Exploring the effects of a warmer climate on power and energy demand in multi-family buildings in a Nordic climate

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ABSTRACT

The need to understand how a warmer climate affects the power and energy demand in cold countries is important for urban planners and policymakers. By using data from utility bills that are commonly available today, together with outdoor temperatures, it is possible to analyze historical and future power and energy demand. The scientific value of this research includes the development of a methodology to explore effects on future heat demand in the Nordic region based on a combination of historical data, building properties, and predictions of future climate. This is achieved by using an energy signature model and regression analysis. Seventy multi-family buildings in Linköping, Sweden, are investigated from 1980 to 2050. The results show that the effects from historical variations in internal heat gains (average annual increase of 1 %) on the specific energy use for space heating (SPH) is minor for the district, i.e., less than 2 % when comparing 2020 and 1980. The opposite is found for variations in outdoor temperatures, where the average specific energy use is predicted to decrease by about 25 % in 2050 compared to 1980, with the used forecast of future climate. This corresponds to a decrease from 127 kWh/(m²·year) to 93–96 kWh/(m²·year). Additionally, the maximum heating power demand of the district is predicted to decrease by about 30 %, from 4,855 kW in 1980 to 3,468 kW in 2050. In conclusion, our results demonstrate a strong effect of decreased SPH and heating power demand in residential districts due to a warmer climate.

1. Introduction

1.2. Background

The ongoing climate change is one of the most pressing issues of our generation. To address this topical issue, the United Nations formed Agenda 2030 (United Nations, 2021), which highlights the transition to sustainable cities and communities as its key focus for the future. The built environment is responsible for 40 % of final energy use and 36 % of CO2 emissions in the EU (European Commission, 2020), making it a significant contributor to climate change. In a Swedish context, it is of special interest to study the energy use related to heating in multi-family buildings. The reasons for this are twofold: as stated in an investigation performed by Rise Research Institutes of Sweden AB (RISE), many multi-family buildings are in need of renovation (The Swedish Government, 2019), and due to the long heating season in a Nordic climate. The energy use for space heating and hot tap water in multi-family buildings is about 20 % (29 TWh) of the total energy use from the residential and service sector (Swedish Energy Agency, 2022b).

Today, we are witnessing shifts in weather patterns due to climate change (IPCC, 2021). (Ciancio et al., 2020) emphasize that changing climatic conditions are expected to have a drastic impact on the future energy demands of the building stock. The International Panel on Climate Change (IPCC) estimates that greenhouse gas emissions from human activities have increased global temperatures by 1.1 °C since 1850–1900 (IPCC, 2021). In addition, the IPCC highlights that the average global temperature is predicted to increase by 1.5 °C or more over the next 20 years. Higher outdoor temperatures are correlated with a decrease in heat demand. This means that the changing ambient climatic conditions will also impact the heat generation from energy utilities. Hence, predicting future energy use in the built environment can assist in constructing a reliable, robust and correctly designed energy system. Another key aspect in predicting energy demand involves providing decision-makers with opportunities to develop standards for energy efficiency in the building sector (Sun et al., 2020). However, it is important to be aware that predicting future building energy use is a multifaceted challenge. Apart from ambient climatic conditions, other

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parameters affecting energy use in the built environment include the pace and design of energy renovation, occupancy density, and behavior. All these parameters have fluctuated historically and consequently affected energy usage in the building stock. Researchers have not treated this topic in much detail due to lack of historical energy supply data, which is especially the case in residential buildings (Wang and Srinivasan, 2017). However, with the current digital transformation in society together with the growing availability of digital energy data, the impact of these uncertainties on building energy usage can be investigated in a time-effective manner using computer-based methods. In fact, the central role of digitalization for fulfilling sustainability goals is highlighted in the European Commission’s digital compass established in 2021 (European Commission, 2021).

In order to generate energy characteristics describing actual building energy performance, power supply data can be processed. By using statistical analysis, such as energy signature (ES) models, this data can be used to calculate energy characteristics describing different processes in buildings. For multi-family buildings located in a Nordic climate, relevant energy indicators are specific heat losses, $Q_{\text{total}}$, balance temperature, $T_b$, hot water circulation (HWC) and hot tap water (HTW). Predictions of $Q_{\text{total}}$ and $T_b$ also enable calculations of the energy use related to space heating (SPH). This means that by using statistical analysis, a more detailed description of the building thermal performance can be obtained compared to heating power supply data alone (Eriksson et al., 2020). It should be noted that when analyzing large building portfolios, such as entire districts or cities, computationally efficient ES models become more important. Such models allow for time-effective analysis of the energy performance in entire building districts.

Predicted energy characteristics generated by an ES model, together with estimations of historical building energy use, enable predictions of future building power and energy demand. Estimations of future power and energy demand can be performed by various data-driven approaches, such as linear regression, AutoRegression Integrated Moving Average (ARIMA) and support vector machines (Sun et al., 2020). These models are commonly used to identify patterns and trends in data, and to make predictions based on historical data.

### 1.3. Purpose and novelty of the research

So far, researchers have successfully used ES models to calculate building performance characteristics, which provide more accurate data of building thermal performance compared to specific energy use, i.e., kWh/(m²·year). Moreover, information regarding specific energy use provides no insight about various building processes, such as specific heat losses and HWC, or maximum power demand, which ES models are capable of. Data describing various building processes are key to developing appropriate energy efficiency measures in a future climate, with additional benefits including the possibility of investigating historical and future power and heat demand. Moreover, to the best of the authors’ knowledge, there is a notable research gap on using ES models to investigate the impact of a warmer climate and variations in internal heat gains on the power and energy demand in building districts, based only on heating supply data from real buildings in operation. With the existing framework for the transition to sustainable cities and communities, ES models are of particular interest due to their ability to computationally screen performance characteristics in large building portfolios. Despite the recent increase in research attention on the effects of a warmer climate in the built environment (Giancio et al., 2020, Salata et al., 2017, Shin et al., 2019, D’Augustino et al., 2022), few scientific investigations have thoroughly explored variations in local climate conditions and varying internal heat gains on power and heat demand. Furthermore, considering the tougher requirements on building energy performance and increasing outdoor temperatures, it is necessary to investigate historical fluctuations in outdoor temperatures and their impact on building heat demand. Consequently, long-term energy policies anchored in future climate conditions can be developed and the impact on future energy supply systems can be analyzed in detail.

The aim of this study is twofold: (1) to investigate the impact of historical fluctuations in outdoor temperatures and historical variations in internal heat gains on building heating power and heating energy demand; and (2) to predict the changes in future power and heating energy demand until 2050. The study is based on the residential district Vasastaden, located in Linköping, Sweden, with a total heated area of about 122,000 m². The aim is fulfilled by development of a methodology using an ES model (Milić et al., 2021, Milić and Rohdin, 2023), which allows for differentiating energy characteristics using solely digital heating power supply data, outdoor temperature, and regression analysis. The results of this paper will contribute to an insight into the relationship between the effects of warmer climate and historical variations in internal heat gains on heating power and energy demand in Nordic climate. Moreover, the differentiation of heat demand into various processes plays an important role in developing appropriate energy efficiency measures in multi-family buildings in a future climate. The presented research is also useful for energy utilities in assessing future heat demands in energy systems. In particular, the analysis of heating power is of special interest due to possible lack of sufficient power generation in energy systems during extreme cold temperatures. Hence, this study will contribute to national decision-makers in how to analyze data related to the heating of buildings, as well as aid energy utilities in planning of future heat supply.

## 2. Theory

### 2.1. Energy systems in buildings

Understanding a building’s energy system is important for investigating historical and future heat demand. In multi-family buildings located in a Nordic climate, the primary task of the energy system is to supply sufficient heat to keep the temperature at a desired level, and to produce HTW. It is important to note that comfort cooling is uncommon in multi-family buildings due to the historically cold climate. Fig. 1 visualizes a common energy system in multi-family buildings located in a Nordic climate. As can be seen in the figure, SPH is required to compensate for losses from transmission, natural ventilation and infiltration. These heat losses are directly dependent on the building’s technical properties and ambient environment, as well as internal heat gains. HWC enables a rapid and continuous flow of HTW at tap points. Heat losses in pipes are a problem for HW systems in multi-family buildings, which vary from building to building depending on piping design. The use of HTW is directly connected to user behavior and the

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### Nomenclature

- $E$: Energy (Wh)
- $P$: Hourly heating power supply (W)
- $Q_{\text{infiltration}}$: Infiltration losses (W/°C)
- $Q_{\text{total}}$: Total specific heat losses (W/°C)
- $Q_{\text{transmission}}$: Transmission losses (W/°C)
- $Q_{\text{ventilation}}$: Ventilation losses (W/°C)
- $T_b$: Balance temperature (°C)

### List of abbreviations

- ES: Energy Signature
- DTPC: Differentiating thermal power characteristics
- HTW: Hot tap water
- HWC: Hot water circulation
- SPH: Space heating

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energy efficiency of e.g., taps and shower heads. Overall, the most important aspect in analysis of the building energy balance is the strong correlation between the ambient environment, building technical properties, and heat supply. This means that future heat supply is linked with the pace of energy renovation in the existing building stock and the effects of a warmer climate. It should be noted that the ventilation heat supply is excluded in Fig. 1 as the studied buildings in this research are naturally ventilated.

2.2. Energy signature models – overview and research

ES models are inverse models for calculating building technical properties based on energy use data and outdoor temperatures. Relevant variables to quantify in multi-family buildings located in a Nordic climate include HWC, heat demand for HTW, specific heat losses (Q_{total}), and balance temperature. ASHRAE has set guidelines for developing ES models with a different number of points, which is directly related to the building energy systems (ASHRAE, 2013). In residential buildings located in a Nordic climate, ES models with three points are the most common, where heating compensates for the energy needed for SPH, HWC and HTW. A visualization of an ES model can be seen in Fig. 2 with the energy use for HWC and HTW described by the baseload.

The consequences of being able to quantify Q_{total} are important since Q_{total} is an indicator of the building thermal performance based on heat losses from transmission, ventilation and infiltration. Hence, by calculations of Q_{total} together with the building balance temperature, an assessment of the technical performance of the buildings can be made. Below, using the actual outdoor temperature for the location, the energy use of a building based on the actual technical performance can be formulated according to Eq. (1).

$$ E = Q_{total} \Psi = (Q_{transmission} + Q_{ventilation} + Q_{infiltration}) \Psi + HTW + HWC $$

in which E is the energy use (Wh), Q_{total} the total heat loss term (W/°C), \Psi the degree hours (°-h), Q_{transmission} the heat losses due to transmission (W/°C), Q_{ventilation} the ventilation losses (W/°C), Q_{infiltration} the infiltration losses (W/°C), HTW the hot tap water (Wh), and HWC the hot water circulation (Wh). Moreover, the quantification of Q_{total} and the balance temperature provides a basis for estimating building energy usage in a historical climate.

Research using ES models was first published in 1987 by (Hammarsten, 1987). An increase in the use of ES models in the building industry has occurred recently with the availability of historic heating supply data. For example, in 2020 (Eriksson et al., 2020) demonstrated the potentialities of extracting more information on building operation solely from building energy data. This is in line with the findings from (Sjogren et al., 2009), who also questioned building energy use as a measure of energy performance. This is because of the connection between internal heat gains and the energy demand for SPH. Other examples of using ES in scientific literature include the work by Park et al. (2016), who estimated the energy efficiency potential in 128 residential complexes in Seoul, South Korea. The results showed that the ES model enables prediction of building energy characteristics and calculations of optimal energy saving measures. The possibilities of calculating performance characteristics, i.e., \( T_b \), HWC and HTW, applying ES models were also shown in a study by Milic et al. (2021). Consequently, this demonstrates the possibilities of using ES for extracting more detailed data on building technical properties compared to specific energy use alone.

It is important to understand the downsides with ES for calculations of building technical properties. For example, accurate heating supply data is needed since a malfunctioning heating supply system will not provide an accurate representation of the building thermal characteristics.

2.3. Prediction of future building energy use in scientific literature

The prediction of building energy use is a key for future energy planning and making informed decisions concerning energy renovation strategies (Amasyali and M. El-Gohary, 2018). Long-term energy demand prediction can play a pivotal role in formulating efficient energy policy objectives and optimizing the allocation of economic resources. This is especially the case considering climate change and its impact on the heat demand of buildings, which is the focus of this research.

As highlighted in a review by Wei et al. (2018), data-driven algorithms have recently gained attention in studies of buildings’ future energy use. The authors also state that data-driven approaches have been successful in predicting future energy loads, as well as mapping regional energy use. Hence, the use of an ES model in this study, together with regression analysis, is in line with the current trends in the research field of predicting building energy use in future.

Common approaches for predicting future building energy use include artificial neural networks, decision trees, support vector machines, statistical regression and genetic algorithms (Wei et al., 2018). (Wang and Srinivasan, 2017) showed in their review on prediction of building energy use that artificial neural networks are the most popular prediction method in scientific literature. The reason for this is their robust prediction performance and ease of implementation. Statistical regression models were the second most widely used prediction method due to their ease of use.
Despite the fact that residential buildings correspond to the largest share of energy use in buildings, there is limited research on prediction models applied in this sector of the built environment (Wang and Srinivasan, 2017). This is especially the case for models predicting long-term energy use, a central theme in this study. The reason for a higher degree of using prediction models in other parts of the building stock, such as in commercial and education buildings, may be explained by a better availability of energy data in these buildings (Wang and Srinivasan, 2017). Examples of applying data-driven models in predicting future energy use in the residential sector include (Farzana et al., 2014; Liu et al., 2021; Shen and Yang, 2020; Chakraborty et al., 2021). Farzana et al. (2014) studied the total future energy use for residential buildings in Chongqing, China, based on different forecasting techniques. Input data was obtained through a questionnaire, as well as from literature. Parameters that affected the energy demand include, among other things, the total number of households, total population, and electrification rate. The results showed that residential energy use is predicted to be three times greater and use of electricity four times greater in 2025 compared to 2012, respectively. Of the investigated techniques, it was shown that artificial neural networks had the highest accuracy with a mean relative percentage error of 0.09%. In contrast to the findings from Farzana et al. (2014), Liu et al. (2021) found that artificial neural networks had the lowest prediction accuracy, an R-squared of 0.62, in a study on predicting monthly electricity demands in the residential sector of Hong Kong to 2090. These differences could be attributed to the consideration of both future climate change and socioeconomic growth in the study by Liu et al. (2021). With regard to the change in electricity demand, an increase of 89% was predicted by 2090 compared to 2018. Moreover, (Shen and Yang, 2020) studied future residential energy use in the state of Texas region to 2060. The investigation was based on five residential building types: mobile, single detached, single attached, 2–4 apartment units, and more than five apartment units, representative of Texas. The study was performed by collecting 20 years of population data and total floor area in Texas, along with building simulation of the building types and regression analysis. The results showed an R-squared higher than 0.99 in the developed model, and an estimated 50% increase in energy use from 2020 to 2060. Additionally, the study found a strong correlation between regional energy use and average outdoor temperature. Furthermore, (Chakraborty et al., 2021) studied the effects of climate change on cooling energy demand between 2020 and 2100, using archetypes of a multi-story building, a single-family house, and an office building in San Antonio and New York. Artificial intelligence, using tree-based ensemble models, was applied in the study. The model was successful in predicting future cooling energy use (R² > 0.90). The highest increase in cooling energy demand was obtained in the single-family house (87–121%), highlighting the need for adaptation and mitigation measures.

Among researchers, there is a shared understanding that climate change is expected to result in increased demand for cooling and decreased demand for heating in residential buildings, and the extent of these changes is dependent on the specific characteristics of climate zones (Yang et al., 2021; Deng et al., 2023; Jalali et al., 2023; Elnagar et al., 2023). Yang et al. (2021) used a comprehensive set of future climate data between 2010 and 2099 for 38 European cities in five climate zones. By employing building energy simulations and exploring 13 different future climate scenarios, the results showed that the average cooling and heating demand in the future varies depending on the climate zone. The study also found that the increase in cooling demand is higher compared to the decreases in heating demand in cold climates. These findings are in line with the results from Deng et al. (2023) and Jalali et al. (2023). Deng et al. (2023) investigated 483 buildings in Geneva, Switzerland, considering climates for 2020, 2050, and 2080. The heating energy demand decreased by around 25% and the cooling energy demand increased by more than twofold by 2050. In their paper, (Jalali et al., 2023) studied six different climate zones in New Zealand for two typical residential buildings and concluded a decrease in heating demand and a significant increase in cooling demand. Another key conclusion by Jalali et al. (2023) is the importance of considering future climate data in the analysis of building energy performance. Moreover, (Elnagar et al., 2023) developed a framework to investigate heating and cooling demand in the Belgian building stock by 2050 and 2090, compared to 2010. Based on building energy simulation procedures, the results showed that building energy renovation holds the potential to both decrease cooling demand and heating demand in the future. In alignment with the findings from Yang et al. (2021), Deng et al. (2023), Jalali et al. (2023), the cooling demand is expected to increase significantly more in future compared to the decrease in heating demand. As stated by Yang et al. (2021), the effects of climate change on future building energy demand, particularly cooling, may be substantial, posing difficulties for both the buildings and the surrounding energy system.

2.4. Energy use and energy requirements in Swedish multi-family buildings

The total energy use for SPH, HTW and HWC in Swedish multi-family buildings was almost 29 TWh in 2021 (Swedish Energy Agency, 2022b), which corresponds to around 20% of the energy use from the residential and service sector. This figure has been relatively constant since the 1990s, while the heated area from this part of the building stock has increased from 155 million m² in 1990 to 208 million m² in 2020 (34%). Consequently, the specific energy use from Swedish multi-family buildings has decreased over time. Fig. 3 shows the average specific energy use for heating from 1984 to 2040 for multi-family buildings on a national level. The average specific energy use between 1984 and 1988 was 227 kWh/(m²⋅year), and the corresponding average for the five last years (2016–2020) is 131 kWh/(m²⋅year). This trend illustrates the poorer energy performance in older buildings compared to newer ones. However, it is important to recognize the effects of climate change on buildings’ energy use for SPH: higher outdoor temperatures lead to a decreased SPH demand. In addition, the poorer the building thermal performance is, the larger the impact of warmer climate on building heat demand.

Requirements for specific energy use (kWh/(m²⋅year)) on new construction of multi-family buildings in Sweden were first introduced in 2006 by The Swedish National Board of Housing (2022). In consideration of the geographical span from the southern to the northern regions of Sweden, covering almost 1,600 km and encompassing diverse climate conditions, the energy requirements vary depending on geographical location. Until 2017, Sweden was divided into four climate zones according to Fig. 4, each of which had different requirements on specific energy use. In 2017, geographical adjustment factors (ranging from 0.8 to 1.9) were introduced, as well as weighting factors for different energy carriers. The weighting factors were later modified in 2020. Table 1 shows the changes in energy requirements from 2006 to today for the location of Linköping 1. As the table shows, the energy performance requirements have changed from 110 kWh/(m²⋅year) in 2006 to 75 kWh/(m²⋅year) in 2020. The same tendency can be seen in other geographical locations in Sweden, i.e., the introduction of tougher energy performance standards.

3. Methodology

The methodology presented in the proposed research includes five steps. A schematic of the methodology is presented in Fig. 5. In Step 1, data related to heating power supply and heated areas for the studied buildings were collected, along with historical outdoor temperatures

1 The presented figures are based on a weighting factor of 1 for the energy carrier. In addition, the geographical location of Linköping corresponds to an adjustment factor of 1.
ES model was implemented for predictions of thermal energy characteristics, which included total specific heat losses ($Q_{\text{total}}$), energy use for HWC and HTW, and balance temperature. In the presented research, this was performed using selected time periods based on time-dependent variations in user behavior and climate (Milić et al., 2021). Using the quantified thermal energy characteristics from Step 3, the historical building heat demand from 1980 to 2020 was estimated in Step 4. This was enabled using outdoor temperature data for the corresponding time period. Additionally, the historical power demand was calculated in this step. Lastly, based on the historical building heat demand, a prediction of future heat demand was made with regression analysis in Step 5. The prediction was performed until 2050 for the scenarios investigated in this study. The heating power demand in 2050 is also predicted in Step 5. Steps 3–5 were implemented in the numerical computing environment MATLAB (Matlab, 2023). The MATLAB program is widely recognized by researchers and data scientists in a number of fields, including statistical modeling and visualization.

### 3.1. Step 1 – Data collection

The data collection can be divided into two parts. First, data required to assess historical fluctuations in terms of internal heat gains in Swedish multi-family buildings and outdoor temperatures. Considered internal heat gains include use of electrical appliances and occupancy density. Consequently, historical patterns in terms of variations in internal heat gains were studied, which are linked with heating energy use in buildings. The collection of data on internal heat gains involved utilizing national statistics on energy use for electrical appliances in residential buildings and data for the total heated area of the building stock from 1980 to 2020 (Swedish Energy Agency, 2022a). Internal heat gains from occupants historically have been estimated based on population density and residential area (Swedish Energy Agency, 2022b; Statistics Sweden, 2022). Outdoor temperature data for the studied historical time period was obtained from ERA5, which is the fifth generation reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Climate Data Store - Copernicus, 2022).

The second part of the data collection consisted of hourly heating power supply data for the studied buildings, which was required for the later implementation of the ES model. Hourly power supply data for the studied buildings for three years have been collected from the local energy utility Tekniska Verken AB. The corresponding outdoor temperatures have been obtained from the Swedish Meteorological and Hydrological Institute (SMHI). To allow for calculations of the specific energy use for heating (kWh/(m$^2$·year)), information about the building’s heated area was required. This data has been collected from GRIPEN, the Swedish energy declaration registry that holds energy-related information on over half a million buildings.

### Table 1

<table>
<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2011</th>
<th>2016</th>
<th>2017</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy requirement kWh/(m$^2$·year)</td>
<td>110</td>
<td>90</td>
<td>80</td>
<td>85</td>
<td>75</td>
</tr>
</tbody>
</table>

1 For new constructions and without supplementary energy use for special circumstances such as small apartments etc.

Fig. 3. Average specific energy in Swedish multi-family buildings between 1984 and 2020 (Swedish Energy Agency, 2022a).

Fig. 4. Traditional climate zones in Sweden (The Land Survey, 2022).

Table 1 Changes in energy requirements for the geographical location of Linköping1, Sweden.

Fig. 3. Average historical energy use for heating in Swedish multi-family buildings - kWh/(m$^2$·yr)


1 0 50 100 150 200 250 300

**Climate zones**

1 2 3 4

Linköping
3.2. Step 2 – Investigated scenarios

The investigated scenarios in the proposed research were developed to investigate the impact of a warmer climate in the future and varying internal heat gains on building heat demand. Therefore, the following three scenarios have been defined.

- Scenario 1: Impact of historically increasing outdoor temperatures. Outdoor temperatures from 1980 to 2020 in Linköping have been used to allow for this analysis.
- Scenario 2: Impact of historically varying internal heat gains. Internal heat gains vary depending on use of electrical appliances and occupancy density. The same time period as in Scenario 1 was considered here.
- Scenario 3: Impact of increasing outdoor temperatures and varying internal heat gains. This scenario considers historical variations in both outdoor temperatures and internal heat gains.

It is important to consider historical trends and fluctuations in the use of electrical appliances due to the correlation with building heat demand. Linear regression of the specific energy use for electrical appliances between 1980 and 2020 resulted in a coefficient of determination ($R^2$) of 0.61, which is presented in Fig. 6. This indicates that the specific energy use for electrical appliances is to a large degree dependent on year. Furthermore, the linear correlation between these variables was used to estimate historical figures on energy use for electrical appliances, corresponding to variations between 20 kWh/(m²·year) in 1980 and 30 kWh/(m²·year) in 2020. A comparable analysis for occupancy density, however, showed no correlation between the variables ($R^2 = 0.01$). Therefore, figures on internal heat gains from occupants were based on up-to-date occupancy density, which corresponded to 17.5 kWh/(m²·year). Heat gains of 80 W/person (Sveby, 2020) and an average residential area of 40 m² in multi-family buildings in Linköping (Statistics Sweden, 2020) have been used to calculate the occupancy density.

3.3. Step 3 – Energy signature model

To allow for calculations of thermal energy characteristics, the DTPC (Differentiating Thermal Performance Characteristics) (Milić et al., 2021; Milić and Rohdin, 2023) ES has been used. The ES model uses selected time periods for quantification of thermal characteristics based on time-dependent variations in climate and occupancy behavior. The main advantages of the DTPC ES model include the use of only heating power supply data with hourly resolution and outdoor temperatures, and no additional data related to occupancy behavior, such as the use of electrical appliances. Quantified thermal characteristics include HTW, HWC, specific heat losses ($Q_{total}$) and balance temperature ($T_b$), which allows for calculations of the total energy use for heating. Hence, the quantified thermal characteristics were used for the estimations of historical heat demand in Step 4 of the proposed methodology.

The selection of time periods for prediction of thermal energy characteristics is a key feature in the DTPC model used. By selecting time periods using daily and seasonal patterns regarding climate and occupant behavior, there is no need for data describing occupant behavior. The robustness of the selected time periods has previously been shown in (Milić et al., 2021). Moreover, it is important to be aware of the limitations of the DTPC model. As the model is designed for districts within a Northern European climate context, the present version of DTPC is limited to buildings with only heat supply and does not include comfort cooling. Additionally, the model is limited to investigating residential buildings. For a more detailed description of the calculation procedure and the selection of time periods in the DTPC ES model, see (Milić et al., 2021; Milić and Rohdin, 2023).

3.4. Step 4 – Estimating historical heat demand

Using data on outdoor temperature along with the quantified thermal energy characteristics from Step 3, i.e., the energy use for HWC and HTW, the specific heat losses and building balance temperature, it was possible to estimate historical heat demand. Eq. (2) shows the calculation procedure for the energy use related to SPH, $E_{SPH}$, based on previously quantified figures for $Q_{total}$ and $T_b$. As previously mentioned, data on historical outdoor temperatures were obtained from ERA5 (Climate Data Store - Copernicus, 2022). Moreover, the historical heat demand was calculated for all three scenarios presented in Section 3.2 between 1980 and 2020.

$$E_{SPH} = \sum_{n=1}^{8760} Q_{n,SPH}(T_b - T_{min})$$

(2)

3.5. Step 5 – Predicting future heat demand

By quantifying annual heat demand from 1980 to 2020, it was possible to predict future heat demand. As previously stated in Section 1.2, the prediction of heat demand was performed to 2050. In this research, a quadratic polynomial model is proposed according to Eq. (3),
in which $a$, $b$ and $c$ corresponds to the coefficients of the equation, and $a \neq 0$.

$$f(x) = a \cdot x^2 + b \cdot x + c$$  \hspace{1cm} (3)

The reason for using a quadratic polynomial model for prediction, rather than a linear model, was that there are large uncertainties in predictions of future climate, for example due to climate tipping points. In addition, a quadratic polynomial model in the prediction of energy use allows for capturing curvilinear trends in the data (Liu, 2016), which is the case for changes in annual energy use as a result of variations in outdoor temperatures. More complex patterns in data require polynomial functions of higher order (Liu, 2016).

4. Description of the research object

4.1. Description of the residential district

The research object consists of 70 multi-family buildings constructed between 1908 and 1945, which are naturally ventilated. The buildings are located in the Vasastaden district in Linköping, Sweden, with the geographic coordinates latitude 58.42 and longitude 15.61. A visualization of the Vasastaden district can be seen in Fig. 7. Vasastaden is characterized by rental properties with roughly 6,000 residents. Hourly energy use data for the studied buildings for three years have been collected from the local energy company, as well as the corresponding outdoor temperatures obtained from SMHI. As previously mentioned, heated areas for the buildings are gathered from GRIPEN. The number of buildings as a function of heated area can be seen in Fig. 8. The heated area of the studied buildings varies between 446 m$^2$ and 4,433 m$^2$, and the total heated area is 121,692 m$^2$.

4.2. Investigated time period- 1980 – 2020

As mentioned above, this research investigates the heat demand from 1980 to 2020 based on quantification of thermal characteristics in the Vasastaden district. The average annual temperature and 5-year moving average in Linköping for the studied time period can be seen in Fig. 9. 1986 corresponds to the year with the lowest 5-year moving average (5.6 °C) and 2018 to the highest (8.0 °C). The average temperature for the whole time period is 6.9 °C. This demonstrates historical changes in the outdoor temperature of Linköping, which is strongly correlated with the energy use for SPH.

5. Results and discussion

Only buildings within the 5th and 95th percentiles for heat demand are included in the results and discussion. This is in order to provide representative figures on the heat demand for the vast majority of buildings in the area, as well as to exclude anomalies such as non-residential activities.

5.1. Energy use for SPH, HTW and HWC in 1980 and 2020

Three different scenarios, presented in Section 3.2, are investigated with regards to the effects on building heat demand in this research: Scenario 1: effects of increasing outdoor temperatures, Scenario 2: impact of varying internal heat gains and Scenario 3: effects of increasing outdoor temperatures and varying internal heat gains. This section presents the specific energy use related to SPH, HWC and HTW, distributed by heated area. These figures are shown for the first year, 1980, and last year, 2020, in which the ES model has been used to quantify the abovementioned energy characteristics.

Fig. 10 presents the specific energy use for SPH distributed by heated area in 2020 for Scenarios 1–3. The same assumptions for internal heat gains are used in 2020 for all three scenarios, hence, there is no difference in energy use between the scenarios. As can be seen in the figure, the specific energy use varies between 42.7 and 132.4 kWh/(m$^2$·year). The highest frequency of the data ranges from 75.0 to 80.0 kWh/(m$^2$·year), which corresponds to a heated area of almost 21,700 m$^2$ (18 % of the total heated area). The average energy use is 75.7 kWh/(m$^2$·year). A corresponding figure of the energy use for SPH in 1980 for the scenarios is presented in Fig. 11. When considering only the impact from varying internal heat gains historically (Scenario 2) corresponding to an average annual increase of 1 %, the difference in energy use for SPH between 1980 and 2020 is minor. The average energy use in 1980 is 76.8 kWh/(m$^2$·year), which is approximately 1.5 % higher compared to

![Fig. 7. The studied district Vasastaden, Linköping (The Land Survey, 2022).](image-url)
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2020. This is explained by the higher internal heat gains in 2020 compared to 1980. Moreover, when considering the outdoor temperatures for 1980, it can be seen that the average energy use for SPH is increased by more than 41% in 1980 for Scenarios 1 and 3 compared to 2020. For both Scenarios 1 and 3, the highest frequency of data ranges from 105 to 110 kWh/(m\(^2\)⋅year).

An aspect that is important to emphasize is that hourly outdoor temperatures are used during the quantification of energy use for SPH. The energy use for SPH is directly correlated with the buildings’ balance temperatures. Seasonal and daily variations in outdoor temperatures will affect a building’s heat demand for SPH. Moreover, high outdoor temperatures during the non-heating season will increase the average annual temperature, but not necessarily decrease the heat demand for SPH. This is because outdoor temperatures are generally above common balance temperatures for buildings during this time period of the year. Consequently, it is not sufficient to solely analyze annual outdoor temperatures in terms of the effect on the energy use related to SPH.

Because both the energy use for HWC and HTW represent the base load in a building, the aggregated energy use for these energy characteristics is presented. Fig. 12 visualizes the energy use for HWC and HTW in 2020 distributed by heated area. As mentioned earlier in this section, there is no difference between the studied scenarios in 2020 since the same assumptions about internal heat gains are used. The average energy use for HWC and HTW is calculated at 26.4 kWh/(m\(^2\)⋅year), and the range varies between 10.4 and 65.1 kWh/(m\(^2\)⋅year). There are larger differences, in percent, in the energy use for HWC and HTW compared to the heat demand for SPH. This is because a smaller percentage of the total energy use is connected to HWC and HTW compared to SPH in multi-family buildings located in a cold climate such as Sweden. Furthermore, since the studied district consists of buildings built between 1908 and 1945, it is important to note that the studied buildings generally have poorer thermal properties compared to more modern buildings.

Fig. 13 shows the energy use in 1980 for HWC and HTW distributed by heated area. Scenarios 2 and 3 have the same energy use because the same assumptions with regards to internal heat gains are used. Scenario 1 is equal to the energy use presented for 2020, also due to the same assumptions about internal heat gains.
5.2. Historical heat demand from 1980 to 2020

In order to make a prediction of this type for the district’s heat demand until 2050, it is necessary to quantify historical heat demand. Fig. 14 shows the specific energy use for SPH between 1980 and 2020 for the multi-family buildings in the studied district. The minimum figure, 25th percentile, median, 75th percentile, and maximum figure are visualized for each year in the studied time period. The interquartile range varies from 23.6 to 27.8 kWh/(m²·year) in the studied scenarios suggesting a rather low spread for the buildings between the lower and upper quartile. However, when comparing the buildings with the highest and lowest specific energy use, the difference corresponds to more than 100 kWh/(m²·year). Moreover, it can be noted that Scenario 2 shows a weak correlation between varying internal heat gains and heat demand for SPH (a maximum difference of 1.5 kWh/(m²·year)). This is despite an average annual increase of 1 % in internal heat gains based on Fig. 6. Regarding Scenarios 1 and 3, the results of this study show an overall trend of decreasing energy use for SPH from 1980 to 2020, corresponding to an annual decrease of 1 %. These findings are a direct result of a warmer climate, as shown in Fig. 9. The five earliest years studied (1980–1984) have, on average, an outdoor temperature 1.7 °C colder compared to the average between 2016 and 2020. The average difference in specific energy use is 15 % in Scenario 1 and 14 % in Scenario 3, which corresponds to around 14 kWh/(m²·year).

Even though the trend of increasing outdoor temperatures and decreasing heat demand for SPH in the studied district is clear, it is important to be aware of fluctuations in the data set. In 2010, with an average outdoor temperature of 4.9 °C, the average annual energy use of the district is 112.0 kWh/(m²·year) in Scenario 3. This is only 3.0 kWh/(m²·year) lower compared to 1985, which is the year with the lowest outdoor temperatures and the highest specific energy use. Consequently, the fluctuation in outdoor temperatures historically shows the complexity in quantifying the energy use connected to SPH for a certain year.

Fig. 15 visualizes the specific energy use related to HWC and HTW between 1980 and 2020 for the studied multi-family buildings. Only Scenarios 2–3 are presented since Scenario 1 considers only the effects from increasing outdoor temperatures, and not the impact from variations in internal heat gains historically. For Scenarios 2 and 3, the interquartile range is 13.7 kWh/(m²·year). However, the average annual difference between the highest and lowest energy use for HWC and HTW is almost fourfold, i.e., 52.8 kWh/(m²·year). Furthermore, the average energy use for HWC and HTW varies between 25.8 kWh/(m²·year) in 1980 and 26.4 kWh/(m²·year) in 2020.

5.3. Predicted heat demand from 2021 to 2050

The quantification of historical heat demand from 1980 to 2020 based on the used ES model allows for prediction of future heat demand,
which is performed to 2050. Fig. 16 shows the average specific energy use for heating from 1980 to 2020 for the investigated scenarios, together with a prediction to 2050 with 95% confidence intervals. The red-dotted lines represent the present energy requirements for new constructions in Linköping, i.e., 75 kWh/(m²·year). Moreover, a visualization of the total energy use for the Vasastaden district can be seen in Fig. 17.

As shown in Figs. 16 and 17, the impact from varying internal heat gains (Scenario 2) on future heat demand is small. It is predicted that the average specific energy use will be decreased by less than 1 kWh/(m²·year) from 2021 to 2050, and that the total energy use for the Vasastaden district is decreased by less than 0.1 GWh annually. However, for Scenarios 1 and 3, the average specific energy use is decreased by 15 and 18 kWh/(m²·year), respectively. Moreover, in comparison with 1980 (127 kWh/(m²·year)) it is predicted that the average specific energy use will be decreased by 24% and 27% by 2050 for Scenarios 1 and 3, respectively. The specific energy use in 2050 is calculated at 96 kWh/(m²·year) in Scenario 1 and 93 kWh/(m²·year) in Scenario 3. In terms of total energy use for the district, the energy use decreased from 14.9 to 11.2 GWh in Scenario 1 and from 14.9 to 10.9 GWh in Scenario 3. Consequently, the findings observed in this research mirror those of previous studies, e.g. (Ciancio et al., 2020; Dirks et al., 2015), concluding a decreased heat demand in future due to climate change.

It is important to be aware of the confidence intervals around the statistical estimates for the predicted years. The differences between the upper and lower value in 2050 for Scenarios 1 and 3 are almost 100 kWh/(m²·year). The lowest value in 2050 is calculated at 44 kWh/(m²·year), with an upper estimate of 141 kWh/(m²·year). Nonetheless, with large variations in outdoor temperatures from one year to another it is of interest to capture possible variations in future heat demand. Additionally, it is important to be aware of the calculation performed, which are based on outdoor temperature data of Linköping, Sweden. Warming occurs faster in polar regions, which means that greater differences will be noticeable in northern Sweden than in the southern regions. Estimates based on RCP 4.5 and 8.5 from the Swedish Energy Agency (The Swedish Energy Agency, 2021) suggest that the building heating demand will decrease by around 15–20% for the period 2036-2065 compared to 1981-2010 for southern Sweden. The corresponding figures for northern Sweden are 15–32%. These estimates are in line with the findings presented in this research.

5.4. Prediction of historical and future power demand

The quantification of thermal characteristics for the research district

![Fig. 15. Energy use for HWC and HTW (kWh/m²·year) between 1980 and 2020.](image1)

![Fig. 16. Predicted average specific energy use for heating to 2050 using quantifications of historical energy use from 1980 to 2020. The red-dotted line shows the energy requirement (75 kWh/(m²·year)) as of 2020 for Linköping with a weighting factor of 1 for the energy carrier.](image2)
allows for prediction of historical and future power demand. A duration diagram for 1980, 2020 and 2050 can be seen in Fig. 18 visualizing the maximum power demand, lowest outdoor temperature and baseload, i.e., the heating power related to HWC and HTW, considering increasing outdoor temperatures and varying internal heat gains. The left y-axis presents the outdoor temperature and the right y-axis the total power for the district. Moreover, Fig. 19 shows a corresponding ES model for the district, with a color bar that represents outdoor temperatures ranging from –25 °C to 35 °C. The maximum power is 4,855 kW, 3,473 kW and 3,468 kW for 1980, 2020, and 2050, respectively. The large difference in maximum heat power demand in 1980 compared to 2020 and 2050 is explained by a significantly lower minimum temperature. 1980 recorded a minimum temperature of –21.7 °C, while in 2020 and 2050, the lowest temperature were -8.3 °C and -7.2 °C, respectively. Moreover, the small difference in maximum power between 2020 and 2050, 0.1 %,
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is explained by that the power demand in 2050 is based on using historical outdoor temperature data between 1980 and 2020, and the fact that 2020 corresponded to the year with the overall highest outdoor temperatures in the historical time period. Nonetheless, the results show that a warmer climate will most likely result in a decreased maximum power demand within residential districts. Consequently, it is possible to integrate new buildings in local district heating systems without substantially affecting the maximum power demand compared to current levels. This is important to highlight due to the growing research interest in heating power during design outdoor temperatures, as peak loads are often costly for energy utility companies as they have a low number of operating hours etc.

6. Conclusions and future work

This research investigates the effects from historical variations in internal heat gains and outdoor temperatures on the energy use for heating in a residential district. In addition, the future heat demand is predicted based on quantifications of energy characteristics, i.e., SPH, and energy use for HWC and HTW, from 1980 to 2020. The analysis was performed using a newly-developed methodology, which involved integrating historical data on outdoor temperatures and internal heat gains through a proven robust ES model, combined with polynomial regression. The prediction of heat demand was performed to 2050. Seventy multi-family buildings with a total heated area of about 122,000 m² were used as the research object. The buildings are located in the residential district of Vasastaden in Linköping, Sweden.

The results of this study show that historical variations in outdoor temperatures have a significant impact on building power and heating energy demand, while the impact of historical fluctuations in internal heat gains is shown to be low. This is despite an average increase of 1 % in internal heat gains between 1980 and 2020. The energy use for SPH, on average, decreased by 1 % from 1980 to 2020. The average energy use for HWC and HTW is calculated at 26 kWh/(m²·year). Quadratic regression to 2050 revealed that the average specific energy use for heating is calculated at 96 kWh/(m²·year) when considering historical variations in outdoor temperatures, and 93 kWh/(m²·year) when also taking into account historical variations in internal heat gains. This is 24 % and 27 % lower compared to the quantified energy use in 1980, which was 127 kWh/(m²·year). Considering all buildings in the studied district, the largest decrease in total energy use from 1980 to 2050 corresponds to 4.0 GWh. Hence the results of this study align with previous research findings and provide additional evidence suggesting that the energy demand for heating will significantly decrease in the future due to a warmer climate. The maximum power of the Vasastaden district is predicted to be 29 % lower in 2050 compared to 1980, which highlights the impact of a warmer climate on maximum heating power demand. As a result, new buildings can be connected to local energy systems, e.g., district heating, without increasing the maximum power demand in the future compared to today.

There are a number of interesting aspects to investigate in future work. Further research can explore the environmental impact increasing outdoor temperatures has in terms of primary energy use, CO₂ emissions, and profitability of the local energy utility. This is achieved by the prediction of energy characteristics using the proposed ES model. Such an analysis can be performed for all multi-family buildings within the local energy system in a computationally efficient manner. Concerning the replicability of the results to other residential districts, it is important to note that this research is grounded in a residential district situated in a cold climate. Therefore, it is difficult to generalize the specific outcomes to regions with a different climate. The reason for this is that all districts are unique in terms of energy characteristics, and climate conditions vary from one region to another. However, the developed methodology can be applied to investigate the effects of a warmer climate on power and energy demand in other residential districts, cities, and regions. Additionally, it is of interest to investigate a higher time resolution for future power and energy demand in multi-family buildings, such as a monthly resolution. Other aspects of interest include urbanization, the introduction of groundwater heat pumps in residential districts, as well as building energy renovation.

Fig. 19. Energy signature model for 1980, 2020 and 2050 for the district. The color bar is based on outdoor temperatures from −25 °C to 35 °C.
CRediT authorship contribution statement

Vlatko Milić: Writing – review & editing. Writing – original draft. Visualization, Methodology, Formal analysis, Data curation. Conceptualization. Patrik Rohdin: Writing – review & editing, Conceptualization, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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