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A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model

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ABSTRACT

Several building-stock modelling techniques have been employed to investigate the impact of energy efficiency measures (EEM), where the description of the building-stock generally consists of an age-type classification to specify building characteristics for groups of buildings. Such descriptions lack the appropriate level of detail to differentiate the potential for EEM within age groups. This paper proposes a methodology for building-stock description using building-specific data and measured energy use to augment an age-type building-stock classification. By integrating building characteristics from energy performance certificates, measured energy use and envelope areas from a 2.5D GIS model, the building-stock description reflects the heterogeneity of the building-stock. The proposed method is validated using a local building portfolio (N = 433) in the city of Gothenburg, where modelled results for space heating and domestic hot water are compared to data from measurements, both on an individual building level and for the entire portfolio. Calculated energy use based on the building-stock description of the portfolio differ less than 3% from measured values, with 42% of the individual buildings being within a 20% margin of measured energy use indicating further work is needed to reduce or quantify the uncertainty on a building level.

1. Introduction

Buildings worldwide account for 32% of the global final energy use and 19% of energy-related greenhouse-gas (GHG) emissions. At the same time, they provide a large potential for cost-efficient energy efficiency measures (EEM) [1–4]. With the aim to harvest these efficiency opportunities, the European Energy Performance of Buildings Directive defines a set of efficiency standards for both new and existing buildings [5,6]. On a national level, Swedish governmental policy aims at considerable reductions in energy use by 2020 and 2050 [7,8]. Resulting from the EU energy efficiency directive [5], energy performance certificates (EPC) were introduced in Sweden in 2006 in order to promote energy efficiency in buildings. On a local level, cities and municipalities have gone further and voluntarily adopted more ambitious targets on energy savings, reductions in GHG emissions and increase in renewable energy through frameworks such as the Covenant of Mayors.[1] The city of Gothenburg has adopted such goals and aims to reduce energy consumption in residential buildings by 30% by 2020 compared to 1995 levels [9]. For the developed world, it is estimated that 80% of the building stock in 2050 will consist of buildings already built [10], which implies a need for application of EEM in the existing stock if the above-mentioned targets are to be met.

There are many examples of building-stock modelling (BSM) being used to evaluate the energy demand of the existing building-stock [11–16]. According to two in-depth review papers by Swan and Ugursal [17], and Kavgic et al. [18], a general distinction can be made between top-down and bottom-up modelling approaches. Top-down models cannot be used to assess the effects from individual EEM and, thus, have not been in focus of this work. Bottom-up models can be divided into two sub-groups; Statistical models and bottom-up engineering models. Statistical models use aggregated data as input, which through regression methods are used

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[1] The Covenant of Mayors was launched by the European Commission to support efforts by local authorities to implement sustainable energy policies.

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to account for specific end-uses based on the energy consumption of the dwellings. A bottom-up engineering model, which is used in this paper, uses a heat balance model to estimates the energy consumption for individual buildings. The buildings used as input to bottom-up models are defined by building properties such as geometry, U-values, climate data, indoor temperature and use of appliances. Thus, to apply a bottom-up engineering model requires detailed input data. Due to aim, data availability and computational time-constraints the building stock is normally represented by sample buildings or archetype buildings, where it is assumed that similar buildings with regard to year of construction, use of the building, type of heating system and building geometry can be represented by an average building. Sample buildings use detailed data for a number of buildings (e.g. as obtained from measurements on individual buildings) combined with weighting factors derived so that the sample buildings reflect the entire building stock. Similarly, archetype buildings use representative theoretical buildings, often defined by construction year and the type or use of the building, to represent all buildings with similar characteristics to allow for assessment of the entire stock. These methods of building description have been successfully used to calculate the potential for EEM in existing residential building-stocks on a national scale [19,20] as well as on an urban scale [21–23].

Recent improvements in data availability have allowed greater focus on urban settings in BSM and include a spatial dimension by integrating geo-referenced data using geographical information systems (GIS) [24–26]. Using GIS in BSM has several advantages: it facilitates merging of data from several databases that is often required by engineering models, it facilitates further analysis and communication by spatially differentiating and visualizing results, and finally it provides a repository for storing and exchanging data through interconnected urban models. The addition of a GIS component to BSM has been carried out to analyse energy policy scenarios in an urban context [24], to assess the urban heat island effect on energy demand [25] as well as to assess environmental impacts of building stocks and potential for EEM [26]. While the introduction of GIS in BSM has allowed an increase in spatial resolution and enabled focus on urban settings, the description of the building-stock using representative buildings has not been adapted to take full advantage of the improved spatial resolution. The method of deriving and scaling a description based on representative buildings to account for the entire stock is based on the assumption that buildings with similar year of construction and use have similar energy performance characteristics. This can be problematic, typically so for older parts of the stock where energy renovations have been applied to varying degree which may result in significant differences in the energy performance for the same type of buildings [27].

As the scope of the above work [24–26] has been to evaluate targets and scenarios at a city or district level, representative buildings have been sufficient to describe the building-stock. In addition, measured data on energy supply that allow for validation and calibration of the building-stock description is commonly only available for a small number of buildings or at a district level, often due to lack of data availability or due to data not being publicly available [17,28]. As a result, validation and calibration of the building-stock description is limited to levels of aggregation set by available data [21]. Obviously, such descriptions should only be used at their intended level of aggregation [29], which in turn calls for a revised method of describing building-stocks for stakeholders needing building specific information such as property portfolio owners and managers. Furthermore, the increase in spatial resolution provided by a differentiated description reduces uncertainties on a stock level as representative buildings may over- or underestimate the energy demand of a specific building, which could result in inaccurate estimates of the potential for energy savings from applying different EEM. In order to increase the accuracy to allow for prioritizing EEM for individual buildings within a stock, measured energy use must be known to allow for validation on a building or property level. The lack of measured consumption data at a disaggregated level has been identified as the single most important obstacle for handling uncertainty in BSM [17,21,28,30,31].

The aim of this paper is to present a methodology for describing urban residential building-stocks that fits analysis of local building portfolios, i.e. where a greater detail in analysis is required compared to modelling a building stock of an entire country or a large region. Thus, the aim is to include a spatial resolution of individual buildings by using building-specific data and to assess data needs and, in particular geo-referenced data, for such a description.

2. Methodology

Building-specific data, envelope area and measured energy use from EPC are linked to each individual building using GIS to achieve a differentiated description of the building-stock of Gothenburg. Preparation and cleaning of the data are done and previously identified quality issues regarding how the heated floor area (HFA) is derived in the Swedish EPC [32,33] are corrected. As the U-value for the buildings are not known from any of the datasets, an age-type classification is developed based on historical building regulations and a historic construction and architectural classification [34] and linked to individual buildings. The proposed methodology is applied to a property manager's regional portfolio of buildings in the city of Gothenburg, consisting of 433 multi-family dwellings[2] with a total HFA of 1 million m^2.

The energy performance of each building in the portfolio is calculated with the building-stock model ECCABS [35] and, to validate the differentiated description of the building-stock, the modelled energy use for space heating (SH) and domestic hot water (DHW) is compared to measured energy consumption data which is based on billing data or measured on site. Finally, a sensitivity analysis for the most relevant input parameters considered uncertain is performed.

2.1. Building-specific datasets and processing

The building-specific data used in this work are retrieved from (a) EPC, (b) GIS data and (c) the property register. Building characteristics from EPC include type of heating, ventilation and air-conditioning (HVAC) systems, number of stories (above and below ground), number of staircases, attachment to other buildings (detached, semi-detached or attached), construction year and HFA. Furthermore, measured energy consumption values are given for non-domestic electricity use, SH and DHW. All EPC available for the city of Gothenburg were retrieved from the National Board of Housing, Building and Planning.

Building characteristics from the GIS data are geometrical data such as building footprints and building height. The City Planning Office of Gothenburg supplied the GIS-data. As the EPC and GIS-data do not contain any common unique identifier, data from the property register were collected from the Swedish National Land Survey to match the building or property ID from EPC to mid-point coordinates of buildings. This was then spatially linked to building footprints that were extruded to create the 2.5D representation shown in Fig. 1, which is used to retrieve the envelope area of each building. The property register also contains information on year of refurbishment and value year, which is an estimate of equivalent age for taxation purposes calculated based on year of construction and year of refurbishment [36]. The value year is weighted based

[2] A multi-family dwelling is for the purpose of this paper defined as a building with 3 or more apartments.

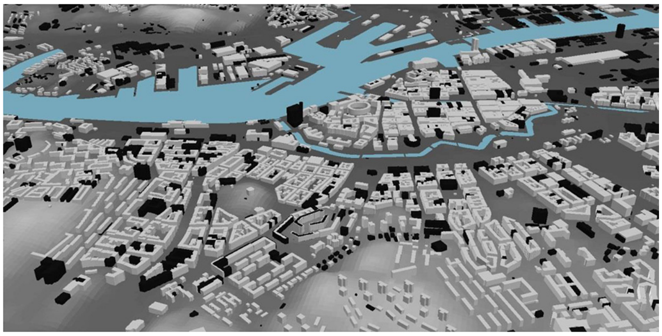

Fig. 1. 2.5D representation of central Gothenburg. Buildings in white have an EPC.

on the economic extent of refurbishment activities or extensions and relates to the expected remaining lifetime of each building.

2.2. Error investigation and preparation of input data set

The most commonly cited source of error in the Swedish EPC is the HFA [32,33]. The HFA is rarely measured in the EPC and is instead obtained by multiplying the living area by 1.15 for buildings without basement and by 1.25 for buildings with a basement. Yet, this procedure gives somewhat inaccurate predictions of the HFA, particularly in two cases. 1. For buildings where all HFA equals the living area, the resulting HFA is overestimated by 15% in the EPC. This is typical for two-story buildings with external staircases and individual external entries to all apartments. 2. For buildings with a basement. As the HFA is derived by multiplying the living area by 1.25, less than half of the basement would be accounted for in a two-story building assuming the area of the basement equals that of the floors above ground. For buildings with three or more stories, the error is less.

Other issues in the particular subset of 433 EPC include coordinate errors (in four instances) and wrong number of stories (in 76 instances). The coordinate errors always occur in pairs and is a result of two building IDs for the same property being mixed in the EPC. The wrong number of stories is likely due to manual input error or partly submerged basements being counted twice as it is given separately for basements above and below ground in the EPC. For the final input dataset, the correct number of stories has been added, the HFA recalculated for buildings with a basement or external staircases and the four instances with jumbled coordinates have been corrected manually.

2.3. U-values and building type-age description

Table 1 lists the average U-values for the different building types employed according to construction period. The U-value of building components is not given in any of the datasets and an average U-value is instead derived based on building type and construction year. Based on architectural history [34] and building regulations, the multi-family dwelling stock of Gothenburg is characterized by seven building types (timber buildings, brick buildings, so called "Landshövdingehus",[3] slab blocks, tower blocks, large slab blocks and courtyard buildings) and further divided by age, according to their year of construction, by five year periods from 1880 and onwards. The five-year division is determined by the recurrence of the architectural types. Out of a theoretical 196 combinations of age group and building type, 32 unique average U-values for the age-type classes are used as not all types are present for all age periods and in many cases the U-value does not change for longer periods (see Table 1).

[3] This is a three storey early to mid 20th century building type, characteristic for the City of Göteborg, for which the bottom storey is made of brick and the top two of wood.

2.4. Matching the building age-type classification to individual buildings

In the databases mentioned above (a–c) there is no single identifier to match the age-type classification to individual buildings, instead the number of stories, age, number of staircases and attachment to other buildings are used to match each building to average U-values which can be seen in Table 2. For buildings for which the year of refurbishment is documented, the U-value is based on the value year rather than construction year. While the actual refurbishment activities taken are not known, the value year at least gives an indication of the economic extent of the refurbishment and provides a more reasonable assumption than using the year of refurbishment or construction year when estimating the U-value. In cases for which the value year has no U-value specified for the building type, the average U-value is based on other building types for the time-period in question. Where there is an overlap of possible building types, tower block is chosen as it by definition excludes any other possibilities. Of the 32 age-type classes given in Table 1, 22 are used to assign an average U-value for the 433 buildings. This is sufficient since older buildings are rare in the portfolio of buildings, with only seven built before 1940.

2.5. Assumptions for non-building specific inputs

As building-specific input data are not available for all parameters required for modelling the energy demand, i.e. not present in EPC or geometrical data, remaining input data have been acquired using assumptions that are more general. In particular: internal heat gains, user behaviour related inputs and set-point temperature (21 °C) are specified according to national building industry standards for energy calculations [38], while ventilation flow rates are assumed to fulfil minimum hygienic standards according to the building code [39]. For buildings using heat pumps (49 buildings of the 433 in the portfolio), the coefficient of performance (COP) is assumed according to tests performed by the Swedish energy agency [40].

2.6. Validation by energy modelling of the building stock

In order to validate the differentiated description of the building stock, the energy use for SH and DHW is calculated using the defined description as input to the ECCABS model [35] and compared to measured energy consumption data on a portfolio level as well as on a building-by-building basis. Although measured data are given separately for SH and DHW in the EPC, they are not measured separately for any of the buildings in the portfolio, but rather divided based on the judgement of the energy expert performing the EPC. As such, results are presented as the sum of calculated and measured energy use for SH and DHW. In addition, a sensitivity analysis is performed for parameters that are uncertain and influential, similar to what has been identified in previous work [31,41]. As indicated above, the energy performance of the portfolio is modelled with the ECCABS model [37], where the energy performance of each building is modelled mathematically in Simulink/Matlab, as a linear explicit discrete time-variant system, based on the lumped system analysis approach. According to the classification of calculation procedures in ISO 13790 [42], the ECCABS model is detailed (hourly specification of the input data and the results) and dynamic (takes into account the thermal mass of the building at each time step). The accuracy of the ECCABS model has been validated by inter-model comparisons and empirical validations [37] and has been used

Table 1
Average U-values for the different building types according to construction period [W/m^2, K].

Construction period	Timber building	Brick building	Landshövdingehus	Slab block	Tower block	Large slab block	Courtyard building
–1905	1.10	1.20	1.00				
1905–1920	1.05	1.20	1.00				
1920–1930	0.95	1.20	1.00	1.35			
1930–1935	0.95	1.20	1.00	1.00			
1935–1940	0.95	1.20	1.00	1.00	1.10		
1940–1950	0.95			0.95	1.10		
1950–1955				0.95	1.10	1.00	
1955–1960				0.90	1.10	1.00	
1960–1965				0.70	1.25	0.95	
1965–1970				0.70	1.25	0.90	
1970–1975				0.70	0.85	0.90	
1975–1980				0.70	0.75	0.80	0.50
1980–1985				0.60	0.60	0.60	0.50
1985–2000				0.55	0.55	0.55	0.50
2000–2010				0.50	0.50	0.50	0.50
2010–2015				0.4	0.4	0.4	0.4

Table 2
Properties for matching the age-type classification in Table 1 to each building in the portfolio.

Building type	Attachment	Stories	Staircases	Construction period
Tower block	Detached	>2	1	1935–2015
Landshövdingehus	Attached/semi detached	3	1+	1880–1940
Brick building	Multiple	>3	Multiple	–1940
Large slab block	Detached/semi detached	>4	Multiple	1950–2015
Slab block	Detached/semi detached	2–4	1+	1930–2015
Timber building	Detached	2	0–1	–1950
Courtyard building	Attached	>3	Multiple	1975–2015

to model the energy performance of the Swedish building-stock [43,44] as well as that of various European countries [20,45].

3. Results

In this section, calculated and measured energy use for SH and DHW are first presented for the entire portfolio and second a building-by-building comparison is shown. Lastly, a sensitivity analysis is carried out to highlight the influence of parameters that are uncertain. Fig. 2 compares modelled and measured energy use for the portfolio (the sum of SH and DHW). While modelled and measured energy use on a portfolio level differ less than 3%, (modelled 136 GWh and measured 139 GWh), the difference for individual buildings can be significant.

The agreement for the portfolio is similar to what was obtained when comparing modelled and measured energy demand on a national building-stock level, using representative sample buildings. Figs. 3 shows the distribution of the margin of modelled to measured energy use in 0.1 intervals, normalized for number of buildings as well as m^2 HFA. As can be seen, there is a wide distribution in the ration of modelled to measured data where 52% of the HFA and 43% of number of buildings are within a 20% margin. Thus, the results also indicate that more accurate predictions of energy use are obtained for larger buildings as the accuracy is higher when comparing HFA rather than the number of buildings. As can be seen from Fig. 4, the deviations become even more apparent when applying energy use per m^2 HFA as basis for comparison between modelled and measured energy use. It is clear that the heating system has a significant impact where the calculated energy use for buildings with a heat pump is consistently underestimated. The opposite can be said for bio-based boilers where calculated energy use is consistently higher than measured energy use.

3.1. Sensitivity analysis

The COP of heat pumps and the indoor set-point temperature are known to be associated with the highest uncertainties of the data

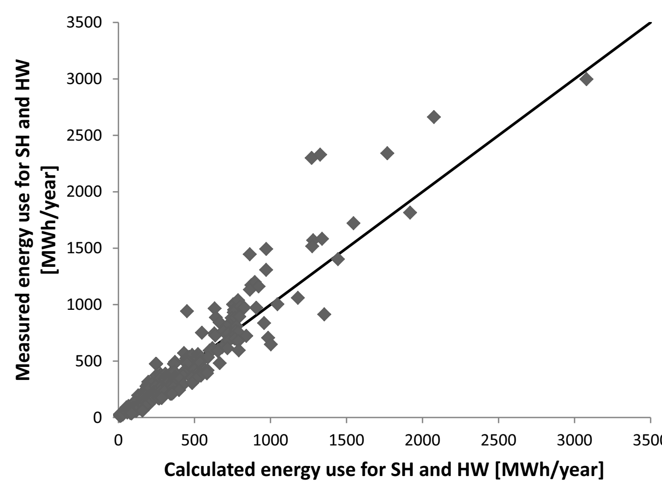

Fig. 2. Calculated and measured energy use for individual buildings (the sum of SH and DHW).

used in this work and therefore a sensitivity analysis is carried out for these two parameters. The COP of heat pumps is investigated according to Table 3 and evaluated for each of the 49 buildings using heat pumps. Out of the 49 buildings with a heat pump, nine have a ground-source heat pump, 34 have an exhaust-air heat pump and five have an air to water heat pump. Furthermore, the set point for indoor temperature is varied between 20 and 24 °C with the initial assumption being 21 °C and evaluated at a portfolio level, see Fig. 5. Although user behaviour has a large impact on the calculated energy performance of individual buildings, none of the data in the databases allows a characterization of the user behaviour and, thus, it has been omitted at this stage.

While the results for the initial assumption of a set-point temperature of indoor temperature of 21 °C show good agreement with measured consumption data, varying the set-point temperature between 20 and 24 °C show that a change in 1 °C has a 10% impact on

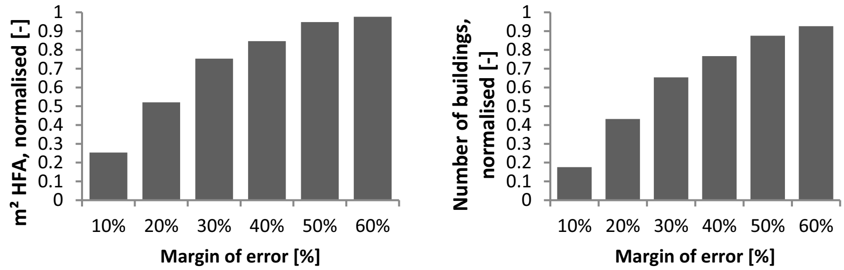

Fig. 3. Distribution of margin of error between calculated and measured energy use (sum of SH and DHW), normalized for m^2 HFA to the left and number of buildings to the right.

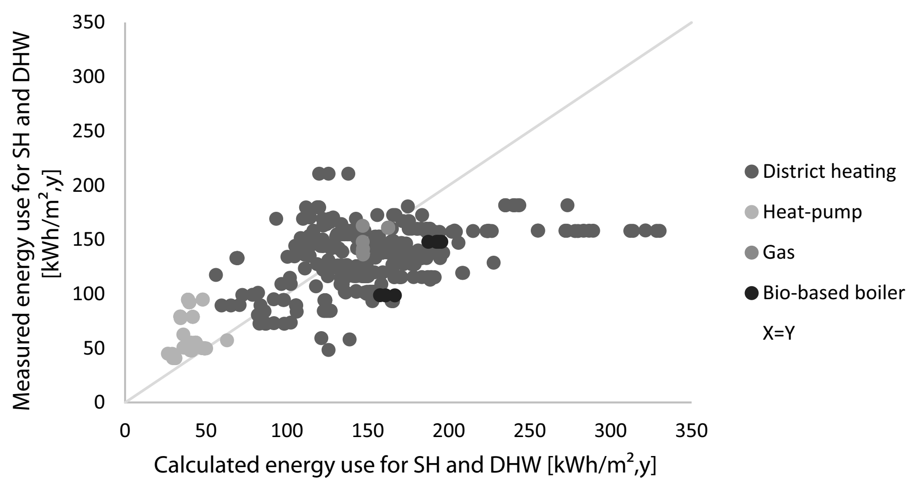

Fig. 4. Calculated and measured energy use per m^2 HFA grouped by heating system.

Table 3
Variation of COP for the different heat-pumps.

Heat pump	Initial COP	Variation 1	Variation 2	Variation 3
Exhaust-air heat pump	2.5	1.5	2	3
Air to water heat pump	2	1.5	2.5	3
Ground-source heat pump	3	2.5	3.5	4

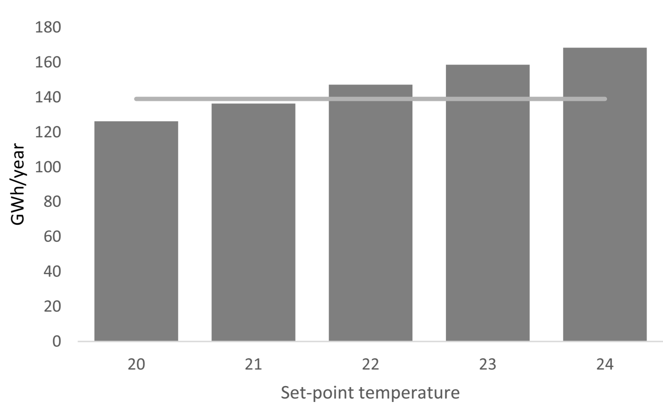

Fig. 5. Sensitivity analysis of change of set-point temperature with a line representing measured energy use for comparison.

the SH demand for the entire portfolio with only minor fluctuations for individual buildings.

Figs. 6 and 7 give calculated energy use against measured consumption for the 49 buildings with a heat pump where the assumption on COP is varied and results are normalized to allow for a better overview. As can be seen, the measured energy consumption differs significantly from calculated energy demand. For ground-source heat pumps and air to water heat pumps, the calculated energy use is consistently underestimated while exhaust-air heat pumps show a more inconsistent behaviour. As can be expected, variations of COP have a major impact on calculated energy use, but as the sample size is small and similar variations occur for buildings with district heating, it is not clear whether the assumptions on COP are exaggerated or if other factors such as user behaviour are the reason.

4. Discussion

Calculated energy use shows good agreement with measured energy use on a portfolio level and 43% of the buildings representing 52% of the HFA have a margin of error less than 20%. There are several possible explanations for the discrepancy between measured and calculated energy use on a building level. First, the reliability of the data can be questioned, both when it comes to values used as input as well as the measured energy consumption stated in the EPC. It is clear that the EPC in particular suffers from quality issues and while the most apparent errors relating to input have been dealt with (HFA), there are two main issues remaining concerning measured energy consumption given in the EPC. 1) Energy for SH and DHW is not measured separately for any of the buildings in the portfolio but rather separated based on the judgement of the energy expert. 2) For some properties that include several buildings of similar type and size, only one measuring point is used which is then divided based on the HFA of the buildings in question, which is the case for 165 of the buildings. This increases the risk that energy use which is not included in the calculation is included in the measured data such as district heating distribution losses or other end-uses not related to SH or DHW use such as engine heaters or

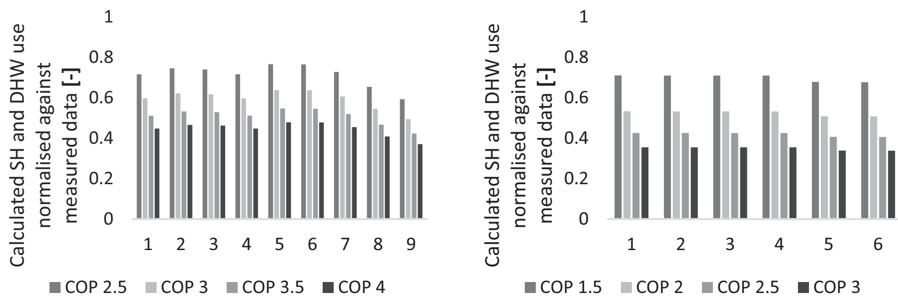

Fig. 6. Calculated energy use (sum of SH and DHW) normalized against measured consumption values for different assumptions on COP of ground-source heat pumps on the left and air to water heat-pumps on the right.

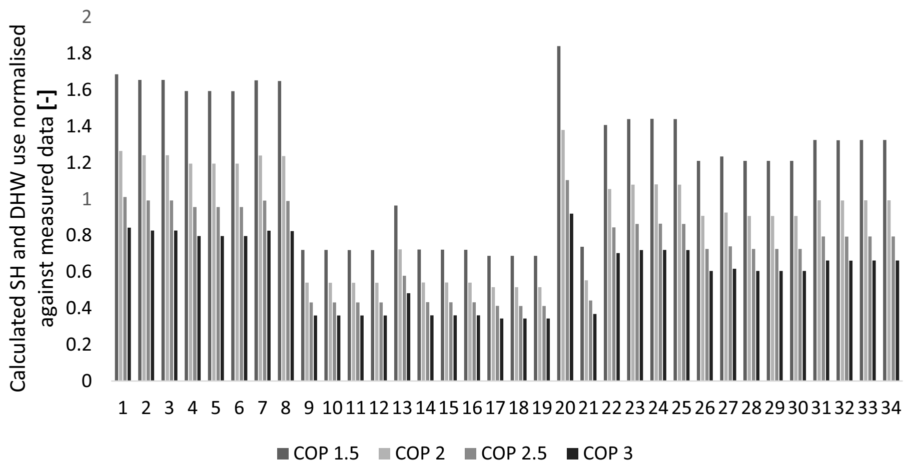

Fig. 7. Calculated energy use (sum of SH and DHW) normalized against measured consumption values for different assumptions on COP of exhaust-air heat pumps.

outdoor lighting which the energy expert would have to account for manually.

Second, part of the deviation between calculated and measured values may also be a result of the methodology used in this work to describe the buildings. In particular, there have been ten cases in the portfolio where a 2.5D geometry has not been sufficient to describe the geometry of a building. For future work there is a potential in using 3D-data together with a digital terrain model (DTM) to more accurately calculate the envelope area on a building level. Additionally, while average U-values have been assigned based on the age-type classification and the value year, using U-values for building components could further improve the accuracy for individual buildings.

Although all of the buildings in the portfolio are classified as residential buildings, it is common for multi-family dwellings to also host commercial activities (this is the case for 136 of the 433 buildings, on average 6.8% of total HFA), typically on the first floor. As the ECCABS model is configured as a lumped model (single-zone model), further improvements can be made by considering these activities when specifying internal heat loads or, to use a multi-zone model that can more accurately represent the actual conditions with the drawback of additional computational time required. The use of multi-zone modelling for building-stocks has previously been investigated for single-family dwellings in the UK [46] but further work is needed to also incorporate multi-family dwellings with mixed use.

The parameters chosen for the sensitivity analysis is similar to previous work that uses reference buildings [41] as well as sample buildings and a factorial sampling analysis as a basis for calibration [31]. It is clearly shown that indoor temperature and the COP of heat pumps have a major impact on results and further work is needed to overcome these uncertainties. While not addressed in this paper, the uncertainty of user behaviour and U-values based on value year requires further attention. Previous work has concluded that in order to better understand, communicate and describe uncertainties, local or building specific consumption data are needed [47]. Although the data set used in this study is unique in the sense that it contains measured energy consumption data on a building or property level, future improvements of how it is utilized could be accomplished by integrating a Bayesian calibration framework similar to what has been successfully implemented previously [31,48].

5. Conclusions

A methodology has been presented for describing urban residential building-stocks that allows a spatial resolution of individual buildings by using building specific data. The methodology consists of using building-specific data from the EPC and envelope areas from a 2.5D GIS-model to augment an age-type classification. The description is validated by comparing modelled data on energy use (the sum of SH and DHW) with measured data from a building portfolio of 433 buildings in the city of Gothenburg. While the description is able to reflect measured energy use on a portfolio level with calculated energy use being within 3%, further work is needed to reduce or quantify the uncertainty on a building level as 43% of building falls within a 20% margin of error. To this end, data needs and availability are not seen as the main hindrance for improving the accuracy on a building level with the exception for SH and DHW not being measured separately in the EPC. Rather, further improvements of the methodology can be made to increase the accuracy on a building level, specifically by forgoing average U-values as well as using a 3D GIS-model for envelope areas. In addition, calibration methods could be incorporated to quantify uncertainties. Future research areas have been identified, explicitly the major impact factors for the variation of COP of different types of heat pumps.

Acknowledgements

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