the EPC data and fewer attributes in the GIS data, In Papers IV and V, it was decided to use a deterministic building classification method. Although the deterministic methods do not fully represent the diversity and heterogeneity of the building stock, they can still provide insight into the building stock where detailed data is lacking.

In the deterministic classification of the buildings based on construction year and type of buildings, a further calibration step could capture part of the variations in the building attributes and improve the accuracy of the model to some extent. The calibration of the model based on the EPC data is a necessary step in improving the reliability and applicability of the model. In Paper IV and Paper V, in an iterative procedure, the thermal properties and infiltration rate of the archetypes were adjusted to reach the least deviation between the simulated and EPC values. However, a more advanced approach to archetype calibration of the influential attributes of the archetypes would ensure that the model is better aligned with the unique attributes of the buildings.

5.1.5 Level of aggregation and validity of the results

In Papers III-V, the validation of the model was done for different spatio-temporal aggregation levels all pointing to higher accuracy of the model on higher aggregations. This means that the model is most reliable when the results are aggregated over the city and over a year. Referring to the validation results, it is still possible to expect an acceptable accuracy at several of the lower aggregations. When more detailed information about buildings is

relatively sufficient, i.e., in the case of the availability of EPCs, a justifiable accuracy can be achieved already on the zip-code level. However, for analysis of the whole building stock, the spatial aggregation from buildings to the city seems necessary.

Paper V also showed that for buildings with EPCs, on the lower spatial resolutions, e.g., city, the effect of temporal aggregation becomes marginal, meaning that the UBEM can be used for the analysis of hourly energy use over the city with no hesitation. This is especially interesting as it proves that despite calibrating the model on the annual level, not only the annual results but also the monthly and hourly results are also accurate and reliable.

5.2 Future work

The field of urban building energy modeling is still under development and this opens up significant opportunities for contributions to the advancement of UBEMs. Here follow a few possible directions for future work.

- Abstracting the building stock into a few building archetypes seems to be an optimal solution for reducing the complexity and extent of UBEMs. Except for a small number of studies, the majority have relied on the deterministic classification of buildings based on variables such as type and year of construction, and so did this thesis. However, deterministic methods cannot capture the diversity of buildings properly and thus the outlook of this work is to make use of statistical and machine-learning techniques to classify the building stock and find the most representative building archetypes. In the case of the use of EPC data, certain considerations regarding the lack of random sampling and uneven distribution of single-family vs multi-family buildings need to be taken into account.
- The choice of renovation scenarios in Paper V was based on the latest codes and standards for the design and construction of low-energy buildings. These general renovation scenarios are expensive to implement in the real world. On the other hand, their effectiveness in improving the energy efficiency of buildings is associated with different factors such as the existing condition and use of the building. Therefore, to ensure the effectiveness and to reduce the costs of the renovation projects, it is recommended to define building-specific renovation scenarios. For this purpose, in a future study, it is aimed to combine the model with smart optimization algorithms that can suggest the best energy retrofit packages for reducing the energy demand of the buildings at minimum cost.
- In addition to energy, life cycle carbon emission and life cycle cost of cities are other important factors towards sustainability which have not

been considered properly in the field of UBEM. The life cycle analysis allows for an analysis of the CO₂ emission and energy use throughout the lifetime of buildings. Combining the life cycle approach with the developed UBEM would advance the decision-making process of energy retrofit of buildings.

- UBEMs are powerful tools for studying and improving the energy performance of existing buildings. Nonetheless, they lack components for planning and analysis of new city districts. Therefore, another outlook of this thesis is to develop an automated framework for planning and design of low-energy city districts. This framework makes use of optimization modeling combined with the UBEM as a promising method for minimum energy benchmarking for new city districts.

6. Conclusion

With a focus on residential buildings, in this thesis and appended papers, the main goal was to develop an urban building energy model that can accurately represent the building stock in cities and simulate its energy demand currently as well as in future scenarios. In Section 1.1, the overarching goals of this thesis were broken down into five aims. The contribution of this thesis to the state-of-the-art of field of urban building energy modeling and the most important findings of the appended papers with respect to the defined aims are summarized as follows.

6.1 Aim i

The first aim of this thesis was to undertake an extensive survey of the existing scientific literature on UBEMs in order to identify the state-of-the-art and best practices in the field. After conducting the review of the field in Paper I, these conclusions were made:

- To take full advantage of possibilities and to facilitate the shortcomings of both data-driven and physical models, UBEMs should move towards hybrid modeling. Hybrid UBEMs include the capabilities of both data-driven and physical models.
- There is a great deal of uncertainty about the building stock, which makes it hard to accurately identify building archetypes. From the review of the previous works, it is suggested to focus, if possible, on statistical methods such as machine-learning techniques for classification, characterization, and calibration of the building archetypes. In the case of the availability of building-level data, the implementation of the statistical archetype development methods would reduce the uncertainty of UBEMs considerably.
- UBEMs are computationally complex and expensive, which emphasizes the need for parallel computing and cloud computing to accelerate the energy simulation procedure. Improved computing power offers the possibility of faster simulation, even for more complex models. Most UBEM studies do not present an estimation of the required computational time for their models which makes them hard to compare.

- In addition, most UBEM studies also lack validation of their models against measured data. As regards the level of uncertainty associated with modeling and simplification techniques, the reliability of the UBEMs is strongly connected with the validation of results. Since not all the previous models were validated, their validity is difficult to judge.
- As regards the buildings' interaction with other components of the urban environment, the possible integration of urban climate models (mesoscale and microclimate), urban mobility models (urban human mobility and transport) and urban energy systems with UBEMs is worth pursuing.

6.2 Aim ii

The second aim of the thesis for evaluating the applicability and accuracy of existing BEM software to be potentially used as a simulation core in the UBEM, leading to the completion of Paper II and Paper III. The following conclusions were made from this aim.

- On aggregated levels (district- or city-level), the models constructed using EnergyPlus give the least deviations from measured data. According to the simulation results of an UBEM for a case study district, the RMSE from hourly measurements was calculated to be 117 kWh for EnergyPlus, while it reached 130 kWh and 203 kWh for TRNSYS and IDA ICE, respectively.
- In terms of applicability, capability and computation time, EnergyPlus has more advantages over the others when used in UBEMs. It delivered a better performance in handling the thermal capacity of buildings, shading obstacles, responses to fluctuations in the weather data, occupancy and load, computation complexity, and computation time.

6.3 Aim iii

The third aim of this thesis was to determine a suitable level of complexity for the thermal building models in the UBEM. This aim was achieved in Paper III, in which it is concluded that:

- The deviation of single-zone building models, i.e., one thermal zone per building, from detailed multi-zone models, i.e., one thermal zone per floor of the building, and core and perimeter zones for each floor (based on ASHRAE 90.1 Appendix G), is negligible. It is also proven that on the aggregated level and for UBEM, the simplified single zone models

do not adversely influence the accuracy of the result but also considerably improve the computation time. With this being said, it is more likely to have even more simplifications in the models and yet reach the results with acceptable accuracy. However, in multi-use buildings, it is still suggested to assign more than one thermal zone to the building model.

- In colder climates, like Sweden, where the heating demand is predominant, the shoebox models, equivalent to LoD1, perform as equally well as models with higher levels of detail, e.g., LoD3. However, in warmer climates where the abstraction of solar radiation by architectural elements such as balconies or overhangs, influences the heating and cooling demand of buildings, the effect of LoD is suggested to be carefully evaluated. Moreover, for scenario planning and use of solar PV systems, the knowledge of characteristics of the roof and therefore higher LoDs is necessary.

6.4 Aim iv

Based on the results for the goals i-iii, the fourth aim of this thesis was to propose a method for the development, calibration, and validation of an UBEM using available and completely open datasets. A summary of the main conclusions from Paper IV and partly Paper Romannum5 where the UBEM was developed, calibrated and validated is presented as follows.

- The two national datasets for building property maps and energy performance certificates facilitate the process of development, calibration and validation of the UBEM of Swedish cities.
- The calibration of the UBEM based on the EPC data improves the accuracy of the model considerably. Among the chosen parameters, the difference between the heated and overall floor area of buildings as well as the estimation of the height of the buildings play the most important role.
- A comparison of the results of the calibrated model with the energy performance of buildings reported in the EPC dataset of the case study city of Borlänge shows that the mean absolute percentage error (MAPE) is 26% on the building level. However, with increasing the spatial aggregation of the results from buildings to the city, the MAPE becomes as low as 10%. This shows that the developed UBEM has a high accuracy in estimating the urban-scale energy demand.

- The validation of the calibrated model against an independent source of data consisting of monthly measurements of energy use in a set of multi-family buildings in Borlänge shows that the MAPE is 29%. However, depending on the season and type of building, the error varies from 0% to 90%.
- The validation of the calibrated UBEM against independent EPCs for the second case study city, Uppsala, shows that the model is not over-fitted to the first case study city and can still perform well for the other cities in Sweden. The MAPE between the annual simulation results and the energy performance of buildings in the EPCs is calculated to be 22%.
- The validation of the calibrated UBEM for the third case study city of Varberg proves that the calibrated model based on EPCs and annual energy measurements can still lead to accurate results on the lower temporal resolutions, especially when the spatial aggregation is high.

6.5 Aim v

The final aim of this thesis was to present the applicability of UBEMs in scenario planning for large-scale energy efficiency improvements. This was conducted in Paper V where concluded that:

- The large-scale energy retrofit of buildings based on the Passive House standards considerably improved the energy efficiency of the city. Regardless of the type of heating system and source of energy, i.e., district heating or electricity, the estimated energy saving could reach 43% annually in the residential building stock of the case study city of Varberg.
- Renovating buildings based on the latest building codes in Sweden, known as BBR, did not affect the energy status of the city substantially (only 6% annually). Analysis of the results proved that the criterion mandating the use of a heat recovery ventilation system brought a major benefit to the Passive House renovation scenario. However, no recommendation on the type of HVAC system is enforced in the BBR.
- Increasing the share of renewable energy in buildings using rooftop PV systems could also improve the energy performance of the city. With the maximum use of the available area, i.e., the areas of the roof with reasonably high solar potential, and having the possibility to feed in the surplus energy to the electricity grid, almost 50% of the total energy demand for electricity and district heating is covered by renewable energy. Over the course of a year, a combination of the Passive House scenario

with the PV system scenario noticeably reduced the energy status of the city to the extent that some areas of the city became net zero and positive energy.

7. Sammanfattning på svenska

Städers växthusgasutsläpp utgör en av de främsta orsakerna till klimatförändringar. Över 75 % av världens utsläpp av växthusgaser härstammar från urbana aktiviteter och deras tillhörande energianvändning. Inom urbana energisystem är byggnadssektorn den största källan till energianvändning och därmed utsläpp av växthusgaser. Uppskattningsvis står byggnader för 40 % av energianvändningen både inom EU och i Sverige. Följaktligen krävs en övergång till ökad energieffektivitet och koldioxidneutralitet, särskilt i städer och inom byggnadssektorn, för att mildra klimatförändringarnas påverkan. För att planera denna omställning är det nödvändigt att först förstå drivkrafterna och mönstren bakom energianvändningen i byggnader och därefter föreslå optimala strategier för ökad energieffektivitet.

De senaste försöken att uppskatta byggnaders energiprestanda har resulterat i utvecklingen av en serie analytiska verktyg för energimodellering på stadsnivå, så kallade "urban building energy models" (UBEMs). En UBEM är en ingenjörsmässig bottom-up-modell som beskriver energianvändningen för stora bestånd av byggnader inom ett specifikt geografiskt område, exempelvis en stadsdel eller en hel stad. I korthet hjälper UBEMs till vid utformning och analys av både nya och befintliga urbana områden och system. De kan användas för att identifiera potentialen för energibesparing, integrera storskaliga energiförbättringar och öka energieffektiviteten i städer. Dessa modeller spelar även en avgörande roll i utvärderingen av energinätets stabilitet och pålitlighet. Dessa fördelaktiga egenskaper hos UBEMs gör dem till värdefulla verktyg för att planera scenarier för minskad energianvändning och koldioxidutsläpp.

Generellt sett är processen för att utveckla en UBEM uppdelad i fem huvudsakliga steg: datainsamling, modellutveckling, simulering, validering och tillämpning. För att utveckla en UBEM krävs tillgång till både geometriska och icke-geometriska egenskaper hos enskilda byggnader inom det geografiska område man vill studera. En förenklad beskrivning av byggnaders geometri, såsom dess geografiska "fotavtryck" och höjder, kan fås via så kallade 3D-stadsmodeller, tredimensionella digitala modeller av byggnaderna i ett område. När det gäller icke-geometriska egenskaper, inklusive byggnaders komponenter, system och driftscheman, krävs individuella eller övergripande byggnadsegenskaper. Även om det inte finns en standardiserad metod för att definiera dessa data, drar de flesta existerande UBEMs nytta av konventionella metoder som innebär att man identifierar representativa typbyggnader, så kallade "arketyper", och överför deras egenskaper till liknande byggnader.

När data samlats in importerades det till en UBEM-simuleringsmotor, där byggnadsmodellerna implementeras och energibehovet beräknas. För att förbättra noggrannheten och tillförlitligheten måste UBEMs även kalibreras och valideras mot faktiska energianvändningsdata. En validerad UBEM kan sedan användas för att utvärdera scenarier och planera förbättringar av energieffektiviteten i städer.

Den här avhandlingen föreslår en metod för att utveckla en UBEM med hjälp av öppet tillgänglig data för det svenska bostadsbeståndet. Denna data inkluderar GIS-baserade fastighetskartor från Lantmäteriet och energideklARATIONER från Boverket. Genom att extrahera byggnadernas fotavtryck från GIS-datat och bestämma deras höjd med hjälp av LiDAR-data (Light Detection and Ranging) i form av punktmoln (båda finns i fastighetskartorna) skapades en noggrann 3D-stadsmodell. Klassificeringen av byggnadsbeståndet i ett fåtal arketyper baserades på byggnadstyp (flerbostadshus eller småhus) och byggnadsår, vilket resulterade i totalt 15 arketyper. Karakteriseringen av dessa arketyper, inklusive byggkomponenter och material, genomfördes baserat på tillgänglig litteratur. I de fall där detaljerad information om byggnaders värmesystem saknades gjordes uppskattningar baserade på arketyppbyggnaderna. Genom en automatiserad process översattes denna information till förenklade byggnadsmodeller med en termisk zon och energibehovet simulerades över olika rumsliga och tidsmässiga nivåer. Modellgränssnittet utvecklades i Python, och byggnadsimuleringsprogrammet EnergyPlus användes för att utföra simuleringarna. Valet av programvara gjordes baserat på EnergyPlus fördelar vad gäller användbarhet, kapacitet och beräkningstid.

Modellen kalibrerades med hjälp av energideklarationerna. Detta ledde till en betydande förbättring av modellens noggrannhet, där det genomsnittliga felet för den simulerade energianvändningen jämfört med faktisk rapporterad energianvändning var cirka 26 %, beräknat på byggnadsnivå. Med ökad rumslig aggregering av resultaten, från enskilda byggnader till stadsnivå, minskade felet till så lite som 10 %. Den utvecklade modellen validerades också med hjälp av oberoende mätdata och över olika rumsliga och tidsmässiga nivåer. Detta säkerställer modellens användbarhet i olika scenarier bortom de som den kalibrerades för. Valideringen av modellen visade att noggrannheten för resultaten vid hög rumslig aggregering, som på stadsnivå, stannade under 30 %.

Efter att ha bekräftat validiteten hos den kalibrerade UBEM-modellen användes den för att förbättra energieffektiviteten i en svensk stad genom tre scenarier för renovering baserade på svenska byggregler (BBR), passivhusstandarder respektive nollenergibyggnader. Medan omfattande renoveringar av byggnader enligt BBR-krav inte hade en betydande påverkan på energiprestandan för bostadsbeståndet, visade sig passivhusscenariot leda till en markant minskning av effektbehovet för både fjärrvärme och el under kalla dagar. Genom att öka andelen solelproduktion på byggnaderna kunde de flesta områden i staden uppnå nära-noll- eller positiv energibalans.

Acknowledgement

I would like to express my appreciation to all those who have supported and contributed to the completion of this thesis. My Ph.D. journey would not have been completed without the unwavering support and assistance I received throughout these years.

First, I would like to acknowledge those who provided financial support to my research. My Ph.D. was performed within the research project "Activity-Based Urban Building and Mobility Energy Modeling (UBMEM) for Planning of Future Cities", as part of the strategic innovation program Viable Cities. This project was financed by the Swedish Energy Agency, VINNOVA and Formas. My research also forms part of the Swedish strategic research program StandUp for Energy.

Second, I would like to thank my supervisors for their endless support, insightful feedback and constant encouragement. My main supervisor, Joakim Widén, professor and head of the Division, who accepted me to the program, mentored me through research (and academia), involved me in discussions, gave me the freedom to explore independently, and trusted my abilities in research as well as teaching. My co-supervisor Joakim Munkhammar, associate professor, who guided me through my Ph.D., enriched my research with his insightful suggestions and taught me and encouraged me to write funding applications. My second co-supervisor, Farshid Shadram, assistant professor, who joined the supervision team halfway through my Ph.D. but had invaluable contributions to my research, and helped me to better understand the field.

Over these years, I had the chance to get to know many people who definitely had an influence on my career as a researcher. Among them are Annica Nilsson, Magnus Åberg, David Lingfors, Umar Hanif Ramadhani, Oskar Lindberg, Lukas Dahlström, Chris Bales, Mengjie Han, Emmanouil Psimopoulos and Giuseppe Peronato, with whom I had the pleasure to work and collaborate. I would also like to acknowledge my colleagues at the Division of Civil Engineering and Built Environment, Azeddine, Beatriz, Dennis, Elahéh, Ewa, Fredrik, Galyna, Gustav, Holger, Ivon, Mahmoud, Mohamad, Petra, Rasmus, Reza, and Svante, or all the inspiring discussions, and fun after works.

I am by all my heart thankful to my parents for loving me and raising me to be an independent liberal woman, and to my siblings for spicing up my life.

And finally, this thesis is dedicated to my dearest husband for all his love, motivation and support. Throughout this journey, there was not a single moment that I spent without his encouragement. Thank you *nafas janam* for everything!

References

- [1] H. Ritchie and M. Roser, "Urbanization," *Our World in Data*, 2018. [Online]. Available: <https://ourworldindata.org/urbanization>
- [2] "How will climate change affect cities, and how can they take action?" Accessed: 2023-03-20. [Online]. Available: <https://urban.jrc.ec.europa.eu/thefutureofcities/climate-action#the-chapter>
- [3] W. F. Lamb, M. W. Callaghan, F. Creutzig, R. Khosla, and J. C. Minx, "The literature landscape on 1.5°C climate change and cities," *Current Opinion in Environmental Sustainability*, vol. 30, pp. 26–34, 2018. [Online]. Available: <https://doi.org/10.1016/j.cosust.2018.02.008>
- [4] D. Reckien, M. Salvia, O. Heidrich, J. M. Church, F. Pietrapertosa, S. De Gregorio-Hurtado, V. D'Alonzo, A. Foley, S. G. Simoes, E. Krkoška Lorencová, H. Orru, K. Orru, A. Wejs, J. Flacke, M. Olazabal, D. Geneletti, E. Feliu, S. Vasilie, C. Nador, A. Krook-Riekkola, M. Matosović, P. A. Fokaides, B. I. Ioannou, A. Flamos, N.-A. Spyridaki, M. V. Balzan, O. Fülöp, I. Paspaldzhiev, S. Grafakos, and R. Dawson, "How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28," *Journal of Cleaner Production*, vol. 191, pp. 207–219, 2018. [Online]. Available: <https://doi.org/10.1016/j.jclepro.2018.03.220>
- [5] R. Freeman and M. Yearworth, "Climate change and cities: problem structuring methods and critical perspectives on low-carbon districts," *Energy Research & Social Science*, vol. 25, pp. 48–64, 2017. [Online]. Available: <https://doi.org/10.1016/j.erss.2016.11.009>
- [6] J. R. Carreón and E. Worrell, "Urban energy systems within the transition to sustainable development. a research agenda for urban metabolism," *Resources, Conservation and Recycling*, vol. 132, pp. 258 – 266, 2018. [Online]. Available: <https://doi.org/10.1016/j.resconrec.2017.08.004>
- [7] U. Eicker, *Urban Energy Systems for Low-Carbon Cities*. Academic Press, 2019. [Online]. Available: <https://doi.org/10.1016/B978-0-12-811553-4.09993-5>
- [8] R. Madlener and Y. Sunak, "Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management?" *Sustainable Cities and Society*, vol. 1, no. 1, pp. 45–53, 2011. [Online]. Available: <https://doi.org/10.1016/j.scs.2010.08.006>
- [9] S. Cajot, M. Peter, J. M. Bahu, A. Koch, and F. MarÃ©chal, "Energy Planning in the Urban Context: Challenges and Perspectives," *Energy Procedia*, vol. 78, pp. 3366–3371, 2015, 6th International Building Physics Conference, IBPC 2015. [Online]. Available: <https://doi.org/10.1016/j.egypro.2015.11.752>
- [10] J. Keirstead, M. Jennings, and A. Sivakumar, "A review of urban energy system models: Approaches, challenges and opportunities," *Renewable and*

- Sustainable Energy Reviews*, vol. 16, no. 6, pp. 3847 – 3866, 2012. [Online]. Available: <https://doi.org/10.1016/j.rser.2012.02.047>
- [11] R. V. Walker, D. Poponi, and B. Lefevre, “Advancing Toward a More Sustainable Urban Energy System,” WRI Ross Center for Sustainable Cities.
- [12] S. Torabi Moghadam, J. Toniolo, G. Mutani, and P. Lombardi, “A GIS-statistical approach for assessing built environment energy use at urban scale,” *Sustainable Cities and Society*, vol. 37, pp. 70 – 84, 2018. [Online]. Available: <https://doi.org/10.1016/j.scs.2017.10.002>
- [13] C. F. Reinhart and C. Cerezo Davila, “Urban building energy modeling - A review of a nascent field,” *Building and Environment*, vol. 97, pp. 196–202, 2016. [Online]. Available: <https://doi.org/10.1016/j.buildenv.2015.12.001>
- [14] T. Hong, Y. Chen, X. Luo, N. Luo, and S. H. Lee, “Ten questions on urban building energy modeling,” *Building and Environment*, vol. 168, p. 106508, 2020. [Online]. Available: <https://doi.org/10.1016/j.buildenv.2019.106508>
- [15] Y. Q. Ang, Z. M. Berzolla, and C. F. Reinhart, “From concept to application: A review of use cases in urban building energy modeling,” *Applied Energy*, vol. 279, p. 115738, 2020. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2020.115738>
- [16] A. Oraipoulos and B. Howard, “On the accuracy of Urban Building Energy Modelling,” *Renewable and Sustainable Energy Reviews*, vol. 158, p. 111976, 2022. [Online]. Available: <https://doi.org/10.1016/j.rser.2021.111976>
- [17] V. C. Broto, “Energy landscapes and urban trajectories towards sustainability,” *Energy Policy*, vol. 108, pp. 755 – 764, 2017. [Online]. Available: <https://doi.org/10.1016/j.enpol.2017.01.009>
- [18] A. Grubler and D. Fisk, *Energizing Sustainable Cities : Assessing Urban Energy*. Taylor & Francis, 2012.
- [19] A. Grubler, X. Bai, T. Buettner, S. Dhakal, D. J. Fisk, T. Ichinose, J. E. Keirstead, G. Sammer, D. Satterthwaite, N. B. Schulz, N. Shah, J. Steinberger, H. Weisz, G. Ahamer, T. Baynes, D. Curtis, M. Doherty, N. Eyre, J. Fujino, K. Hanaki, M. Kainuma, S. Kaneko, M. Lenzen, J. Meyers, H. Nakanishi, V. Novikova, K. S. Rajan, S. Seo, R. M. Shrestha, P. R. Shukla, A. Sverdlík, and J. Sathaye, “Urban Energy Systems,” in *Global Energy Assessment (GEA)*, T. B. Johansson, N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri, Eds. Cambridge: Cambridge University Press, 2012, pp. 1307–1400. [Online]. Available: <https://doi.org/10.1017/CBO9780511793677.024>
- [20] J. Keirstead and A. Sivakumar, “Using Activity-Based Modeling to Simulate Urban Resource Demands at High Spatial and Temporal Resolutions,” *Journal of Industrial Ecology*, vol. 16, no. 6, pp. 889–900, 2012. [Online]. Available: <https://doi.org/10.1111/j.1530-9290.2012.00486.x>
- [21] J. Keirstead and N. Shah, *Urban Energy Systems: An Integrated Approach*. Taylor & Francis, 2013.
- [22] C. Brandoni and F. Polonara, “The role of municipal energy planning in the regional energy-planning process,” *Energy*, vol. 48, no. 1, pp. 323–338, 2012. [Online]. Available: <https://doi.org/10.1016/j.energy.2012.06.061>
- [23] K. Asarpota and V. Nadin, “Energy Strategies, the Urban Dimension, and Spatial Planning,” *Energies*, vol. 13, no. 14, p. 3642, 2020. [Online]. Available: <https://doi.org/10.3390/en13143642>

- [24] M. Shepero and J. Munkhammar, "Spatial Markov chain model for electric vehicle charging in cities using geographical information system (GIS) data," *Applied Energy*, vol. 231, pp. 1089–1099, 2018. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2018.09.175>
- [25] J. Allegrini, K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, and R. Evins, "A review of modelling approaches and tools for the simulation of district-scale energy systems," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1391 – 1404, 2015. [Online]. Available: <https://doi.org/10.1016/j.rser.2015.07.123>
- [26] X. Zhang, M. Lovati, I. Vigna, J. Widén, M. Han, C. Gal, and T. Feng, "A review of urban energy systems at building cluster level incorporating renewable-energy-source (RES) envelope solutions," *Applied Energy*, vol. 230, pp. 1034–1056, 2018. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2018.09.041>
- [27] "Sustainable buildings for Europe's climate-neutral future," 2019, Accessed: 2020-11-27. [Online]. Available: <https://ec.europa.eu/easme/en/news/sustainable-buildings-europe-s-climate-neutral-future>
- [28] S. A. Kalogirou, "Building integration of solar renewable energy systems towards zero or nearly zero energy buildings," *International Journal of Low-Carbon Technologies*, vol. 10, no. 4, pp. 379–385, 2015. [Online]. Available: <https://doi.org/10.1093/ijlct/ctt071>
- [29] "Boverket," Accessed: 2023-05-11. [Online]. Available: <https://www.boverket.se/>
- [30] "International Passive House Association," Accessed: 2023-05-11. [Online]. Available: <https://passivehouse-international.org/>
- [31] "International Passive House Institute," Accessed: 2023-04-22. [Online]. Available: <https://passiv.de/>
- [32] "The Swedish Forum for Energy-Efficient Building (FEBY)," Accessed: 2023-04-14. [Online]. Available: <https://www.feby.se/>
- [33] R. K. Jaysawal, S. Chakraborty, D. Elangovan, and S. Padmanaban, "Concept of net zero energy buildings (NZEB) - A literature review," *Cleaner Engineering and Technology*, vol. 11, p. 100582, 2022. [Online]. Available: <https://doi.org/10.1016/j.clet.2022.100582>
- [34] S. Attia, "Chapter 2 - Evolution of Definitions and Approaches," in *Net Zero Energy Buildings (NZEB)*. Butterworth-Heinemann, 2018, pp. 21–51. [Online]. Available: <https://doi.org/10.1016/B978-0-12-812461-1.00002-2>
- [35] A. Ahmed, T. Ge, J. Peng, W. C. Yan, B. T. Tee, and S. You, "Assessment of the renewable energy generation towards net-zero energy buildings: A review," *Energy and Buildings*, vol. 256, p. 111755, 2022. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2021.111755>
- [36] E. Commission, J. R. Centre, Y. Saheb, S. Shnapp, and D. Paci, *From nearly-zero energy buildings to net-zero energy districts*. Publications Office, 2019. [Online]. Available: <https://doi.org/10.2760/693662>
- [37] M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic, "A review of bottom-up building stock models for energy consumption in the residential sector," *Building and Environment*, vol. 45, no. 7, pp. 1683–1697, 2010. [Online]. Available:

- <https://doi.org/10.1016/j.buildenv.2010.01.021>
- [38] L. G. Swan and V. I. Ugursal, "Modeling of end-use energy consumption in the residential sector: A review of modeling techniques," *Renewable sustainable energy reviews*, vol. 13, no. 8, pp. 1819–1835, 2009. [Online]. Available: <https://doi.org/10.1016/j.rser.2008.09.033>
- [39] K. Fabbri and V. Tarabusi, "Top-down and Bottom-up Methodologies for Energy Building Performance Evaluation at Meso-scale Level-A Literature Review," *Civil Engineering and Architecture Research*, vol. 1, no. 5, pp. 283–299, 2014.
- [40] W. Li, Y. Zhou, K. Cetin, J. Eom, Y. Wang, G. Chen, and X. Zhang, "Modeling urban building energy use: A review of modeling approaches and procedures," *Energy*, vol. 141, pp. 2445–2457, 2017. [Online]. Available: <https://doi.org/10.1016/j.energy.2017.11.071>
- [41] F. Johari, G. Peronato, P. Sadeghian, X. Zhao, and J. Widén, "Urban building energy modeling: State of the art and future prospects," *Renewable and Sustainable Energy Reviews*, vol. 128, p. 109902, 2020. [Online]. Available: <https://doi.org/10.1016/j.rser.2020.109902>
- [42] S. Fathi, R. Srinivasan, A. Fenner, and S. Fathi, "Machine learning applications in urban building energy performance forecasting: A systematic review," *Renewable and Sustainable Energy Reviews*, vol. 133, p. 110287, 2020. [Online]. Available: <https://doi.org/10.1016/j.rser.2020.110287>
- [43] N. Abbasabadi and M. Ashayeri, "Urban energy use modeling methods and tools: A review and an outlook," *Building and Environment*, vol. 161, p. 106270, 2019. [Online]. Available: <https://doi.org/10.1016/j.buildenv.2019.106270>
- [44] A. Nutkiewicz, Z. Yang, and R. K. Jain, "Data-driven Urban Energy Simulation (DUE-S): A framework for integrating engineering simulation and machine learning methods in a multi-scale urban energy modeling workflow," *Applied Energy*, vol. 225, pp. 1176 – 1189, 2018. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2018.05.023>
- [45] Z. Yang, J. Roth, and R. K. Jain, "DUE-B: Data-driven urban energy benchmarking of buildings using recursive partitioning and stochastic frontier analysis," *Energy and Buildings*, vol. 163, pp. 58–69, 2018. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2017.12.040>
- [46] S. Lo, B. Norton, and A. Mannis, "Domestic energy use and air quality; a case study of the city of Belfast," *Applied Energy*, vol. 68, no. 1, pp. 1–18, 2001. [Online]. Available: [https://doi.org/10.1016/S0306-2619\(00\)00044-1](https://doi.org/10.1016/S0306-2619(00)00044-1)
- [47] P. Nageler, G. Schweiger, H. Schranzhofer, T. Mach, R. Heimrath, and C. Hochenauer, "Novel method to simulate large-scale thermal city models," *Energy*, vol. 157, pp. 633 – 646, 2018. [Online]. Available: <https://doi.org/10.1016/j.energy.2018.05.190>
- [48] C. Cerezo Davila, C. F. Reinhart, and J. L. Bemis, "Modeling boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets," *Energy*, vol. 117, pp. 237 – 250, 2016. [Online]. Available: <https://doi.org/10.1016/j.energy.2016.10.057>
- [49] R. Nouvel, A. Mastrucci, U. Leopold, O. Baume, V. Coors, and U. Eicker, "Combining GIS-based statistical and engineering urban heat consumption

- models: Towards a new framework for multi-scale policy support,” *Energy and Buildings*, vol. 107, pp. 204 – 212, 2015. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2015.08.021>
- [50] N. Ghiassi and A. Mahdavi, “Reductive bottom-up urban energy computing supported by multivariate cluster analysis,” *Energy and Buildings*, vol. 144, pp. 372–386, 2017. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2017.03.004>
- [51] F. Biljecki, J. Stoter, H. Ledoux, S. Zlatanova, and A. Çöltekin, “Applications of 3D City Models: State of the Art Review,” *ISPRS International Journal of Geo-Information*, vol. 4, no. 4, pp. 2842–2889, 2015. [Online]. Available: <https://doi.org/10.3390/ijgi4042842>
- [52] G. Peronato, J. Kämpf, E. Rey, and M. Andersen, “Integrating urban energy simulation in a parametric environment: a Grasshopper interface for CitySim,” in *Proceedings of PLEA 2017*, Edinburgh, 2017. [Online]. Available: <https://infoscience.epfl.ch/record/228832?ln=en>
- [53] R. Kaden and T. H. Kolbe, “City-wide total energy demand estimation of buildings using semantic 3D city models and statistical data,” *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-2/W1, pp. 163–171, 2013. [Online]. Available: <https://doi.org/10.5194/isprsannals-II-2-W1-163-2013>
- [54] R. Ma, C. Geng, Z. Yu, J. Chen, and X. Luo, “Modeling city-scale building energy dynamics through inter-connected distributed adjacency blocks,” *Energy and Buildings*, vol. 202, p. 109391, 2019. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2019.109391>
- [55] A. Schaefer and E. Ghisi, “Method for obtaining reference buildings,” *Energy and Buildings*, vol. 128, pp. 660 – 672, 2016. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2016.07.001>
- [56] A. T. Booth, R. Choudhary, and D. J. Spiegelhalter, “Handling uncertainty in housing stock models,” *Building and Environment*, vol. 48, pp. 35–47, 2012. [Online]. Available: [10.1016/j.buildenv.2011.08.016](https://doi.org/10.1016/j.buildenv.2011.08.016)
- [57] J. Sokol, C. Cerezo Davila, and C. F. Reinhart, “Validation of a Bayesian-based method for defining residential archetypes in urban building energy models,” *Energy and Buildings*, vol. 134, pp. 11–24, 2017. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2016.10.050>
- [58] C. S. Monteiro, A. Pina, C. Cerezo, C. Reinhart, and P. Ferrão, “The Use of Multi-detail Building Archetypes in Urban Energy Modelling,” *Energy Procedia*, vol. 111, pp. 817–825, 2017.
- [59] A. A. Famuyibo, A. Duffy, and P. Strachan, “Developing archetypes for domestic dwellings—An Irish case study,” *Energy and Buildings*, vol. 50, pp. 150–157, 2012. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2012.03.033>
- [60] O. Pasichnyi, J. Wallin, and O. Kordas, “Data-driven building archetypes for urban building energy modelling,” *Energy*, vol. 181, pp. 360–377, 2019. [Online]. Available: <https://doi.org/10.1016/j.energy.2019.04.197>
- [61] G. Tardioli, R. Kerrigan, M. Oates, J. O’Donnell, and D. P. Finn, “Identification of representative buildings and building groups in urban datasets using a novel pre-processing, classification, clustering and predictive

- modelling approach,” *Building and Environment*, vol. 140, 2018. [Online]. Available: <https://doi.org/10.1016/j.buildenv.2018.05.035>
- [62] M. H. Kristensen, R. E. Hedegaard, and S. Petersen, “Hierarchical calibration of archetypes for urban building energy modeling,” *Energy and Buildings*, vol. 175, pp. 219–234, 2018. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2018.07.030>
- [63] J. Widén and E. Wäckelgård, “A high-resolution stochastic model of domestic activity patterns and electricity demand,” *Applied Energy*, vol. 87, no. 6, 2010. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2009.11.006>
- [64] D. Fischer, A. Härtl, and B. Wille-Haussmann, “Model for electric load profiles with high time resolution for German households,” *Energy and Buildings*, vol. 92, pp. 170–179, 2015. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2015.01.058>
- [65] D. Fischer, T. Wolf, J. Scherer, and B. Wille-Haussmann, “A stochastic bottom-up model for space heating and domestic hot water load profiles for German households,” *Energy and Buildings*, vol. 124, pp. 120–128, 2016. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2016.04.069>
- [66] E. McKenna and M. Thomson, “High-resolution stochastic integrated thermal-electrical domestic demand model,” *Applied Energy*, vol. 165, pp. 445–461, 2016. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2015.12.089>
- [67] G. Happle, J. A. Fonseca, and A. Schlueter, “A review on occupant behavior in urban building energy models,” *Energy and Buildings*, vol. 174, pp. 276–292, 2018. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2018.06.030>
- [68] D. Robinson, F. Haldi, J. Kämpf, P. Leroux, D. Perez, A. Rasheed, and U. Wilke, “CITYSIM: Comprehensive Micro-Simulation of Resource Flows for Sustainable Urban Planning,” in *Proceedings of the Eleventh International IBPSA Conference, Glasgow, Scotland, 2009*, p. 8.
- [69] E. Barbour, C. C. Davila, S. Gupta, C. Reinhart, J. Kaur, and M. C. González, “Planning for sustainable cities by estimating building occupancy with mobile phones,” *Nature Communications*, vol. 10, no. 1, p. 3736, 2019. [Online]. Available: <https://doi.org/10.1038/s41467-019-11685-w>
- [70] W. Wu, B. Dong, Q. R. Wang, M. Kong, D. Yan, J. An, and Y. Liu, “A novel mobility-based approach to derive urban-scale building occupant profiles and analyze impacts on building energy consumption,” *Applied Energy*, vol. 278, p. 115656, 2020. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2020.115656>
- [71] M. Mosteiro Romero, I. Hischer, J. Fonseca, and A. Schlueter, “A novel population-based occupancy modeling approach for district-scale simulations compared to standard-based methods,” *Building and Environment*, vol. 181, p. 107084, 2020. [Online]. Available: <https://doi.org/10.1016/j.buildenv.2020.107084>
- [72] G. Happle, J. A. Fonseca, and A. Schlueter, “Context-specific urban occupancy modeling using location-based services data,” *Building and Environment*, vol. 175, p. 106803, 2020. [Online]. Available: <https://doi.org/10.1016/j.buildenv.2020.106803>
- [73] V. S. K. V. Harish and A. Kumar, “A review on modeling and simulation of

- building energy systems,” *Renewable and Sustainable Energy Reviews*, vol. 56, 2016. [Online]. Available: <https://doi.org/10.1016/j.rser.2015.12.040>
- [74] Y. Chen, T. Hong, and M. A. Piette, “City-Scale Building Retrofit Analysis: A Case Study using CityBES,” in *Proceedings of the 15th International IBPSA Conference, San Francisco, CA, USA, 2017*, p. 8.
- [75] D. Wang, J. Landolt, G. Mavromatidis, K. Orehounig, and J. Carmeliet, “CESAR: A bottom-up building stock modelling tool for Switzerland to address sustainable energy transformation strategies,” *Energy and Buildings*, vol. 169, pp. 9–26, 2018. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2018.03.020>
- [76] J. A. Fonseca and A. Schlueter, “Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts,” *Applied Energy*, vol. 142, pp. 247–265, 2015. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2014.12.068>
- [77] J. A. Fonseca, T. A. Nguyen, A. Schlueter, and F. Marechal, “City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts,” *Energy and Buildings*, vol. 113, pp. 202–226, 2016. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2015.11.055>
- [78] C.-K. Wang, S. Tindemans, C. Miller, G. Agugiaro, and J. Stoter, “Bayesian calibration at the urban scale: a case study on a large residential heating demand application in Amsterdam,” *Journal of Building Performance Simulation*, vol. 13, no. 3, pp. 347–361, 2020. [Online]. Available: [10.1080/19401493.2020.1729862](https://doi.org/10.1080/19401493.2020.1729862)
- [79] E. Delzendeh, S. Wu, A. Lee, and Y. Zhou, “The impact of occupants’ behaviours on building energy analysis: A research review,” *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1061–1071, 2017. [Online]. Available: <https://doi.org/10.1016/j.rser.2017.05.264>
- [80] L. Leroy, S. Letellier-Duchesne, and M. Kummert, “Using Model Calibration to Improve Urban Modeling,” in *Proceedings of the Sixteenth International IBPSA Conference, Rome, Italy, 2019*, pp. 3531–3539. [Online]. Available: <https://doi.org/10.26868/25222708.2019.210707>
- [81] X. Fu, W. Tian, Y. Sun, C. Zhu, and B. Yin, “Uncertainty Analysis of Urban Building Energy Based on Two-Dimensional Monte Carlo Method,” in *Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019)*, ser. Environmental Science and Engineering, Z. Wang, Y. Zhu, F. Wang, P. Wang, C. Shen, and J. Liu, Eds. Singapore: Springer, 2020, pp. 1315–1323. [Online]. Available: https://doi.org/10.1007/978-981-13-9528-4_133
- [82] S. Heiple and D. J. Sailor, “Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles,” *Energy and Buildings*, vol. 40, no. 8, pp. 1426–1436, 2008. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2008.01.005>
- [83] M. H. Kristensen, R. Choudhary, R. H. Pedersen, and S. Petersen, “Bayesian Calibration of Residential Building Clusters Using A Single Geometric Building Representation,” in *Proceedings of the 15th International IBPSA Conference, San Francisco, CA, USA, 2017*, p. 10.

- [84] S. Nagpal, J. Hanson, and C. Reinhart, “Auto-Calibrated Urban Building Energy Models as Continuous Planning Tools,” in *Proceedings of SimAUD, Delft, the Netherlands*, 2018, p. 5.
- [85] S. Nagpal, C. Mueller, A. Aijazi, and C. F. Reinhart, “A methodology for auto-calibrating urban building energy models using surrogate modeling techniques,” *Journal of Building Performance Simulation*, pp. 1–16, 2018. [Online]. Available: <https://doi.org/10.1080/19401493.2018.1457722>
- [86] K. Sun, T. Hong, S. C. Taylor-Lange, and M. A. Piette, “A pattern-based automated approach to building energy model calibration,” *Applied Energy*, vol. 165, pp. 214–224, 2016. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2015.12.026>
- [87] X. Yang, M. Hu, N. Heeren, C. Zhang, T. Verhagen, A. Tukker, and B. Steubing, “A combined GIS-archetype approach to model residential space heating energy: A case study for the Netherlands including validation,” *Applied Energy*, vol. 280, p. 115953, 2020. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2020.115953>
- [88] P. Remmen, M. Lauster, M. Mans, M. Fuchs, T. Osterhage, and D. Müller, “TEASER: an open tool for urban energy modelling of building stocks,” *Journal of Building Performance Simulation*, vol. 11, no. 1, pp. 84–98, 2018. [Online]. Available: <https://doi.org/10.1080/19401493.2017.1283539>
- [89] M. Braulio-Gonzalo, M. D. Bovea, M. J. Ruá, and P. Juan, “A methodology for predicting the energy performance and indoor thermal comfort of residential stocks on the neighbourhood and city scales. A case study in Spain,” *Journal of Cleaner Production*, vol. 139, pp. 646–665, 2016. [Online]. Available: <https://doi.org/10.1016/j.jclepro.2016.08.059>
- [90] Y. Q. Ang, Z. M. Berzolla, S. Letellier-Duchesne, V. Jusiega, and C. Reinhart, “Ubem.io: A web-based framework to rapidly generate urban building energy models for carbon reduction technology pathways,” *Sustainable Cities and Society*, vol. 77, p. 103534, 2022. [Online]. Available: <https://doi.org/10.1016/j.scs.2021.103534>
- [91] Y. Chen, T. Hong, and M. A. Piette, “Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis,” *Applied Energy*, vol. 205, pp. 323–335, 2017. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2017.07.128>
- [92] N. Buckley, G. Mills, C. Reinhart, and Z. M. Berzolla, “Using urban building energy modelling (UBEM) to support the new European Union’s Green Deal: Case study of Dublin Ireland,” *Energy and Buildings*, vol. 247, p. 111115, 2021. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2021.111115>
- [93] O. Pasichnyi, F. Levihn, H. Shahrokni, J. Wallin, and O. Kordas, “Data-driven strategic planning of building energy retrofitting: The case of Stockholm,” *Journal of Cleaner Production*, vol. 233, pp. 546–560, 2019. [Online]. Available: <https://doi.org/10.1016/j.jclepro.2019.05.373>
- [94] U. Perwez, K. Shono, Y. Yamaguchi, and Y. Shimoda, “Multi-scale ubem-bipv coupled approach for the assessment of carbon neutrality of commercial building stock,” *Energy and Buildings*, vol. 291, p. 113086, 2023. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2023.113086>
- [95] S. HosseiniHaghighi, P. M. A. de Uribarri, R. Padsala, and U. Eicker,

- “Characterizing and structuring urban GIS data for housing stock energy modelling and retrofiting,” *Energy and Buildings*, vol. 256, p. 111706, 2022. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2021.111706>
- [96] I. Mansó Borrás, D. Neves, and R. Gomes, “Using urban building energy modeling data to assess energy communities’ potential,” *Energy and Buildings*, vol. 282, p. 112791, 2023. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2023.112791>
- [97] Z. Lin, T. Hong, X. Xu, J. Chen, and W. Wang, “Evaluating energy retrofits of historic buildings in a university campus using an urban building energy model that considers uncertainties,” *Sustainable Cities and Society*, vol. 95, p. 104602, 2023. [Online]. Available: <https://doi.org/10.1016/j.scs.2023.104602>
- [98] A. Katal, M. Mortezaadeh, and L. L. Wang, “Modeling building resilience against extreme weather by integrated CityFFD and CityBEM simulations,” *Applied Energy*, vol. 250, pp. 1402–1417, 2019. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2019.04.192>
- [99] R. E. Hedegaard, M. H. Kristensen, T. H. Pedersen, A. Brun, and S. Petersen, “Bottom-up modelling methodology for urban-scale analysis of residential space heating demand response,” *Applied Energy*, vol. 242, pp. 181–204, 2019. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2019.03.063>
- [100] J. Clarke, *Energy Simulation in Building Design*, J. Clarke, Ed. Oxford: Butterworth-Heinemann, 2001. [Online]. Available: <https://doi.org/10.1016/B978-075065082-3/50002-4>
- [101] Y. J. Huang, J. Broderick, and R. International, “A Bottom-Up Engineering Estimate of the Aggregate Heating and Cooling Loads of the Entire U.S. Building Stock,” in *Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, US, 2000*, p. 15.
- [102] “DOE2,” Accessed: 2020-09-24. [Online]. Available: <http://www.doe2.com/>
- [103] A. Parekh, “Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses,” in *Proceedings of 9th Conference of IBPSA Montréal, Canada, 2005*, p. 8.
- [104] D. Robinson, N. Campbell, W. Gaiser, K. Kabel, A. Le-Mouel, N. Morel, J. Page, S. Stankovic, and A. Stone, “SUNtool - A new modelling paradigm for simulating and optimising urban sustainability,” *Solar Energy*, vol. 81, no. 9, pp. 1196–1211, 2007. [Online]. Available: <https://doi.org/10.1016/j.solener.2007.06.002>
- [105] J. H. Kämpf and D. Robinson, “Optimisation of urban energy demand using an evolutionary algorithm,” in *Proceedings of the Eleventh International IBPSA Conference, Glasgow, Scotland, 2009*, p. 6.
- [106] D. Thomas, C. Miller, J. Kämpf, and A. Schlueter, “Multiscale co-simulation of energyplus and CITYSIM models derived from a building information model,” in *Proceedings of the Fifth German-Austrian IBPSA Conference RWTH Aachen University, 2014*, p. 8.
- [107] “STANET network analysis for gas, water, electricity, district heating and sewage,” Accessed: 2020-09-24. [Online]. Available: <http://stafu.de/en/home.html>
- [108] C. F. Reinhart, T. Dogan, J. A. Jakubiec, T. Rakha, and A. Sang, “UMI - An urban simulation environment for building energy use, daylighting and

- walkability,” in *Proceedings of the 13th Conference of International Building Performance Simulation Association, Chambéry, France*, 2013.
- [109] L. Dahlström, T. Broström, and J. Widén, “Advancing urban building energy modelling through new model components and applications: A review,” *Energy and Buildings*, vol. 266, p. 112099, 2022. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2022.112099>
- [110] M. Åberg, J. Carlsson, and A. M. Nilsson, “Improved efficiency for distribution and use of district heating: A simulation study of retrofitting a Swedish apartment complex from the 1970’s,” *Journal of Building Engineering*, vol. 20, pp. 559–568, 2018. [Online]. Available: <https://doi.org/10.1016/j.job.2018.09.005>
- [111] “Lantmäteriet,” Accessed: 2020-09-28. [Online]. Available: <https://www.lantmateriet.se/>
- [112] “Vattenfall Heat Home Page,” Accessed: 2020-09-28. [Online]. Available: <https://www.vattenfall.se/fjarrvarme/>
- [113] S. Quintana, P. Huang, M. Han, and X. Zhang, “A top-down digital mapping of spatial-temporal energy use for municipality-owned buildings: A case study in borlänge, sweden,” *Buildings*, vol. 11, no. 2, 2021. [Online]. Available: <https://doi.org/10.3390/buildings11020072>
- [114] M. Herrera, S. Natarajan, D. A. Coley, T. Kershaw, A. P. Ramallo-González, M. Eames, D. Fosas, and M. Wood, “A review of current and future weather data for building simulation,” *Building Services Engineering Research and Technology*, vol. 38, no. 5, pp. 602–627, 2017. [Online]. Available: <https://doi.org/10.1177/0143624417705937>
- [115] “Swedish meteorological and hydrological institute (SMHI),” Accessed: 2023-05-22. [Online]. Available: <https://www.smhi.se/>
- [116] “EnergyPlus,” Accessed: 2023-05-22. [Online]. Available: <https://energyplus.net/>
- [117] “Photovoltaic geographical information system (PVGIS),” Accessed: 2023-05-22. [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/#TMY
- [118] “Shiny weather data,” Accessed: 2023-05-22. [Online]. Available: <https://shinyweatherdata.com/>
- [119] J. P. Holman and P. R. S. White, *Heat transfer*. London: McGraw-Hill, 1992.
- [120] X. Q. Li, Y. Chen, J. D. Spitler, and D. Fisher, “Applicability of calculation methods for conduction transfer function of building constructions,” *International Journal of Thermal Sciences*, vol. 48, no. 7, pp. 1441–1451, 2009. [Online]. Available: <https://doi.org/10.1016/j.ijthermalsci.2008.11.006>
- [121] J. E. Seem, “Modeling of Heat Transfer in Buildings,” Ph.D. dissertation, University of Wisconsin-Madison, 1987.
- [122] M. Manfren, P. Caputo, and G. Costa, “Paradigm shift in urban energy systems through distributed generation: Methods and models,” *Applied Energy*, vol. 88, no. 4, pp. 1032–1048, 2011. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2010.10.018>
- [123] “TRNSYS : Transient System Simulation Tool,” Accessed: 2023-05-22. [Online]. Available: <http://www.trnsys.com/>
- [124] “IDA ICE - Simulation Software | EQUA,” Accessed: 2023-05-22. [Online].

- Available: <https://www.equa.se/en/ida-ice>
- [125] “ASHRAE,” Accessed: 2023-05-22. [Online]. Available: <https://www.ashrae.org>
- [126] R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart, “Modeling daylight availability and irradiance components from direct and global irradiance,” *Solar Energy*, vol. 44, no. 5, pp. 271–289, 1990. [Online]. Available: [https://doi.org/10.1016/0038-092X\(90\)90055-H](https://doi.org/10.1016/0038-092X(90)90055-H)
- [127] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes, 4th Edition*, 4th ed. Wiley, 2013.
- [128] G. P. Mitalas and J. G. Arseneault, “Fortran IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs.” National Research Council of Canada, Tech. Rep., 1972.
- [129] B. Gebhart, *Heat Transfer*. McGraw-Hill, 1971.
- [130] “ISO 13370:2017,” Accessed: 2023-05-22. [Online]. Available: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/57/65716.html>
- [131] “3D Design Software,” Accessed: 2023-05-22. [Online]. Available: <https://www.sketchup.com/page/homepage>
- [132] H. Ledoux, F. Biljecki, B. Dukai, K. Kumar, R. Peters, J. Stoter, and T. Commandeur, “3dfier: automatic reconstruction of 3d city models,” *Journal of Open Source Software*, vol. 6, no. 57, p. 2866, 2021. [Online]. Available: <https://doi.org/10.21105/joss.02866>
- [133] D. Lingfors, J. Bright, N. Engerer, J. Ahlberg, S. Killinger, and J. Widén, “Comparing the capability of low- and high-resolution lidar data with application to solar resource assessment, roof type classification and shading analysis,” *Applied Energy*, vol. 205, pp. 1216–1230, 2017. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2017.08.045>
- [134] C. Björk, L. Reppen, L. Nordling, and Formas, *Såbyggdes villan: svensk villaarkitektur från 1890 till 2010*. Stockholm: Formas, 2009, vol. 2009:3, Swedish.
- [135] C. Björk, L. Reppen, and P. Kallstenius, *Såbyggdes husen 1880-2000: arkitektur, konstruktion och material i våra flerbostadshus under 120 år*. Stockholm: Svensk Byggtjänst, 2013, Swedish.
- [136] “TABULA WebTool,” Accessed: 2023-05-22. [Online]. Available: <http://webtool.building-typology.eu/#bm>
- [137] T. Catalina, J. Virgone, and V. Iordache, “Study on the impact of the building form on the energy consumption,” in *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, 2011.
- [138] “Boverkets byggregler BBR,” 2020. [Online]. Available: <https://www.boverket.se/globalassets/publikationer/dokument/2020/konsoliderad-bbr-2011-6-tom-2020-4.pdf>
- [139] D. Lingfors, “Solar Variability Assessment and Grid Integration : Methodology Development and Case Studies,” Ph.D. dissertation, Uppsala University, 2015, publisher: Uppsala University, Department of Engineering Sciences.
- [140] “IPM Insights Metrics,” Accessed: 2023-07-22. [Online]. Available: <https://>

- //docs.oracle.com/en/cloud/saas/planning-budgeting-cloud/pfusu/insights_metrics.html#GUID-DCE33A1F-73EB-4087-97D9-92AA3CAD8B06
- [141] P. Nageler, G. Schweiger, M. Pichler, D. Brandl, T. Mach, R. Heimrath, H. Schranzhofer, and C. Hochenauer, "Validation of dynamic building energy simulation tools based on a real test-box with thermally activated building systems (TABS)," *Energy and Buildings*, vol. 168, pp. 42–55, 2018. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2018.03.025>
- [142] J. Widén, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård, and E. Wäckelgård, "Constructing load profiles for household electricity and hot water from time-use data-Modelling approach and validation," *Energy and Buildings*, vol. 41, no. 7, pp. 753–768, 2009. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2009.02.013>
- [143] J. Widén, A. M. Nilsson, and E. Wäckelgård, "A combined Markov-chain and bottom-up approach to modelling of domestic lighting demand," *Energy and Buildings*, vol. 41, no. 10, pp. 1001–1012, 2009. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2009.05.002>
- [144] M. H. Kristensen, A. Brun, and S. Petersen, "Predicting Danish residential heating energy use from publicly available building characteristics," *Energy and Buildings*, vol. 173, pp. 28–37, 2018. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2018.05.011>
- [145] U. Ali, M. H. Shamsi, C. Hoare, E. Mangina, and J. O'Donnell, "A data-driven approach for multi-scale building archetypes development," *Energy and Buildings*, vol. 202, p. 109364, 2019. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2019.109364>
- [146] S. Torabi Moghadam, S. Coccolo, G. Mutani, P. Lombardi, J.-L. Scartezzini, and D. Mauree, "A new clustering and visualization method to evaluate urban heat energy planning scenarios," *Cities*, vol. 88, pp. 19–36, 2019. [Online]. Available: <https://doi.org/10.1016/j.cities.2018.12.007>
- [147] O. Pasichnyi, J. Wallin, F. Levihn, H. Shahrokni, and O. Kordas, "Energy performance certificates - New opportunities for data-enabled urban energy policy instruments?" *Energy Policy*, vol. 127, pp. 486–499, 2019. [Online]. Available: <https://doi.org/10.1016/j.enpol.2018.11.051>
- [148] "Energy Performance Certificates across Europe - From design to implementation," The Buildings Performance Institute Europe (BPIE), Tech. Rep., 2010.
- [149] C. Ahern and B. Norton, "A generalisable bottom-up methodology for deriving a residential stock model from large empirical databases," *Energy and Buildings*, vol. 215, p. 109886, 2020. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2020.109886>
- [150] M. Österbring, E. Mata, L. Thuvander, M. Mangold, F. Johnsson, and H. Wallbaum, "A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model," *Energy and Buildings*, vol. 120, pp. 78–84, 2016. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2016.03.060>
- [151] M. Mangold, M. Österbring, and H. Wallbaum, "Handling data uncertainties when using Swedish energy performance certificate data to describe energy usage in the building stock," *Energy and Buildings*, vol. 102, pp. 328–336,

2015. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2015.05.045>
- [152] J. von Platten, C. Holmberg, M. Mangold, T. Johansson, and K. Mjörnell, “The renewing of Energy Performance CertificatesâReaching comparability between decade-apart energy records,” *Applied Energy*, vol. 255, 2019. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2019.113902>
- [153] Y. Li, S. Kubicki, A. Guerriero, and Y. Rezgui, “Review of building energy performance certification schemes towards future improvement,” *Renewable and Sustainable Energy Reviews*, vol. 113, 2019. [Online]. Available: <https://doi.org/10.1016/j.rser.2019.109244>
- [154] A. Sola, C. Corchero, J. Salom, and M. Sanmarti, “Simulation Tools to Build Urban-Scale Energy Models: A Review,” *Energies*, vol. 11, no. 12, p. 3269, 2018. [Online]. Available: <https://doi.org/10.3390/en11123269>
- [155] G. Dall’O’, A. Galante, and M. Torri, “A methodology for the energy performance classification of residential building stock on an urban scale,” *Energy and Buildings*, vol. 48, pp. 211–219, 2012. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2012.01.034>
- [156] L. Frayssinet, F. Kuznik, J. L. Hubert, M. Milliez, and J. J. Roux, “Adaptation of building envelope models for energy simulation at district scale,” *Energy Procedia*, vol. 122, pp. 307–312, 2017. [Online]. Available: <https://doi.org/10.1016/j.egypro.2017.07.327>
- [157] R. Nouvel, A. Mastrucci, U. Leopold, O. Baume, V. Coors, and U. Eicker, “Combining GIS-based statistical and engineering urban heat consumption models: Towards a new framework for multi-scale policy support,” *Energy and Buildings*, vol. 107, pp. 204–212, 2015. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2015.08.021>
- [158] R. Buffat, A. Froemelt, N. Heeren, M. Raubal, and S. Hellweg, “Big data GIS analysis for novel approaches in building stock modelling,” *Applied Energy*, vol. 208, pp. 277–290, 2017. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2017.10.041>
- [159] V. Castán Broto and H. Bulkeley, “A survey of urban climate change experiments in 100 cities,” *Global Environmental Change*, vol. 23, no. 1, pp. 92 – 102, 2013. [Online]. Available: <https://doi.org/10.1016/j.gloenvcha.2012.07.005>
- [160] J. H. Kämpf and D. Robinson, “A simplified thermal model to support analysis of urban resource flows,” *Energy and Buildings*, vol. 39, no. 4, pp. 445–453, 2007. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2006.09.002>
- [161] Y. Wu and L. Zhong, “An integrated energy analysis framework for evaluating the application of hydrogen-based energy storage systems in achieving net zero energy buildings and cities in canada,” *Energy Conversion and Management*, vol. 286, p. 117066, 2023. [Online]. Available: <https://doi.org/10.1016/j.enconman.2023.117066>
- [162] O. R. Rethnam and A. Thomas, “A community building energy modelling - life cycle cost analysis framework to design and operate net zero energy communities,” *Sustainable Production and Consumption*, 2023. [Online]. Available: <https://doi.org/10.1016/j.spc.2023.04.022>
- [163] T. Lv, Y. Lu, Y. Zhou, X. Liu, C. Wang, Y. Zhang, Z. Huang, and Y. Sun, “Optimal Control of Energy Systems in Net-Zero Energy Buildings

- Considering Dynamic Costs: A Case Study of Zero Carbon Building in Hong Kong,” *Sustainability*, vol. 14, no. 6, 2022. [Online]. Available: <https://doi.org/10.3390/su14063136>
- [164] J. Salom, J. Widén, J. Candanedo, I. Sartori, K. Voss, and A. Marszal, “Understandin net zero energy buildings: Evaluation of load matching and grid interaction indicators,” in *Proceedings of the 12th Conference of International Building Performance Simulation Association, Sydney, Australia*, 2011.
- [165] S. Charani Shandiz, B. Rismanchi, and G. Foliente, “Energy master planning for net-zero emission communities: State of the art and research challenges,” *Renewable and Sustainable Energy Reviews*, vol. 137, p. 110600, 2021. [Online]. Available: <https://doi.org/10.1016/j.rser.2020.110600>
- [166] R. Nouvel, M. Zirak, V. Coors, and U. Eicker, “The influence of data quality on urban heating demand modeling using 3D city models,” *Computers, Environment and Urban Systems*, vol. 64, pp. 68–80, 2017. [Online]. Available: <https://doi.org/10.1016/j.compenvurbsys.2016.12.005>
- [167] International Energy Agency, “In support of the G8 Plan of Action,” in *Deploying Renewables: Principles for Effective Policies*. OECD, 2008, pp. 15–198. [Online]. Available: <https://doi.org/10.1787/9789264042216-1-en>
- [168] E. Vaughan and J. Turner, “The Value and Impact of Building Codes,” Accessed: 2023-05-22. [Online]. Available: <https://www.eesi.org/papers/view/the-value-and-impact-of-building-codes>
- [169] E. Harmon, “Improving Building Codes to Prepare for Climate Impacts,” 2019. [Online]. Available: <https://www.mapc.org/resource-library/building-codes-climate-2/>
- [170] K. Andreanidou, P. Barbosa, P. Bertoldi, M. Follador, R. Glancy, S. Kilkis, A. Kona, N. Labanca, O. Lah, V. Palermo, S. Rivas, T. Serrenho, P. Zancanella, and P. Zangheri, “Guidebook "How to develop a Sustainable Energy and Climate Action Plan (SECAP),"” The European Union, Luxembourg, Technical guidance KJ-NA-29412-EN-N, 2018. [Online]. Available: <https://doi.org/10.2760/223399>
- [171] R. A. Enker and G. M. Morrison, “The potential contribution of building codes to climate change response policies for the built environment,” *Energy Efficiency*, vol. 13, no. 4, pp. 789–807, 2020. [Online]. Available: <https://doi.org/10.1007/s12053-020-09871-7>
- [172] A. Gouldson, S. Colenbrander, A. Sudmant, F. McAnulla, N. Kerr, P. Sakai, S. Hall, E. Papargyropoulou, and J. Kuylenstierna, “Exploring the economic case for climate action in cities,” *Global Environmental Change*, vol. 35, pp. 93–105, 2015. [Online]. Available: <https://doi.org/10.1016/j.gloenvcha.2015.07.009>

Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 2286

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology”.)

Distribution: publications.uu.se
urn:nbn:se:uu:diva-508080



ACTA UNIVERSITATIS
UPSALIENSIS
2023