

# Development and validation of energy signature method – Case study on a multi-family building in Sweden before and after deep renovation

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## ABSTRACT

Building energy use constitutes a large part of total energy use, both in the European Union and Sweden. Due to this energy use, and the resulting emissions, several goals for energy efficiency and emissions have been set. In Sweden, a large portion of multi-family buildings were built between 1960 and 1980, which have major energy savings potential. The purpose of this paper is further development and validation of previously introduced energy signature method and its inherent parameters. The method was applied on a multi-family building where thermal energy data supplied by the district heating company was available before and after deep renovation. Using IDA ICE, a building energy simulation (BES) software model was created of the building, to aid in validation of the energy signature method. The paper highlighted the accuracy of the proposed energy signature (PES) method and a sensitivity analysis on the inherent parameters have been performed. The results showed new ways of treatment of the thermal energy data and revealed how more information can be extracted from this data.

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## 1. Introduction

The amount of energy used by buildings and their resulting contribution to greenhouse gas emissions has caused the European Union to set several goals for the energy use of buildings [1,2]. These goals also apply to the building stock in Sweden, where additional goals have been set for energy efficiency and CO<sub>2</sub> emissions [3]. Of the total energy used in Sweden in 2015, almost 39% was by the building and service sectors, in which half of the energy was used for space heating (SH) and domestic hot water (DHW) demand [4]. More than one-fourth [5] of multi-family buildings in Sweden were constructed from 1964 to 1974, in the so-called Million Program [6], when over a million housing units were built. Out of these million units, two-thirds were built as apartments in multi-family buildings [7]. Due to deterioration, these buildings are now in need of renovation, which also presents an opportunity to improve their thermal performance.

In Swan and Ugursal's [8] review, two main ways of studying the energy use of the residential sector were identified: top-down and bottom-up. In contrast to top-down methods, which considers entire sectors as energy sinks and does not differentiate between individual end users' energy use, bottom-up methods include all methods that use input data on a level that is lower than an entire sector and can account for individual end uses, buildings or groups of buildings [8]. The authors found two distinct bottom-up methodologies: statistical and engineering methods [8]. Fumo [9] stated that the method for studying a building stock depends on the type of data available: physical building characteristics versus statistical data. A major advantage of statistical methods is that, since these methods use real data, they account for the effects of occupant behavior [8]. In engineering methods, this behavior has to be modelled according to some assumptions, which can lead to a large gap between the predicted and actual energy use [10].

Zhang, O'Neill, Dong and Augenbroe [11] evaluated four statistical building energy use models: Gaussian process regression (GPM), Gaussian mixture regression (GMM), change-point (CP) regression model and artificial neural network (ANN), where CP models showed good performance. CP models, also called "energy signature" (ES) models, is a way to relate a buildings' energy use

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## Nomenclature

IDA ICE	IDA indoor climate and energy
BES	Building energy simulation
IHG	Internal heat generation
DH	District heating
DHW	Domestic hot water
DHWC	Domestic hot water circulation
ES	Energy signature
PES	Proposed energy signature
CV(RMSE)	Coefficient of variation of the root mean square error
NMBE	Normalized mean bias error
$R^2$	Coefficient of determination
SH	Space heating
$E_{tot}$	Percentage difference in total annual energy use
U-value	Heat transfer coefficient ( $W/(m^2 \cdot ^\circ C)$ )
$Q_{tot}$	Building total heat loss coefficient ( $W/^\circ C$ )
$Q_{transmission}$	Heat loss coefficient, due to transmission ( $W/^\circ C$ )
$Q_{ventilation}$	Heat loss coefficient, due to ventilation ( $W/^\circ C$ )
$Q_{infiltration}$	Heat loss coefficient, due to infiltration ( $W/^\circ C$ )
$V_{supply}$	Supply ventilation flow rate ( $m^3/s$ )
$V_{exhaust}$	Exhaust ventilation flow rate ( $m^3/s$ )
$T_b$	Balance temperature ( $^\circ C$ )
$P_{dhw}$	Domestic hot water demand (W)
$P_{dhwc}$	Domestic hot water circulation (W)
$P_{dh, sup}$	Supplied district heating to the building (W)
$P_{solar}$	Solar gains (W)
$P_{trans}$	Losses from construction parts (W)
$P_{vent}$	Ventilation losses (W)
$P_{infil}$	Losses by involuntary infiltration (W)
$P_{ihg}$	Internal heat generation gains (W)
$\eta$	Thermal efficiency of ventilation system heat exchanger (-)
$\rho$	Density ( $kg/m^3$ )
$C_p$	Specific heat capacity ( $J/(kg \cdot ^\circ C)$ )

to outdoor climatic variables [12]. Three parameters change-point models have been developed and tested in ASHRAE research project RP-1050, as the Inverse Model Toolkit (IMT), and has yielded accurate results [13–15].

An ES model can be used for an individual building that has heating and/or cooling requirements [16], or for the building stock of a city, as demonstrated by Anjomshoaa and Salmanzadeh [17]. Fumo and Rafe Biswas [18] believe that regression models should receive extra attention, since they are relatively easy to implement and require less computing power than other statistical methods, and as Zhang et al. [11] stated, these methods are simple, robust and accurate. Moreover, the method assesses parameters that characterize the physical properties of the building envelope as well as the operation of the heating/cooling system [16,19].

Time resolution is important when using measured data, as intervals of one hour or less can create problems with correlating the regression to the data, because of random disturbances such as occupancy behavior, ventilation rates and solar gains [20]. For small time intervals e.g. 1 h, it is necessary to use a dynamic model that can capture the random elements of the energy use [21]. Nonetheless, greater time intervals have also been used successfully. Some examples include Anjomshoaa and Salmanzadeh [17] and Park et al. [22], both of whom used monthly data, as well as Vesterberg et al. [23], who used smoothed data for every four days over two years.

The ES method has also been found to be reliable and to produce results agreeing with the real energy use. Ghiaus

[20] compared energy use calculated by regression to real energy data for five European cities, and found relative errors between –10.4 and 5.3%. Vesterberg et al. [23] found that the variations in transmission losses were less than 2% compared to real data. Kim and Haberl [16] used a calibration method on two single-family houses, and found that accuracy levels were acceptable according to ASHRAE (14-2014) guidelines. In [24], the ES method used and described in [16], was also utilized to study energy renovation potential in three single-family houses.

Vesterberg et al. [23] studied the robustness and accuracy of linear regression models on two houses in Umeå, Sweden. Data was collected for two years, and was then smoothed to every four days, suppressing some of the dynamic behavior of the building. The authors found that the measured data and regression model had high agreement, and concluded that their method can be a good way to improve building energy simulation accuracy, which was one of their purposes [23]. This work was continued in [19], where the calibration technique gave results that fell within the accuracy requirement. They [19] also wrote that the data can be collected in a non-intrusive way, which is preferable if the buildings under study are occupied. In a study conducted by Rohdin et al. [25], an ES method was developed using simple linear regressions, characterized by three parameters: balance temperature ( $T_b, ^\circ C$ ), DHW demand ( $P_{dhw}$ , W) and total heat loss coefficient ( $Q_{tot}$ ,  $W/^\circ C$ ). The statistical models described here could all be called inverse models, as described in [26], in that they use data about a building to estimate its physical properties.

The purpose of this paper is further development of previously introduced ES methods and analyzing the ES's inherent parameters. The accuracy of the predicted inherent parameters by ES methods is compared with building energy simulation (BES) software. In this case, IDA Indoor Climate and Energy (ICE) was used, and hereafter called BES. The method was developed by investigation of a case study building, a multi-family tower in Gävle, Sweden, where thermal energy data, based on hourly billing district heating (DH) metering, was available both before and after deep renovation. The novelty with the proposed method lies to a large extent within periodization of data for analysis: domestic hot water circulation (DHWC) and DHW losses are determined in periods with outside temperature higher than  $T_b$ , while  $Q_{tot}$  is determined using winter nighttime datasets, when outside temperature is lower than  $T_b$ . This type of periodization has not been studied earlier, since datasets are commonly based on one or more daily averaged values.

## 2. Case study building and energy efficiency measures

The building is situated in the city of Gävle (170 km north of Stockholm) in a district called Sättra, which was built during the abovementioned Million Program period. This district is a planned community according to the New Town Movement, and is a so-called “ABC-stad”, which translates to “Work-Residences-Center Community.” The district is intact from that period and has since 2011 been classified as a cultural heritage environment of national interest, known as “The White City.” Changes to the building exteriors are now greatly restricted and must conform to the original designs including surrounding, such as park areas. The building owner, AB Gavlegårdarna, has since the early 2000s renovated buildings in the area prior to the national interest status. The national interest status has affected use permits and costs of technical solutions for envelope improvements, e.g. balcony, render type and new window placement increased costs by 26% to make the façade appearance correct [27].

When performing energy efficiency measures, the ambition was to reduce the specific energy use by 50%. The specific thermal energy use of the building before renovation was 128.3 and



Fig. 1. Multi-family tower block in Gävle studied in this paper, real building (left) and BES model (right).

122.4 kWh/(m<sup>2</sup>·year), 2013 and 2014 respectively. After renovation (2018) it was 71.7 kWh/(m<sup>2</sup>·year). The vast majority of this decrease in energy use (average 43%) is due to the deep energy renovation that the building underwent, described in more detail below.

Built in 1965, the building consists of five stories with 27 apartments and an attic, Fig. 1. The heated floor area of the building was 2674 m<sup>2</sup> before renovation and 2830 m<sup>2</sup> after. The increase (6%) is due to heating of the attic, which contains storage space and technical equipment (ventilation and elevator system), where only the latter was formerly heated. The building has a DH substation on the ground floor, but has no air conditioning system. DHWC is used in the building to reduce the amount of time it takes for the occupants to receive hot tap water and to avoid growth of legionella.

Energy efficiency measures consisted of adding insulation to the external walls (80 mm) and roof (300 mm), changing the exhaust ventilation system to one with both supply and exhaust with heat recovery, as well as replacing windows and doors. The walls and roofing of previously unheated attic areas were upgraded, from being made of uninsulated wood to concrete with insulation. Flooring on the ground floor was also completely replaced, and after renovation consisted of a concrete slab with 100 mm EPS (Expanded Polystyrene) insulation underneath the slab. The DHWC piping was changed from only encompassing the ground floor, to being present on all floors, due to new building regulations. In December 2014, temperature gauges were installed in the hallway of each apartment, and access to this data was available.

As is the case for more than 90% of Sweden's multi-family buildings [28], this building is heated by DH. Thermal energy demand data was collected as kilowatt (kW) per hour, from 2013 to 2018, provided by the local energy company Gävle Energi AB (GEAB), in whole units. In 2014 the data contained five outliers and these outliers were removed when the data was used. For 2013, measurement data was missing for one day, April 29. The building underwent deep renovation in 2015 and 2016. Therefore, energy statistics for 2013 and 2014 represented a non-renovated building and 2017 and 2018 represented the renovated building. Climate files for these years were gathered from the Swedish Meteorological and Hydrological Institute. Household electricity use could not be gathered, due to the General data protection regulation (GDPR) but was given for a similar neighboring building as approximately 23.8 kWh/(m<sup>2</sup>·year). Table 1 summarizes information about the building.

DHW demand was provided by the building owner from 2009 to 2018, in m<sup>3</sup> per month. According to Swedish building regulations, DHW should be heated to a minimum temperature of 50°C, and the maximum temperature should be 60°C, in order to prevent the growth of legionella and to reduce the risk of scalding.

In this paper, it was assumed that incoming cold water was heated to the average of these, 55°C. This has also been confirmed by measurements on a similar building in the same area [32]. For the incoming cold water temperature, monthly average measurements performed in Stockholm [33] were used. This was used since the minimum and maximum incoming cold water temperature range from 4.5°C in February, to 16.0°C in August [33]. Infiltration rate had previously been measured in several apartments in two different similar buildings in other projects [34,35]. The values obtained from these Blower door measurements varied from 0.3 to 0.75 l/(s·m<sup>2</sup>) at 50 Pa pressure difference, where the area is the enclosing area of the depressurized zone, according to Swedish norms. *U*-values for windows (before renovation) were based on the assumption that an extra pane with low-energy film had been added to the original windows, and that the original windows were 2-pane with *U*-value of approximately 2.9 W/(m<sup>2</sup>·°C).

### 3. Methods for obtaining and validating energy signature parameters

#### 3.1. Description of energy signature parameters

One of the ways of obtaining ES parameters was developed by Rohdin et al. [25]. The results of this method, and its parameters, are shown as an example in Fig. 2. This method works by finding the highest R<sup>2</sup> value for *T<sub>b</sub>* between 10 and 20°C. The three param-

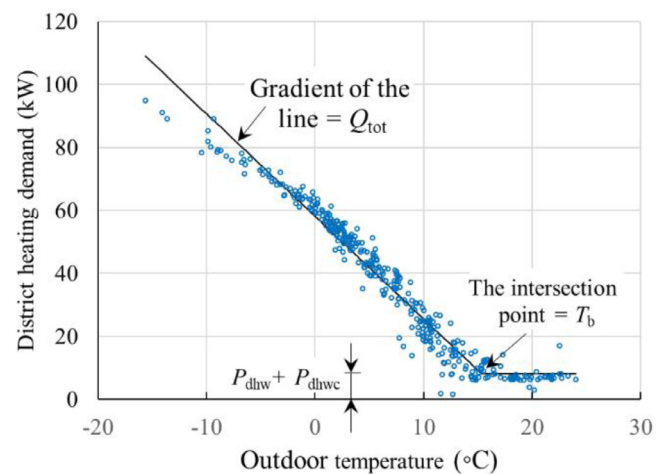


Fig. 2. Example of ES parameters as found by the ref [25] method. Note that measured values are shown as daily average values. The figure is presented in this way since it makes the parameters clearer and easier to see.

**Table 1**  
Summary of building information and how it was established, before and after renovation.

Parameter	Before renovation		After deep renovation	
	Value	Source/method	Value	Source/method
Indoor temperature	21 (°C)	Average measurements starting from 3 Dec 2014	22 (°C)	Average measurements over entire year
Ventilation air flows (supply/exhaust)	0/900 (l/s)	Property manager	900/1100 (l/s)	Measurements and property manager
Ventilation heat exchanger efficiency	–	–	25 to 90%	One year measurement by property owner
External walls bottom floor	0.87 W/(m <sup>2</sup> · °C)	Based on drawings	0.30 W/(m <sup>2</sup> · °C)	Based on drawings
External walls rest of building	0.52 W/(m <sup>2</sup> · °C)	Based on drawings	0.24 W/(m <sup>2</sup> · °C)	Based on drawings
Roof, attic	0.47 W/(m <sup>2</sup> · °C)	Based on drawings	0.14 W/(m <sup>2</sup> · °C)	Based on drawings
Roof, rest of building	0.22 W/(m <sup>2</sup> · °C)	Based on drawings	0.08 W/(m <sup>2</sup> · °C)	Based on drawings
Floor to ground	0.34 W/(m <sup>2</sup> · °C)	According to report [29]	0.32 W/(m <sup>2</sup> · °C)	Based on drawings
Doors and windows	2.1 W/(m <sup>2</sup> · °C)	Initially double-glazed windows with an additional pane.	1.1 W/(m <sup>2</sup> · °C)	Property manager
Number of occupants	51	Based on Swedish standard [30]	51	Based on Swedish standard [30]
Building facility electricity	9.2 kWh/(m <sup>2</sup> · year)	Measurement	15.3 kWh/(m <sup>2</sup> · year)	Measurement
Thermal bridges	Various linear thermal transmission coefficients	15–20% of total transmission losses [31]	Various linear thermal transmission coefficients	15–20% of total transmission losses [31]
Infiltration (at 50 Pa pressure diff.)	0.5 l/(s · m <sup>2</sup> ) (envelope area)	Average of Blower door measurements from different apartments	0.4 l/(s · m <sup>2</sup> ) (envelope area)	Average of Blower door measurements from different apartments
DHW demand	88,700/62,800 (2013/2014) (kWh/year)	Measured in m <sup>3</sup> per month	72,100 (kWh/year)	Measured in m <sup>3</sup> per month

eters in Fig. 2 are also used in the present study (hereafter called proposed energy signature (PES) method). The total heat loss coefficient,  $Q_{tot}$ , is the sum of losses by transmission, ventilation and infiltration, as shown in Eq. (1).

$$Q_{tot} = Q_{transmission} + Q_{ventilation} + Q_{infiltration} \quad (1)$$

$P_{dhw}$  represents the DHW demand of the building. Both in ref [25] and PES method, it is assumed that the DHW demand is equal all year around, thus representing an aspect of the building that is assumed to be independent of outside temperature. Finally,  $T_b$  represents the temperature where heating is needed ( $<T_b$ ) versus not needed ( $>T_b$ ).

### 3.2. Description of the PES method

The PES method is based on the power balance in Eq. (2), where the left side is power being added to the building, and the right side are power losses from the building, for outdoor temperatures below  $T_b$ .

$$P_{solar} + P_{ihg} + P_{dh,sup} = P_{trans} + P_{vent} + P_{infil} + P_{dhw} + P_{dhw} \quad (2)$$

where  $P_{solar}$  are solar gains,  $P_{ihg}$  are internal heat generation gains,  $P_{dh,sup}$  is the supplied DH to the building,  $P_{trans}$  are losses from construction parts,  $P_{vent}$  are ventilation losses,  $P_{infil}$  are losses by infiltration and  $P_{dhw}$  are losses by DHWC demand. For outdoor temperatures above  $T_b$ , the power balance is defined as Eq. (3).

$$P_{dh,sup} = P_{dhw} + P_{dhw} \quad (3)$$

As described in the introduction section, the purpose of this paper was to analyze the parameters of ES;  $Q_{tot}$ ,  $P_{dhw}$ ,  $P_{dhw}$  and  $T_b$ .  $P_{dhw}$  and  $P_{dhw}$  were investigated in periods where the outside temperature was higher than  $T_b$ .  $Q_{tot}$  was quantified during winters, December through February, when the outside temperature was lower than  $T_b$ . In this way,  $T_b$  is the center point of the method. With this,  $P_{dhw}$  and  $P_{dhw}$  are determined in non-heating periods, whereas  $Q_{tot}$  is determined in heating periods. This periodization of data, and using nighttime values

(Section 3.3), is considered by the authors to be one of the novel ideas of this paper. The process for quantifying these parameters is described in more detail in Sections 3.2.1 through 3.2.4.

Another key finding in the PES method, compared to ref [25] and other ES methods [16,18,21,22], is that PES is able to find DHWC demand. In ref [25], DHWC demand is included in DHW demand, as shown in the baseline in Fig. 2.

Fig. 3 shows an overview, first of how the BES model was validated, and then of the proposed method of finding ES parameters. The PES method starts by an initial value for  $T_b$ . This value is then used to calculate  $Q_{tot}$ ,  $P_{dhw}$  and  $P_{dhw}$ . With these parameters a new value for  $T_b$  can be found. The new  $T_b$  is then compared to the previous one, and the process is repeated until convergence is achieved. Note that the method does not include electricity demand.

#### 3.2.1. Total heat loss coefficient, $Q_{tot}$

$Q_{tot}$  represents losses by ventilation, infiltration and transmission, and can be expressed according to Eq. (4).

$$Q_{tot} = Q_{trans} + Q_{vent} + Q_{infil} \quad (4)$$

$Q_{tot}$  has the unit W/°C, being the slope of the gradient (see Fig. 2). Substituting  $Q_{tot}$  for building losses in Eq. (2) yields the power balance in Eq. (5).

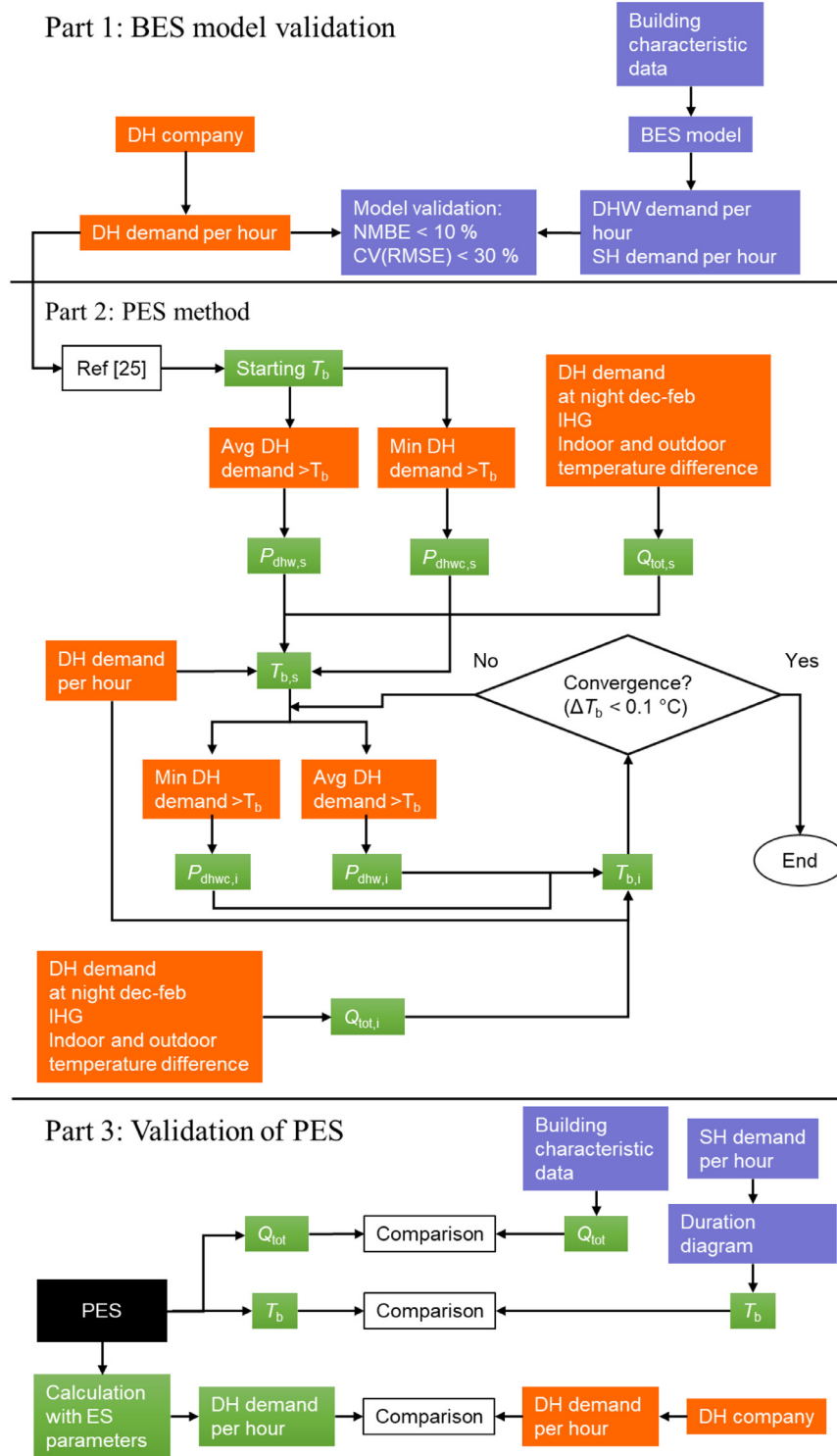
$$P_{solar} + P_{ihg} + P_{dh,sup} = Q_{tot} * (T_{indoors} - T_{outdoors}) + P_{dhw} + P_{dhw} \quad (5)$$

Rearranging Eq. (5) gives  $Q_{tot}$  as Eq. (6).

$$Q_{tot} = \frac{P_{solar} + P_{ihg} + P_{dh,sup} - P_{dhw} - P_{dhw}}{T_{indoors} - T_{outdoors}} \quad (6)$$

In Eq. (6), there are several parameters that are difficult to model and/or to measure;  $P_{solar}$ ,  $P_{ihg}$ ,  $P_{dhw}$  and  $P_{dhw}$ , and the proposed method in this paper thus tries to eliminate or minimize the influence of these parameters. This is achieved by quantifying  $Q_{tot}$  in cold periods with predominantly SH demand, no insolation and minimal IHG (internal heat generation), which in Sweden corresponds to nighttime (12:00 AM–5:00 AM) in December through





**Fig. 3.** Flowchart for validation of the BES model and the proposed method of finding ES parameters. Orange represents measured data, purple represents BES and green is for ES. Note that when  $Q_{tot}$ ,  $P_{dhw}$  and  $P_{dhw,c}$  are found again in the iterative process, the same inputs (DH demand, IHG (internal heat generation), temperature difference) are used. Subscripts s and i represent starting and iterative parameter, respectively.

February. Any occupied residential building, whatever time period is used, will have more or less IHG, and by studying nighttime values, its influence on  $Q_{tot}$ , is minimized.

Fig. 4 shows the average DH demand for all days from December through February, and it shows that during the night, the DH demand is relatively stable, and at its lowest level. In this paper, it is assumed that the only DH demand at night is SH and DHWC.

At normal operation, DHWC is the smallest amount of DH used by the building, and has been shown to be present year-round [36].

$Q_{tot}$  was calculated as the average value of each hour from 12:00–5:00 AM, December through February (in total 450 values). During these hours in Sweden, the building has a heating need, there is no DHW demand and the solar contribution to the building is zero. This means that Eq. (6) reduces to Eq. (7).

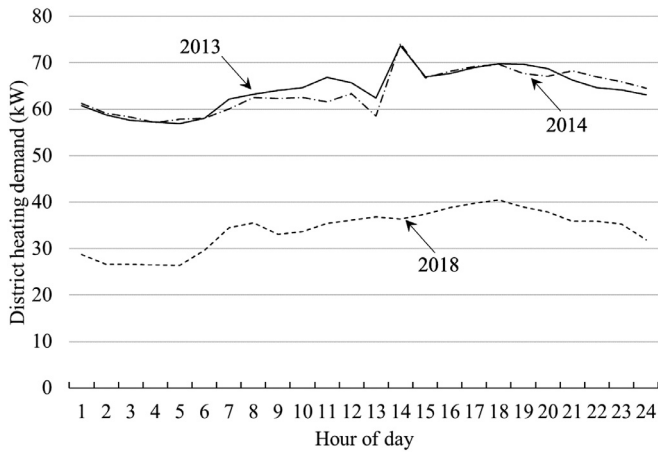


Fig. 4. Average DH (SH, DHW and DHWC) demand for all days from December through February, in 2013, 2014 and 2018.

$$Q_{tot} = \frac{P_{dh,sup} + P_{ihg} - P_{dhwc}}{T_{indoors} - T_{outdoors}} \quad (7)$$

where  $P_{ihg}$  was estimated and is described in this paragraph, and  $T_{indoors}$  as well as  $T_{outdoors}$  were based on measured values. Measurement for  $T_{indoors}$  in 2013 was not available, thus it was set to the same as in 2014. IHG was estimated with the assumption that the yearly household electricity (23.8 kWh/(m<sup>2</sup>·year)) that had been provided from another similar building, was evenly distributed over each day. To distribute this electricity use over the hours of each day, Widén et al.'s model [37] for apartments was adapted. The hourly electricity use was distributed in such a way that it resembled this figure, which gave electricity use at night to 2.9 kW, of which 70% was assumed to be converted into useful heating energy. Building facility electricity was assumed to be equal all year around, and values from Table 1 were used, where again 70% was assumed to be converted into useful heating energy. To also account for sleeping occupants, each family member was assumed to emit 60 W of heat, and the number of people was set to the same as in the model, 51 (Table 1). In 2013 and 2014 total IHG was 6.9 kW (2.58 W/m<sup>2</sup>) and in 2018 it was 9.1 kW (3.22 W/m<sup>2</sup>).

To investigate whether it is necessary to take effects of dynamic heat storage into account, two methods were proposed. Instead of using hourly for  $T_{outdoors}$ , the first method used average values over one day, two days and four days, in a similar way as in [23,38]. In the other method, the maximum and minimum outdoor temperatures for each day were evaluated. If they were more than

5°C apart, it was theorized that dynamic heat storage could have a significant impact on  $Q_{tot}$ , and thus these days were omitted.

### 3.2.2. Domestic hot water circuit demand, $P_{dhwc}$

According to measurements of DHWC in 12 Swedish multi-family households [39], DHWC losses can vary between 2.3 and 28 kWh/(m<sup>2</sup>·year). For the building in this paper, this corresponds to a value for  $P_{dhwc}$  between 0.7 kW and 8.3 kW. The method for finding  $P_{dhwc}$  is based on the assumption that when the outside temperature is higher than a building's  $T_b$ , the only DH demand will be DHW and DHWC. In this way, the method is a further development of the ref [25] method. Fig. 5 shows DH demand for the building in 2014, sorted by outdoor temperature and the rectangle shows roughly which area was studied when finding  $P_{dhwc}$  for this year. Note that since Fig. 5 displays 2014, outliers have been removed.

The PES method for determining  $P_{dhwc}$  has four steps:

- Find days that have at least one instance of outdoor temperature that is at a higher temperature than  $T_b$ .
- For these days, collect all hourly heating demand.
- Extract only the minimum demand on each day.
- Calculate  $P_{dhwc}$  by the average of all these minimum values.

### 3.2.3. Domestic hot water demand, $P_{dhw}$

$P_{dhw}$  was calculated as the average of all hourly DH demand, found at an outside temperature over  $T_b$ , similar to the way  $P_{dhwc}$  was calculated. To only calculate DHW demand,  $P_{dhwc}$  was subtracted.

### 3.2.4. Balance temperature, $T_b$

The balance temperature is formulated according to Eq. (8) [40]

$$T_b = T_i - \frac{P_{ihg} + P_{solar}}{Q_{tot}} \quad (8)$$

Substituting this in Eq. (2) gives Eq. (9) as.

$$P_{dh,sup} = Q_{tot} * (T_b - T_{outdoors})^+ + P_{dhw} + P_{dhwc} \quad (9)$$

$T_b$  was determined using Eq. (9), where values for  $T_b$  between 10 and 20°C were investigated, in steps of 0.1°C. For each temperature, energy use per hour was calculated using Eq. (9). In Eq. (9),  $P_{dh,sup}$  is the measurement provided per hour by the local DH company. It is the same as  $P_{dh,sup}$  in Eq. (2), and has been influenced by gains and losses from the building during a year. The plus sign above the parenthesis means that when the difference between  $T_b$  and  $T_{outdoors}$  was below zero, the first part of Eq. (9) was zero. For each  $T_b$  between 10 and 20°C, CV(RMSE) (Coefficient of variation of the root mean square error),  $R^2$  and percentage difference in total annual energy use (here called  $E_{tot}$ ), were calculated

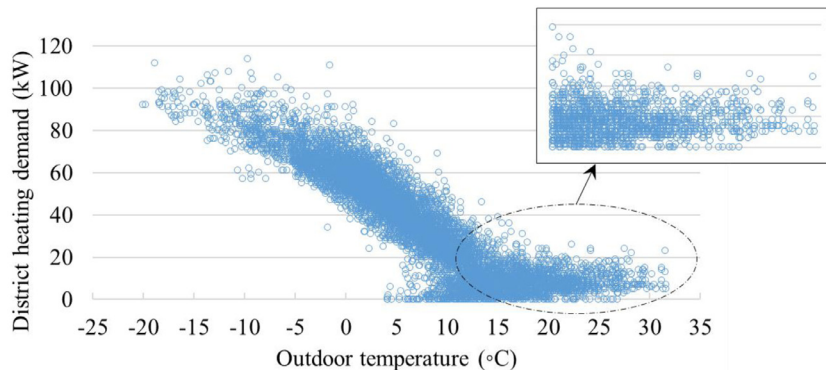


Fig. 5. Hourly DH demand sorted by outdoor temperature in 2014, with zoom-in on the area where  $P_{dhwc}$  was investigated.

and compared to statistics. These three statistical measurements were calculated for 2013, 2014 and 2018, and the resulting  $T_b$  that gave the best result on the three statistical measurement mentioned above, was assumed to be the  $T_b$  for that year.

### 3.3. Validation of energy signature parameters

Given that PES is a new method, it should also be validated using established methods. As mentioned previously, this was achieved by using IDA ICE version 4.8, which is called BES in this paper. BES is a simulation tool that can model thermal indoor climate and energy use of buildings [41]. It has been validated according to ASHRAE standard 140-2004, which found that BES performs on a similar level to other building energy simulation software [42]. The simulation software has also been used successfully by many researchers for varying purposes. Hesaraki and Holmberg [43] studied energy use and thermal comfort of five semi-detached houses that used low temperature hydronic heating, and found that the simulation and measurement results had small divergence. Hilliaho, Lahdensivu and Vinha [44] found that BES was effective when studying highly glazed areas, such as balconies. It has been used to study indoor environment and energy use on renovated and non-renovated multi-family buildings [45]. Salvalai [46] successfully used the same software to model the performance of a water-to-water heat pump. It has been shown to give accurate results when studying heat emission from hydraulic radiators [47]. Using the same software, Tuominen et al. [48] studied energy use of the whole Finnish building stock. Gustafsson et al. [49] found accurate results for annual energy use of a building identical to the one studied in this paper, and their purpose was to assess the influence of large-scale energy efficiency on the local DH system.

As described in Section 1, the drawback of a physical model, such as one made in BES, is that it relies on a large amount of descriptive input data. From another viewpoint, this is also an advantage, since it is possible to study the effects that different inputs have e.g. on energy use in a building.

A major benefit of BES is that the results are separated into SH and DHW demands. As shown in the last part of Fig. 3, the SH demand was used to make a duration diagram, in a similar fashion as in [45]. The duration diagram was used to find a value for  $T_b$ , by investigating when the difference between the temperature achieved by the heating system and the outside temperature was less than 0.1°C.

BES also gives results about the heating loss factor based on the input data that has been provided, meaning that  $Q_{tot}$  can be extracted as a value that is independent of factors such as IHG and DHW. This has been expressed in Eq. (1) (Section 3.1).  $Q_{transmission}$  is dependent on the inputs given in the BES model and could be retrieved from the result page in BES.  $Q_{ventilation}$  and  $Q_{infiltration}$  were calculated using Eqs. (10) and 11.

$$Q_{ventilation} = \dot{V}_{supply} * \rho_{air} * C_{p,air} * (1 - \eta) \quad (10)$$

$$Q_{infiltration} = (\dot{V}_{exhaust} - \dot{V}_{supply}) * \rho_{air} * C_{p,air} \quad (11)$$

where  $\dot{V}_{supply}$  is supply ventilation flow rate in m<sup>3</sup>/s,  $\dot{V}_{exhaust}$  is the exhaust ventilation flow rate in m<sup>3</sup>/s,  $\rho$  is air density which was set to 1.2 kg/m<sup>3</sup>,  $C_p$  is specific heat capacity of the air which was set to 1006 J/(kg·°C) and  $\eta$  is the thermal efficiency of the ventilation heat exchanger.  $\eta$  was set to 76%, which was calculated by weighing all values from the minimum outside temperature up to an assumed  $T_b$  of 12°C. It should be mentioned that using another  $T_b$ , such as 10°C, for this case yields a very small difference in thermal efficiency (<2%). In the non-renovated building model, ventilation losses are accounted for in infiltration losses, meaning that  $Q_{ventilation}$  is zero.

### 3.4. BES model of the studied building

The original model was developed by [50], and has been modified to represent the building under study. Data was acquired from the building owner (AB Gavlegårdarna) as well as previous studies that had been made on this or similar buildings [29,34]. An evidence-based approach was used when judging which input data should be used [51]. In November 2018, a visit was also organized to this and two similar buildings, to investigate the efficiency of the ventilation system heat exchanger. First, the non-renovated model was created and validated, and then renovation measures were applied to the same model. Much of the input data to the building model is shown in Table 1. Additional information is given in the paragraphs below.

The schedule for occupancy presence, their use of lighting and devices as well as their DHW use each hour, was made with adaptation of Widén et al.'s [37] model for apartments. To account for airing losses, 4.0 kWh/(m<sup>2</sup>·year) was added to the SH demand of the model results, according to Swedish standard [30]. For 2018, supply and exhaust ventilation temperatures were provided, and the thermal efficiency of the ventilation system was calculated as a dependency on outside temperature. The efficiency varied from 25 to 90%, and this dependency was put into the model. As stated in Section 2, household electricity was given for a similar neighboring building as approximately 23.8 kWh/(m<sup>2</sup>·year). This value was used as a starting point for input to the model and was changed both to higher and lower values, until the best model agreement was found. Before renovation the resulting delivered household electricity to the model was 10.9 kWh/(m<sup>2</sup>·year) and after renovation it was 13.0 kWh/(m<sup>2</sup>·year). These values are both lower than the measured value, which is feasible since the other similar building contains tenant-owned apartments, while the building studied in this paper contains rented apartments, and there is greater chance that tenant-owned apartments have higher household electricity use, according to Swedish statistics and peer-reviewed papers [52,53]. It was also known that from the average amount of rented apartments in 2014 (67%) the amount of rented apartment climbed to 100% at the start of 2018, which should result in relatively higher household electricity use.

Initial values for thermal bridges were set according to values from a previous study done on a similar building [35], and if needed these values were changed so that thermal bridge losses accounted for 15 to 20% of total transmission losses, according to experience on Swedish buildings [31]. The model was validated by NMBE (Normalized mean bias error) and CV(RMSE) [54] where accuracy requirements were 10 and 30%, respectively, according to ASHRAE guidelines [38]. Chakraborty and Elzarka [55] also suggest that  $R^2$  value can be used to determine that there is a relatively linear relationship between model and measurement results. Measurement on indoor temperature was used to investigate if there was a correlation between the outside temperature and inside temperature and if this had to be accounted for in the model. It was found that this correlation was weak, and annual average values were used for the indoor set point temperature.

## 4. Results

In this section, results of the BES model are first compared with statistics. This is followed by PES method results, information about its parameters, validation and sensitivity analysis of the PES parameters and finally duration diagram for 2013, 2014 and 2018.

### 4.1. BES model

Table 2 shows a summary of the agreement between the predicted BES results with the measured values of the build-

**Table 2**  
Summary of results of BES models.

Year	Before renovation		After renovation
	2013	2014	2018
NMBE	−0.9%	−1.0%	−0.9%
CV(RMSE)	24.8%	24.7%	31.2%
R <sup>2</sup>	86.9%	85.7%	72.1%
Specific thermal energy use [kWh/(m <sup>2</sup> · year)]	137.5	125.0	70.8
Diff. in specific energy use to statistics [kWh/(m <sup>2</sup> · year)]	9.2	2.6	3.2

ing energy use by highlighting the values for NMBE, CV(RMSE) and R<sup>2</sup>.

For 2018, Table 2 shows that the model does not meet the accuracy requirement of CV(RMSE), which should be lower than 30%. Because of this, CV(RMSE) and R<sup>2</sup> were also calculated in heating demand periods (September 15 to May 15) and periods without heating demand, in 2018. For the heating demand period CV(RMSE) was 26.6% and R<sup>2</sup> was 64.0% and for non-heating period CV(RMSE) and R<sup>2</sup> were 52.4% and 26.9%, revealing that after renovation the model has greater accuracy in the heating periods. Although renovation measures were finished in 2017, this year was not used in the analysis since the heating demand varied in an unreasonable manner during the year. It was known that at the start of 2017, 45% of the apartments were rented (occupied), while at the end of the year this had risen to more than 90%. The main reason for omitting 2017 was that this increase in occupancy presence was difficult to model in the BES model. The change in DH demand over the year also had a relatively large impact on  $Q_{tot}$  calculated by PES, depending on whether it was calculated at the start or the end of 2017. Other factors might also have contributed to the change in heating demand, e.g. adjustments in the new ventilation system.

Fig. 6 shows load curves for measured data and the BES models. For all three years, Fig. 6 shows that the models have better agreement during the heating period, versus the non-heating period, where the heating period is below approximately 6000 h.

#### 4.2. Results of PES

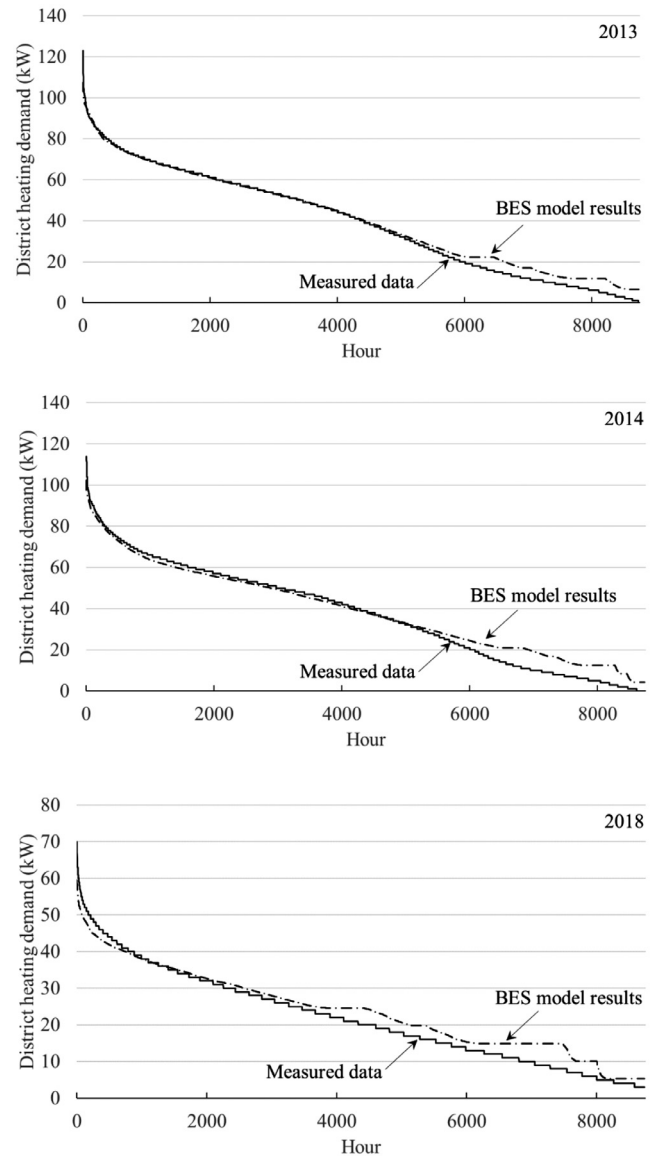
In Section 3.2.1, two methods were proposed to investigate if it is necessary to account for dynamic heat storage when calculating  $Q_{tot}$ . Results of this investigation are shown in Table 3, where it can be seen that the variation in  $Q_{tot}$  is small, roughly between 1 and less than 4%. As a result, in order to account for dynamic heat storage, one-day average values were used in all calculations.

Table 4 shows resulting PES parameters, when  $T_b$  has converged, as well as comparison parameters and results of ref [25]. Note that ref [25] does not separate DHW and DHWC losses, but they are included in the same parameter.  $Q_{tot}$  from BES input data was explained in Section 3.3 and  $T_b$  from BES duration diagram is shown in Section 4.3. No other data was available for  $P_{dhwc}$ , thus no comparison parameter is available.

**Table 3**

Relative comparison of  $Q_{tot}$  from using hourly values for  $T_{outdoors}$ , against using different methods of accounting for dynamic heat storage: average over 1–4 days and a maximum allowed difference in maximum and minimum temperature over each day.

	2013	2014	2018
Hourly values	1.00	1.00	1.00
1–day average	1.02	1.01	1.02
2–day average	1.02	1.01	1.01
4–day average	1.02	1.01	1.02
Max 5°C difference in temperature	1.03	1.03	1.00



**Fig. 6.** Load curves for the BES models and the measured data for 2013, 2014 and 2018.

In addition to comparing the PES parameters against other sources, these parameters were used to calculate DH demand per hour (Eq. (9)). This was then compared to measurement using the same three statistical measurements; CV(RMSE), R<sup>2</sup> and  $E_{tot}$ . Results of this are shown in Table 5. Table 5 shows that the PES method has similar results as the BES models, in that CV(RMSE) is above 30% for 2018. It is presumed that this is for the same reason as the BES model, and that DHW demand creates the largest discrepancies between the model and statistics. Table 5 also shows



**Table 4**

All results of PES method, as well as comparison results from other sources and ref [25]. For PES, the three headings, CV(RMSE),  $R^2$  and  $E_{tot}$ , refer to the methods of finding its parameters.  $Q_{tot}$  is shown with two decimal places to aid in comparison between the methods.

		PES			Comparison parameters	ref [25] parameter values
		CV(RMSE)	$R^2$	$E_{tot}$		
$P_{dhwc}$ (kW)	2013	2.9	2.9	2.9	–	–
	2014	2.5	3.0	2.5	–	–
	2018	3.7	3.9	3.7	–	–
$P_{dhw}$ (kW)	2013	8.5	8.5	8.5	AB Gavlegårdarna 10.1	–
	2014	6.3	5.9	6.3	7.2	–
	2018	8.6	8.5	8.6	8.2	–
$P_{dhwc} + P_{dhw}$ (kW)	2013	11.4	11.4	11.4	–	11.4
	2014	8.8	8.9	8.8	–	8.8
	2018	12.3	12.4	12.3	–	12.3
$Q_{tot}$ (kW/°C)	2013	2.80	2.80	2.80	BES input data 2.98	2.82
	2014	2.90	2.90	2.90	2.98	3.24
	2018	1.44	1.44	1.44	1.48	1.57
$T_b$ (°C)	2013	15.2	15.1	15.2	BES duration diagram 14.8	15.1
	2014	16.2	14.9	16.2	15.4	14.9
	2018	11.3	10.5	11.3	11.1	10.5

**Table 5**

Statistical agreement of energy use per hour calculated using the PES parameters, against measured DH demand. The table should be read from top to bottom, hence the coloring.

	PES parameter established with CV(RMSE)	PES parameter established with $R^2$	PES parameter established with $E_{tot}$
2013			
Deviation quantified with CV(RMSE)	25.7%	25.7%	25.7%
Deviation quantified with $R^2$	83.8%	83.8%	83.8%
Deviation quantified with $E_{tot}$	0.2%	-0.4%	0.2%
2014			
Deviation quantified with CV(RMSE)	29.0%	30.1%	29.0%
Deviation quantified with $R^2$	81.2%	81.4%	81.1%
Deviation quantified with $E_{tot}$	-0.5%	8.4%	-0.5%
2018			
Deviation quantified with CV(RMSE)	35.4%	35.8%	35.4%
Deviation quantified with $R^2$	63.4%	63.5%	63.4%
Deviation quantified with $E_{tot}$	1.7%	4.6%	1.7%

that using CV(RMSE) or  $E_{tot}$  parameters yields the same and the best results.

#### 4.2.1. Sensitivity analysis of PES results

In the method developed in this paper, a measured value for household electricity was used, 23.8 kWh/(m<sup>2</sup>·year). This makes it necessary to examine if the method is valid if measurements could not have been obtained. In this case, the authors would have used the Swedish household norm for household electricity of 30 kWh/(m<sup>2</sup>·year) [30], where 70% was assumed to become useful heating and the method of distributing electricity use over the day described in Section 3.2.1 was used. This is an increase in household electricity of 25%, which has a direct impact on  $Q_{tot}$ , but since  $Q_{tot}$  is important parameter in PES method, it will also affect all other parameters. The predicted difference in  $P_{dhwc}$  was between -2.44 and 0%, for  $Q_{tot}$  between -1.95 and -0.78%, for  $P_{dhw}$  between 0 and 1.24% and for  $T_b$  between 0 and 1.80% by implementing the Swedish household norm for household electricity instead of the measured value. The maximum and minimum values presented in the previous sentences are the maximum and minimum values for 2013, 2014 and 2018, respectively. Because of this limited effect on the parameters, it can be said that the method would have worked just as well if household electricity measurement could not have been assessed.

$P_{dhw}$  and  $P_{dhwc}$  both depend on  $T_b$ , thus an analysis was made to see how sensitive they are to changes in  $T_b$ , see Table 6. The change in  $T_b$ ,  $\pm 2.5^\circ\text{C}$  was based on Karlsson, Roos and Karlsson's

[56] analysis of what parameters have the biggest impact on  $T_b$ , in residences. They found that IHG has the biggest impact on  $T_b$ , and for their minimum and maximum values for IHG,  $T_b$  varies from approximately 12.5 and 17.5°C. This 5°C difference was assumed to induce a variation in  $T_b$  of  $\pm 2.5^\circ\text{C}$ .

It was also investigated what impact the number of people and their contribution of IHG have on  $Q_{tot}$ . A 10% difference in the number of people gave changes in  $Q_{tot}$  of 0.5 and 0.8%, before and after renovation.

#### 4.3. Balance temperature, $T_b$ , predicted by BES and PES method

Fig. 7 shows duration diagram for outside temperature and the contribution of SH to the building for 2013, 2014 and 2018. This has been obtained by dividing the hourly SH demand by  $Q_{tot}$  from input data (2.98 and 1.48 kW/°C, Table 4). In this case, both SH demand and  $Q_{tot}$  are given by the BES model, as shown in Eq. (12).

$$T_b = \frac{SH \text{ demand}_{BES \text{ model}}}{Q_{tot, BES \text{ model}}} \quad (12)$$

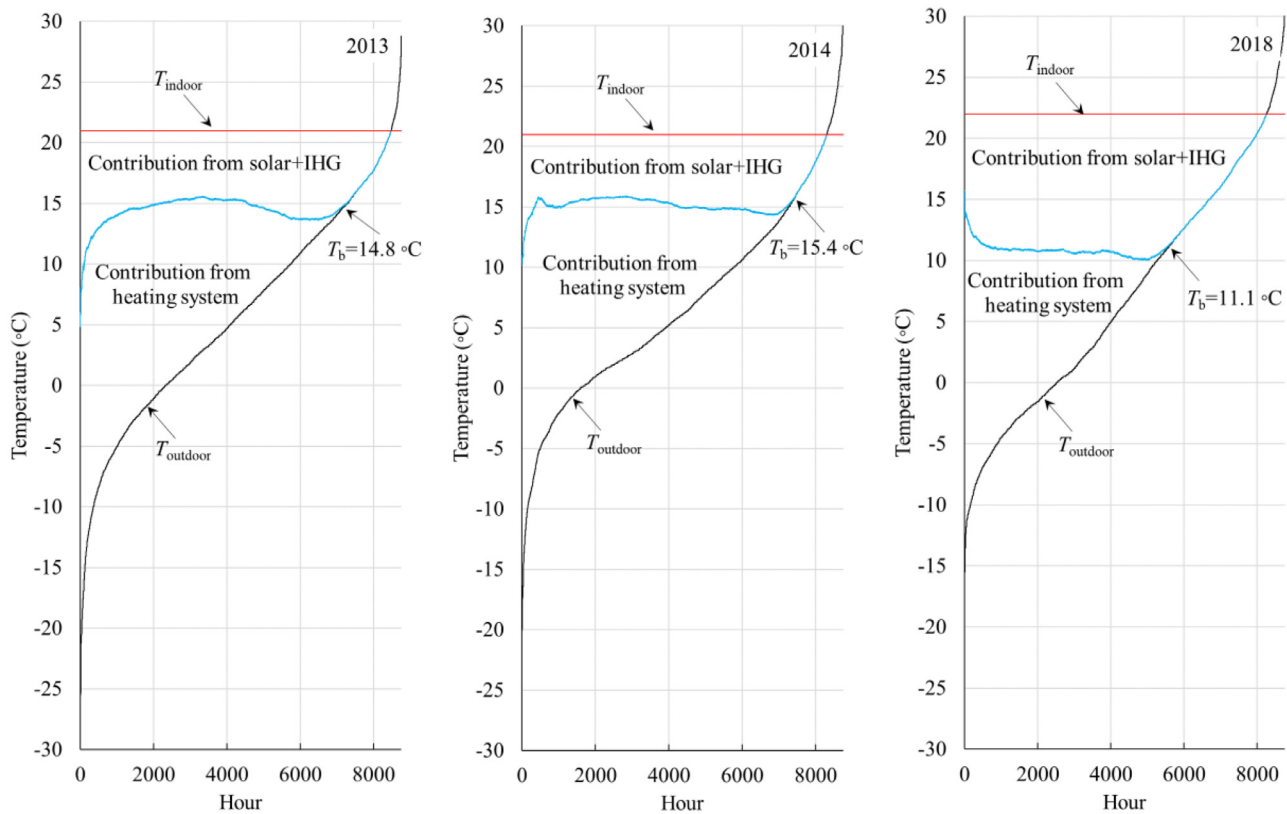
where SH demand is the sum of losses by transmission, ventilation and infiltration, considering contributions from solar gains and IHG. Overheating is not present in Fig. 7, since it was not relevant for the present study. Fig. 7 shows that  $T_b$  is approximately 14.8, 15.4 and 11.1°C, 2013, 2014 and 2018, respectively. The corresponding PES values are 15.2, 16.2 and 11.3°C.

**Table 6**Analysis of how sensitive  $P_{dhw}$  and  $P_{dhw}$  are to changes in  $T_b$ , 2013, 2014 and 2018.

Relative temperature to $T_b$ ( $\Delta T$ )	2013			2014			2018	
	$P_{dhw}$ (kW)	Increase in $P_{dhw}$ from $\Delta T = 0^\circ\text{C}$		$P_{dhw}$ (kW)	Increase in $P_{dhw}$ from $\Delta T = 0^\circ\text{C}$		$P_{dhw}$ (kW)	Increase in $P_{dhw}$ from $\Delta T = 0^\circ\text{C}$
-2.5	4.1	41%		3.2	28%		4.3	16%
-2	3.6	24%		3.1	24%		4.2	14%
-1.5	3.3	14%		3.0	20%		4.1	11%
-1	3.2	10%		2.7	8%		3.9	5%
-0.5	3.1	7%		2.6	4%		3.8	3%
0	2.9	0%		2.5	0%		3.7	0%
0.5	2.8	-3%		2.4	-4%		3.6	-3%
1	2.7	-7%		2.2	-12%		3.6	-3%
1.5	2.6	-10%		2.1	-16%		3.5	-5%
2	2.6	-10%		1.9	-24%		3.5	-5%
2.5	2.3	-21%		1.8	-28%		3.5	-5%

Relative temperature to $T_b$ ( $\Delta T$ )	2013			2014			2018	
	$P_{dhw}$ (kW)	Increase in $P_{dhw}$ from $\Delta T = 0^\circ\text{C}$		$P_{dhw}$ (kW)	Increase in $P_{dhw}$ from $\Delta T = 0^\circ\text{C}$		$P_{dhw}$ (kW)	Increase in $P_{dhw}$ from $\Delta T = 0^\circ\text{C}$
-2.5	7.1	-16%		6.2	-5%		8.2	-5%
-2	7.4	-13%		6.1	-6%		8.2	-5%
-1.5	7.8	-8%		6.0	-8%		8.3	-3%
-1	7.9	-7%		6.3	-3%		8.4	-2%
-0.5	8.2	-4%		6.3	-3%		8.5	-1%
0	8.5	0%		6.5	0%		8.6	0%
0.5	8.6	1%		6.5	0%		8.7	1%
1	8.9	5%		6.5	0%		8.8	2%
1.5	9.0	6%		6.6	2%		8.9	3%
2	9.3	9%		6.8	5%		9.0	5%
2.5	9.7	14%		6.9	6%		9.1	6%

**Fig. 7.** Duration diagram for the BES model, 2013, 2014 and 2018. Shows how much the heating system contributes to heating the building, relative to outside temperature and the  $T_b$ .

## 5. Discussion

As far as the authors know, it is uncommon to have access to energy data both before and after deep renovation, and to be able to apply an ES method in both cases. In this paper, after the building has undergone deep renovation,  $T_b$  and other ES parameters are more sensitive to variations in IHG, which also means that there is a need for more accurate prediction of IHG. This is shown in the sensitivity analysis, where changes in IHG yield larger changes in  $Q_{tot}$ . The decrease in  $Q_{tot}$  and  $T_b$  after renovation also means that occupancy behavior will have a larger impact on all results and parameter values. To improve the performance of the PES method, it should be applied to other buildings, both of the same and different kinds of buildings than the one used in this paper. DH measurements were given as both SH and DHW demand, and were not separated. One future measure should be to install a separate meter for DHW.

The BES model is shown to have good agreement compared to statistics, with the exception of 2018 (Table 2), where DHW demand during summer causes larger discrepancy between model and measurement. In the non-heating period, DHWC and especially DHW dominate the DH demand, and in this paper these factors have been found to be challenging to model with available data. In large part this is because DHW demand is dependent on occupant behavior, and the DHW demand varies for different people [57], and is dependent on the number of occupants [58–60]. George, Pearre and Swan [60] found that for 119 homes, while there was a predictable pattern of DHW use, with peaks in the morning and in the evening, there were also homes that did not follow this trend. They also found that DHW demand had a weekly as well as a seasonal variation [60]. This dependency can be seen, not only in 2018, but for all years in the load curves (Fig. 6), where the models have greater accuracy below approximately 6000 h. In Fig. 6 it can also be seen that the BES model has a step-wise behavior in the non-heating period. This is due to how BES models DHW use in a building, which is set as levels between 0 and 100% for each hour of the day. To model the occupant's DHW and household electricity use over each day, the work of Widén et al. [37] has been used. This is considered a good method to model these behaviors, since in [37] the data was high resolution and had been validated against a relatively large sample size, as well as having the advantage of having taken place in Sweden.

There are a few input variables and factors in the BES model, which have necessitated some estimations or assumptions.  $U$ -values for the non-renovated model have been based on drawings from the construction phase of the building, which took place in the 1960s. DHW demand has been measured each month, and in  $m^3$ , where estimations have been made on the heating need of the incoming cold water. Measurement on household electricity use have not been available for the studied building, but for a neighboring similar building. As shown in the sensitivity analysis (Section 4.2.1), changes in household electricity use has a relatively small impact on the results.

The method for finding  $P_{dhw}$  is a further development of ref [25] method, and this type of linear regression has been shown to be a valid method to estimate a building's thermal performance [20,22,23]. The results for  $P_{dhw}$  are in good agreement with measurement on other buildings in Sweden [39]. To improve the validity of this method, measurements should be carried out.

Table 4 shows that for  $Q_{tot}$ , PES is close to the BES input data. For 2014, PES also shows results that are closer than the ref [25] method, suggesting that this new method yields results for  $Q_{tot}$  that are closer to what  $Q_{tot}$  is meant to represent: the heat loss coefficient of a building envelope, independent of occupant behavior and insolation. In 2013 and 2018, it is not possible to say whether the PES method of finding  $Q_{tot}$  yields a better result

than the one by the ref [25] method, using only one decimal point (see Table 4). Despite the model not agreeing to the accuracy requirement for the whole year in 2018 (see Table 2), the  $Q_{tot}$  based on BES input data is considered valid, since  $Q_{tot}$  is relevant in the heating period of the building's operation, and for this period the BES model was found valid. Since  $Q_{tot}$  is calculated at night, the PES method has the advantage of being under minor influence of IHG. The sensitivity analysis also showed that  $Q_{tot}$  is insensitive to changes in household electricity use, which constitutes a large part of IHG.

For  $P_{dhw}$ , PES results for all years deviate from the measured (AB Gavlegårdarna) by between 3.7 and 18.1%. Combining  $P_{dhw}$  and  $P_{dhw}$  yields PES results that are basically identical to ref [25]. The PES method assumes that the DHW demand is constant all through the year, when in reality DHW is changing from hour to hour, day to day and season to season. To improve the results, and to validate the method further, it could be investigated if there are other buildings in the same city that have available DHW data for every hour. Another way would be to perform an additional measurement for DHW. With these data it could be possible to develop a more advanced model for DHW demand, although this was not the purpose of this paper.

As for the sensitivity of  $P_{dhw}$  and  $P_{dhw}$ , Table 6 shows that they are insensitive in the range of  $T_b \pm 2.5^\circ\text{C}$ . Table 6 also shows that for both  $P_{dhw}$  and  $P_{dhw}$ , results are comparatively less sensitive in 2018. The thermal energy data provided by GEAB was rounded to whole numbers, which creates some uncertainty when investigating  $P_{dhw}$  and  $P_{dhw}$ . As Fig. 5 shows, when calculating  $P_{dhw}$  and  $P_{dhw}$ , a large portion of the values used are below 10 kW, and at these low levels rounding to whole numbers can make a relatively large difference. This uncertainty could be alleviated to a great extent using one decimal point in the measurement of DH demand.

Results predicted by PES method for  $T_b$  are in good agreement with the values given by the BES duration diagram. They are also closer to BES results than  $T_b$  calculated by ref [25]. Table 4 shows that  $T_b$  is roughly one degree higher in 2014 compared to 2013. It was known that the number of rented apartments was declining from the first day to the last day of 2014, thus it is reasonable that the number of rented apartments, and by extension number of occupants, was even higher in 2013. This can explain some of the difference in  $T_b$  between these two years.

With some exceptions, results show that using CV(RMSE) or  $E_{tot}$  to find PES parameters yields the same parameter values, while  $R^2$  gives different results (see Table 4). Apart from  $P_{dhw}$  in 2014 the difference between the method results are less than 10%. If one of these should be chosen to represent the PES method, Table 5 shows that using parameters established either with CV(RMSE) or with  $E_{tot}$  gives results that are comparatively closer to measured DH demand. This is also supported by CV(RMSE) and  $E_{tot}$  having  $T_b$  closer to BES duration diagram, compared to  $R^2$ .

The studied building underwent deep renovation with the ambition to reduce the specific energy use with 50%. Based on statistics, the renovation was close to succeeding, since the thermal energy use prior to renovation was 128.3 kWh/( $m^2 \cdot \text{year}$ ) for 2013, down to 71.7 kWh/( $m^2 \cdot \text{year}$ ), in 2018, after renovation. By studying the PES parameters, there is no actual need to perform simulations with normalized occupants and climate data. A comparison of  $Q_{tot}$ , from PES, shows 2.80 and 1.40 kW/ $^\circ\text{C}$  before and after renovation. With a reduction of the value for  $T_b$ , from 15.2 $^\circ\text{C}$  to 11.3 $^\circ\text{C}$ , Eq. (9) indicates a substantial reduction in DH which compensates transmission losses. As for the DHW and DHWC losses, after renovation they apparently had a slight increase. This increase was not due to change in occupant habits ( $P_{dhw}$ ), instead owing to changes in the DHWC distribution system, which was extended from previously only being installed in the basement, to

every story; obviously increasing  $P_{\text{dhw}}$ . The increase in DHW and DHWC total losses is 8%.

## 6. Conclusions

The purpose of this paper was to develop a new method of finding energy signature parameters, based on a three-parameter change-point linear model. The parameters were total heat loss coefficient ( $Q_{\text{tot}}$ ), domestic hot water demand ( $P_{\text{dhw}}$ ) and balance temperature ( $T_b$ ). To accomplish this, district heating demand for a multi-family building in Sweden was investigated, both before and after deep renovation, as well as taking advantage of a BES (IDA ICE) model of the same building, for validation purpose. To fulfill the purpose of the paper, it was also necessary to develop a method to find domestic hot water circulation demand ( $P_{\text{dhw}}$ ). The developed method (called PES, proposed energy signature) works in an iterative manner, where  $T_b$  is the convergence parameter.

$T_b$  is considered the center point of the PES method, since  $Q_{\text{tot}}$  was quantified in winter months (December through February), when outside temperature is lower than  $T_b$ , and  $P_{\text{dhw}}$  and  $P_{\text{dhw}}$  were found in periods when the outside temperature was higher than  $T_b$ . In addition to this,  $Q_{\text{tot}}$  was quantified at night (12:00 AM–5:00 AM), in order to eliminate or minimize the influence of unknown parameters such as solar gains and internal heat generation. In using nighttime values and the periodization of data, this paper demonstrates alternative ways to investigate energy signature parameters, and how to deduce more information about a building's operation using measured data. The authors considers this to be the main novel ideas of this paper.

It was also investigated if it is necessary to account for dynamic heat storage for prediction of  $Q_{\text{tot}}$ , and the results showed that this was not the case. As for the sensitivity of the method, increasing household electricity by 25% only changed all the previously mentioned parameters by between  $-2.4$  and  $1.8\%$ , showing that the method is insensitive to changes in household electricity.  $P_{\text{dhw}}$  and  $P_{\text{dhw}}$  were determined relative to  $T_b$ , and they were found to be insensitive to changes of  $T_b$  within the interval of  $\pm 2.5^\circ\text{C}$ .

It was found that the BES model and the PES method have good agreement, though less so after deep renovation. This was believed to have been caused by an increased sensitivity to internal heat generation and domestic hot water consumption patterns.

## Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

## CRediT authorship contribution statement

**Martin Eriksson:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Jan Akander:** Methodology, Software, Validation, Investigation, Writing - review & editing. **Bahram Moshfegh:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision, Funding acquisition.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.enbuild.2020.109756](https://doi.org/10.1016/j.enbuild.2020.109756).

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