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From social science surveys to building energy modeling: Investigating user-building interaction for low-carbon heating solutions in Europe

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ABSTRACT

An extensive, representative, and, multi-country tailored survey questionnaire eliciting social practices with heat as an energy service and the relative perceptions about heating devices was submitted to a randomized sample of more than 6,000 potential end-users in Europe within the framework of the Horizon 2020 project SWS-HEATING. The project is developing an innovative seasonal thermal energy storage unit for residential use. Moreover, within the project, the role of occupancy variability and use conditions in the performance of the proposed system is assessed. The present study focuses on tailor-made user-building interaction models to be implemented into dynamic simulation for the assessment of the proposed and similar systems starting from the sociological assessment of such large-scale survey results. These models take advantage from the knowledge raised by the findings of the social survey to frame for the first time occupants' behavior scenarios representative of South, central, and North European countries. In this way, the influence of cultural context and demographic factors and their relation to heating practices are considered when developing these tailored occupant behavior models. Results show the non-negligible influence (up to 43% in the coldest climate) of implementing these models on predicted building heating energy needs, as quantitative demonstration of the role of societal-related variables on final energy use estimation.

1. Introduction

Building energy efficiency and renewable energy transition process must involve building users as key players (Qadir et al., 2021). Occupant behavior, indeed, is well-acknowledged to be one of the main variables affecting buildings' energy efficiency and systems performance (Da and Hong, 2018), as physical interventions (Carletti et al., 2018). Therefore, it must be consistently considered by using tailor-made models for building thermal-energy performance evaluation, energy simulation, and design optimization (Feng et al., 2015). Specifically, it appears to be a fundamental input when predicting the expected energy efficiency of innovative systems, e.g. heating systems (Piselli and Pisello, 2019).

For example, occupant behavior profiles, have a non-negligible impact on real energy use and indoor environmental quality in buildings, since they rule the performance required to these systems (Hong et al., 2017). Martinaitis et al. (2015) investigated the importance of the correct definition of occupancy in dynamic energy simulation by varying occupancy profiles (standard profile, family with children, retired couple, and young couple). Results in terms of primary energy demand revealed differences below 5% for the occupancy profile of more than two persons compared with the standard profile, while, for the other two profiles, the energy demand varied from 14% to 21%. When interacting with the building and its systems, occupants affect the real energy use directly and indirectly via different actions aimed at achieving indoor comfort conditions (Day et al., 2020).

In addition, different occupants' personal factors have a relevant role in building final energy performance (Pisello et al., 2016, https://www.scopus.com/record/display.uri?eid=2-s2.0-85053046523&origin=resultslist&sort=cp-f&src=s&st1=pisello&st2=a&nlo=1&nlr=20&nls=count-f&sid=eb30d5bb47da8491805052ced83a28ed&sot=anl&sdt=aut&sl=40&s=AU-ID%28%22Pisello%2c+Anna+Laura%22+54896291600%29&relpos=44&citeCnt=36&searchTerm=&featureToggles=FEATURE_NEW_DOC_DETAILS_EXPORT:1). The influence of dwelling and occupant characteristics on domestic

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electricity consumption patterns were analyzed by statistical approaches in (McLoughlin et al., 2012). The household composition was found to be one of the variables most influencing the total domestic electricity consumption.

Furthermore, Ðurišić et al. (2020) showed the importance of income, family composition, routines, and region in determining household electricity consumption in Montenegro. More specifically, Chen et al. (2013) determined that occupant age is a more significant factor than income and revealed that the household socio-economic and behavior variables can explain 28.8% of the variation in heating and cooling energy consumption. In this view, understanding the influence of cultural and demographic factors and how they relate to heating habits appears a relevant, yet little explored aspect to be addressed when evaluating the applicability of new systems.

Researchers in the field of occupant behavior are seeking to better develop accurate models of occupants' presence and actions in buildings (Carlucci et al., 2020b) that take into account also contextual aspects based on different purposes (Xu et al., 2014). In fact, the choice of the most appropriate occupant behavior model firstly depends on the building context (Gaetani et al., 2016).

In general, two main types of models exist in the literature: deterministic, which determines occupant actions based on boundary conditions using a deterministic correlation function, and stochastic, which consider the stochastic nature of occupant behavior through probabilistic models (Hong et al., 2018). The main advantage of using a deterministic occupant behavior model, which is based on schedules (i.e. average value model), is the ease of development and application to a range of adaptive behaviors (Heydarian et al., 2020) and building types. Such models form is based on the assumption that the sole time of the week or month of the year allows making predictions for the occupant's presence and behavior. Therefore, they do not take into account the randomness of occupants' response to identical stimuli (Mahdavi et al., 2017).

However, studies suggest that complex stochastic models do not necessarily always perform better than simplified deterministic models (Da and Hong, 2018). With the aim to develop tailor-made models, results from experimental survey campaigns can be used to develop occupant behavior models. Although this approach has been little applied in literature, it can help understand the influence of personal factors (Masrahi et al., 2021) more than other data-based approaches, e.g. based on the statistical analysis of energy consumption data (Braulio-Gonzalo et al., 2021). Indeed, it provides interdisciplinary information on people's energy practices and subjective perceptions about sustainable energy transition (Abdelkader, 2020). He et al. (2021) exploited the results of a national survey submitted in Singapore to develop different behavior styles that represent levels of occupants' energy-saving consciousness. They showed a potential energy saving due to occupant behavior improvement up to 21%. On the contrary, Almeida et al. (2020) collected occupants' perceptions of energy use through questionnaires in order to quantify the real energy use due to occupant behavior in low- and high-performance buildings in Australia. A higher impact on occupant behavior was demonstrated in the low-performance building than in the green building. Similarly, Annaqeeb et al. (2020) investigated occupants' perceptions about their own presence and use of building devices to develop schedules of social models to be implemented in dynamic simulation.

The present work is developed within the framework of the Horizon 2020 (H2020) project SWS-HEATING (*Development and Validation of an Innovative Solar Compact Selective-Water-Sorbent-Based Heating System*), which has the purpose to develop an innovative seasonal thermal energy storage (STES) unit for heating applications and investigate its exploitability. The project involves the submission of an extensive tailored survey questionnaire to assess users' expectations and practices in interacting with the heating system and their perceptions of innovative systems, such as the one proposed, in different countries in Europe. In this panorama, the purpose of this work is to take advantage for the first time of the evidence raised up by the sociological assessment of such large-scale survey results to develop tailored user-building interaction models depending on the cultural context. Therefore, the novelty of this work is to provide a framework for country representative occupant behavior models based on extensive social surveys to directly quantify user behavior role in final energy need. These newly developed models allow taking into account different occupant behavior scenarios when evaluating the performance of the proposed and additional innovative systems in their potential real conditions of use. In this work, the developed occupant behavior models are implemented in standard building models as a test bed of the influence in predicted building heating energy performance.

1.1. The H2020 project SWS-HEATING

As previously mentioned, the H2020 project SWS-HEATING has the purpose to develop an innovative STES unit with a novel storage material and configuration, namely a sorbent material embedded in a compact multi-modular sorption STES unit. This innovative system is specifically designed for low-carbon heating applications since it allows to take advantage of the collected solar energy, mostly available during summer, in the less sunny winter period by shifting and storing it. Moreover, this will be achieved by implementing a more compact and high-performing STES system compared to existing technologies. In fact, the system will use novel sorbent materials of Selective Water Sorbents (SWS) family that are characterized by high heat storage density and, thus, enable to considerably reduce the storage volume with negligible thermal losses compared to acknowledged materials.

The project focuses on the development of this system, as a promising alternative to other low-carbon heating solutions, e.g. heat pumps, other solar energy systems, biomass boilers, district heating, etc. Indeed, as above-mentioned, this system will have the advantage to provide solar energy all year round with reduced fluctuations, while reducing the dimensions of the thermal energy storage compared to other existing technologies in order to be more easily integrated into single-family residential buildings. However, the proposed system is still under development and additional work is needed to bring it to the marketing level with a competitive price. During the project, the proposed STES unit will be designed and its expected performance will be evaluated through numerical and experimental analysis for residential single-family building applications in Europe.

In this framework, the analyses carried out in this work contribute to the definition of the boundary conditions for the numerical assessment of the developed STES system performance. In particular, residential building dynamics are defined in terms of different user-building interaction models to be used in building dynamic simulation, as described in the following section. According to the project goal, different models are developed to be representative of three climate contexts in the south, central, and north Europe. These models are preliminarily tested for standard residential building applications in this work.

2. Methods

The research work was developed in the following steps:

- submission of a series of original nationally representative surveys in key countries in Europe eliciting users' heating practices and perception of innovative low-carbon systems;

- analysis of the results of the survey according to the purpose of this study;
- development of user-building interaction models for building dynamic simulation for selected countries (Germany, Spain, Sweden) based on the findings of the survey combined with existing knowledge;
- assessment of the influence of the developed occupant behavior models on standard residential buildings' energy performance through dynamic simulation.

2.1. Three nationally representative surveys

A survey of social attitudes was designed in order to cover the wide target of people's preferences about and satisfaction with their heating systems, their practices with heat as an energy service, as well as social knowledge, acceptance, and engagement with low-carbon systems, e.g. the developed innovative STES unit or others above-mentioned. To this aim the survey was submitted in the beginning of 2020 (January to March) on a large scale to more than 10,000 respondents in five European countries. Therefore, the influence of COVID pandemic was not considered in order not to bias this analysis, as the COVID pandemic had a strong impact on citizen behavior.

The countries were selected to be representative of high-income and high-emitting European countries, while characterized by different locations, winter climate, length of the heating season, energy market (i.e. dominated by fossil fuels or renewable energy sources), but also sociodemographic composition and climate change and energy data. However, to the purpose of this study, three countries are considered in order to be representative of south, central, and north Europe, according to the SWS-HEATING project aims, namely Spain, Germany, and Sweden, respectively. Accordingly, the considered sample comprises 6070 respondents spread across Germany (N = 2009), Spain (N = 2038), and Sweden (N = 2023).

In detail, the questionnaire explored the socioeconomic and demographic attributes of respondents, their heating knowledge and awareness, their heating practices and dynamics, their heating satisfaction and preferences, and their heating priorities and business models, across five sections. A 4-point or 5-point Likert scale was used in most questions. The specific questions used in this work are described in the following sub-section. Further details on the questionnaire development and the survey submission are described in two papers generally focused on the results of the survey and already published papers by Sovacool et al. (2021b,a).

2.2. From survey results to user-building interaction models

This study takes advantage of the results of the extensive survey on heating practices and preferences among European consumers to develop, for the first time in such a large scale social science related survey, tailor-made user-building interaction models per country to be implemented in building dynamic energy simulation. Among all survey questions, those used to this purpose and the information obtained from each question are listed below:

- Information about heating control availability and setting was gained from the question "*What level of control do you have over your current heating and hot water system?*"
- Information about the average preferred heating set-point temperature was gained from the question "*Thinking about your general temperature setting preferences, how warm should your home be during the winter (in* °C*)?*"
- Information about (i) heating switch-on period during the year, (ii) heating switch-on time during the day, and (iii) windows opening practices in winter was gained from the question "*Thinking about common or acceptable heating practices, to what extent to you agree with the following statements?*"

Since the survey was focused on heating preferences and practices, only those ones related to the heating attitudes were used to the purpose, of the whole user-building interaction schedules implemented in dynamic simulation (Pisello et al., 2015) (listed in the following sub-section). The remaining occupant-related schedules are defined according to existing references in literature, as detailed in the following sub-section.

2.3. Development of novel user-building interaction models

Building on the survey results, three deterministic models of user-building interaction are newly developed by following acknowledged procedures (Mahdavi et al., 2017). In fact, country-specific models are defined for each of the considered countries, i.e. Spain, Germany, and Sweden. The purpose is to develop models tailored to the preferences and practices in each country to evaluate the influence of this variable in the performance of the proposed system. These models are developed when referring to the occupancy of a residential single-family building, according to the purposes of the SWS-HEATING project. The innovative STES unit designed in the project, indeed, is intended for this specific application. Accordingly, different user-building interaction schedules are defined. Schedules are defined separately for working days and weekends/holidays. Moreover, schedules are differentiated for two thermal zones within the residential building, i.e. the living area and the sleeping area.

According to the existing knowledge in the field of occupant behavior (Da and Hong, 2018), the occupant behaviors and occupant-building interactions listed as follows are considered in this study. These occupant behaviors and interactions within the building are selected as able to influence the thermal-energy performance of the building and its heating energy needs (relevant for the purposes of the project). Such specific occupant behaviors are active and passive human-based parameters, i.e. occupant interactions directly to heating system management and indirectly affecting the heating system performance (Pisello et al., 2015). Therefore, the following schedules are considered for the dynamic modeling:

(1) Occupancy presence, the information provided are:
  - schedule of presence inside the building during the day, for a typical weekday and weekend;
  - maximum heat gain (W/m^2) associated to the presence of people inside the room and the heat gain fraction during the different hours of the day.

(2) Thermostat operation, the information provided are:
  - schedule of switch on/off during the day, for a typical weekday and weekend, which depends on practices and on the occupancy presence schedule;
  - temperature set-points and set-backs for heating and cooling.

(3) Natural ventilation control, the information provided are:
  - schedule of windows opening/closing during the day, for a typical weekday and weekend, which depends on practices and on the occupancy presence schedule.

(4) Mechanical ventilation use, the information provided are:
   - schedule of switch on/off during the day, for a typical weekday and weekend, which depends on the occupancy presence schedule.

(5) Domestic hot water (DHW) use, the information provided are:
   - schedule of use during the day, for a typical weekday and weekend, which depends on the occupancy presence schedule.

(6) Equipment (electrical devices and appliances) use, the information provided are:
   - schedule of switch on/off during the day, for a typical weekday and weekend, which depends on the occupancy presence schedule.

(7) Lighting use, the information provided are:
   - schedule of switch on/off during the day, for a typical weekday and weekend, which depends on the occupancy presence schedule.

(8) Windows shading operation, the information provided are:
   - schedule of use during the day (on/off), for a typical weekday and weekend, which depends on practices and on the occupancy presence schedule.

As regards the maximum heat gain (W/m^2) associated to the presence of people, it depends on the density of people inside the building, i.e. persons/m^2, and, therefore, to the household composition. The household composition is determined by the number and demographics of the people living in the building, which characterize the family typology. The most suitable family typology to be considered in this study is selected according to the population representativeness in the European Union Eurostat data from (Eurostat Statistics Explained, 2017). In order to consider the more severe scenario for energy demand among the most common family types in the European Union, a three-person household composed by two parents and a child is selected (Piselli et al., 2018). Accordingly, two different values of people density for the living area and the sleeping area are identified depending on the area ratio.

In the SWS-HEATING project, building dynamic simulation is carried out through TRNSYS simulation platform. However, as reported below, the user-building interaction models are developed using a common format that can be implemented in several dynamic simulation engines, such as EnergyPlus used in this work.

2.4. Assessment of the influence of user-building interaction models

For this study, the developed user-building interaction models are tested when implemented in acknowledged standard building models to assess their influence of expected final building energy performance. EnergyPlus simulation engine v8.4 (Crawley et al., 2000) is used to simulate the dynamic energy performance of the buildings, which allows inputting variable occupant-behavior schedules. In detail, two ASHRAE-validated standard building models representative of different typologies of residential building are selected as case studies: single-family house (*Case 600*) (ASHRAE, 2001) and mid-rise apartment building (ANSI/ASHRAE/IES, 2016). The latter model is a rectangular prism shaped building with 23 apartments spread over three floors with a central distribution area. The area of each apartment is 88.25 m^2.

As regards to envelope characteristics, the external walls are steel framed with stucco, gypsum board, thermal insulation, and internal gypsum board, while the roof has external waterproof membrane, thermal insulation, and metal decking. The single-family house is a simpler model with single-floor squared plant (area equal to 48 m^2). It has a wooden structure with fiberglass and plaster board in both external walls and roof.

Admittedly, the use of these standard building models involves an error in terms of building materials and components (and, thus, envelope thermos-physical properties) with respect to the most common solutions in the different considered countries. Given the lower thermal mass of the materials of the standard building models, the effect of some of the occupant-related inputs, e.g. natural ventilation, could be slightly overestimated compared to applications in more massive buildings (such as the German typical residential constructions (EPISCOPE, 2012)). However, they were not modified to be more closely representative of the typical building typologies in each country, in order to have the same building models and, therefore, to highlight the sole effect of user-building interaction variation. For the same reason, for both buildings, the HVAC system is simulated with the Ideal Loads air system, i.e. a simple loads energy system accounting for an ideal air-conditioning unit, to avoid the influence of the HVAC system efficiency in the calculated energy performance.

These building models are selected for this analysis as internationally reliable validated building models and not to be specifically representative of residential buildings in the considered countries. Therefore, standard ASHRAE models are kept in the original form by only simplifying the existing HVAC system to Ideal Loads air system.

Furthermore, model inputs in terms of site location are implemented for each climate context, according to EnergyPlus weather files (U.S. Department of Energy's (DOE) Building Technologies Office (BTO), 2016), i.e. Stockholm in Sweden, Regensburg in Germany, and Madrid in Spain. Thereafter, two sets of models are simulated: the standard models (*standard*) and the customized models that further implement the newly developed tailored user-building interaction models (*customized*), in each climate context and for each residential building typology (total of twelve models, namely two *standard* and two *customized* – one per residential building typology – per the three counties).

On the contrary, the *standard* models are kept with the original occupancy inputs that are standard occupancy models generally used in building dynamic simulation. In this way, the input parameters that vary among the different climate contexts are those related to the user-building interaction schedules and to climate. Moreover, the input parameters that vary between the *standard* and the *customized* model in each climate context are only those related to the user-building interaction schedules. Thus, it is possible to assess the sole influence of the developed tailored user-building interaction models on final building energy performance. Since the research is focused on heating, as the developed occupant behavior models, the results of the dynamic simulation are analyzed in terms of annual heating energy needs.

3. Results and discussion

The results highlight the outcomes from the survey that are considered to develop the user-building interaction models for each country. In addition, the various developed schedules are presented.

3.1. Survey outcomes

This section shows the main outcomes from the survey, with a more detailed analysis offered by Sovacool et al. (2021a,b), relevant to the goals of this work for Spain, Germany, and Sweden. In general, considering all the countries, almost 74% of respondents reported having basic or moderate personal control overheating. Therefore, this setting is considered for the occupant heating control modeling.

As regards the mildest climate context, i.e. Spain, in general respondents show to be less attached to heating compared with the other two countries. In fact, only about half (49%) of the respondents consider heating as the most important energy service in the household. This attitude appears to be influenced by the moderate climate conditions, where also cooling plays an important role in the annual energy balance. Spain presents the highest percentage of respondents who believe that low-carbon heating should save not only money but also energy and is needed to protect the environment. On the other hand, Spanish respondents show the highest percentage, i.e. 15%, of preferences for very warm homes (greater than 25 °C) and a significant percentage of people, i.e. 34%, who believe that homes should be warm enough in winter to wear lightweight clothing (shorts and t-shirts). On average, the preferred thermostat temperature in winter is 21.8 °C. Concerning existing heating technologies, the majority of Spanish households have a gas boiler for heating and DHW and a thermostat in the living room for temperature control. Usually, the gas boiler has winter mode (heating and DHW) and summer mode (only DHW) and the change is done around April–May and in November by the user manually. Finally, many people tend to open occasionally the windows in winter to let in fresh air (64%). On the contrary, during summer, windows opening attitudes consist in keeping the windows closed during the day, while open in the evening.

In Germany, which represents the central European context, heating is largely considered as the most important energy service in the household (61% vs. 49% in Spain). A non-negligible percentage of respondents, much higher than other countries (35%), declare to consider as a common/acceptable practice to heat their homes all year round. In addition, 36% of respondents (similarly to Spain) believe that homes should be warm enough in winter to wear shorts and t-shirts. Nevertheless, Germans stand out as reasonable consumers since only about 7% of respondents argue excessively warm homes. In winter, the mean preferred thermostat temperature is 21.3 °C, namely 0.5 °C lower than in Spain. Regarding the existing heating technologies, in the majority of homes in Germany (more than 90%), heating and DHW are typically supplied by the same heating appliance with gas, oil, and also district heating as the most common energy carriers. In terms of windows operation, the percentage of people that is used to open windows in winter to get fresh air is even higher than in Spain, i.e. 77%. Moreover, they use to tilt the windows even in the cold season, not only to open it for short periods, and even in a few houses provided with mechanical ventilation systems and heat recovery. This habit highlighted by the survey is in line with the indications provided by the Germany's main environmental protection agency (Umweltbundesamt (UBA), 2017), who recommends ventilating at least three times a day for at least 3–5 min for health, better comfort, and fresh air. In summer, window opening is also used to ventilate excess heat mainly at night.

Finally, in Sweden, which is characterized by the coldest climate conditions among the selected countries, heating is considered as the most important energy service in the household to the same extent as in Germany (60%). A peculiarity, compared to the other countries, is the high percentage of Swedes that desire heat for the sake of their pets, i.e. 38%, due to the much lower peak outdoor temperatures in winter compared to the other two countries. Moreover, Sweden presents the highest percentage among surveyed countries, i.e. 45%, of respondents that believe that homes should be warm enough in winter to wear lightweight clothing. However, in line with Germany, only about 7% of respondents argue excessively warm homes. These outcomes suggest that Swedes can tolerate and are comfortable with lower air temperatures in the cold season. In fact, the average preferred thermostat temperature in winter is 21.0 °C, i.e. lower than in the other two countries. Concerning the existing heating systems, most of the buildings are heated either by district heating (43%) or electrically driven heating systems such as heat pumps. The latter is mainly used in the outskirts and rural areas, where district heating is not available. Accordingly, the heating system is often turned off and on automatically. As regards ventilation, air tightness is considered of utmost importance, and all windows are double glazed or, in new buildings, triple glazed. During summer, it is common to ventilate excess heat by opening the windows, while during the rest of the year, ventilation by opening windows is not encouraged and is used only for short periods to exchange air (59%).

3.2. User-building interaction models

Based on the above-described findings of the survey, several insights are obtained for the development of the different user-building interaction schedules listed before. As previously mentioned, only some behaviors and practices could be inferred from the results of the survey, i.e. thermostat operation and heating practices and natural ventilation control in winter. The remaining schedules are defined according to existing knowledge in literature, starting from the specific profile of occupancy presence in each country, i.e. Spain (Cuerda et al., 2019), Germany (Weissmann et al., 2017), and Sweden (SVEBY, 2012; Widén, 2010) and user-building interaction models (Day et al., 2020). The considered occupancy presence schedules are reported in Figs. 1, 2, and 3 for Spain, Germany, and Sweden, respectively, which show the occupancy presence in a typical working day and weekend for the building as whole and for the living and sleeping area separately. Figs. 1a, 2a, and 3a show that Spanish and Swedish families are expected to leave the house later in the morning compared to Germans, both in weekdays and weekends. During the daytime of a typical working day, the whole German and Swedish family is mainly expected not to be at home, while the Spanish profile accounts for the possibility of some components of the family to stay at home during daytime. Regarding the evening hours, families in all countries are mainly expected to be at home in weekdays. Additional differences are found, instead, in terms of weekend occupancy. Both German and Spanish families are assumed to be half time at home and half time out during the daytime in weekends, while the Swedish family is mainly assumed to be out during the central hours of the day. These occupancy presence schedules are average profiles for each case study country and, therefore, they do not take into account singular conditions, e.g. work over time. Anyway, during some hours of the day, the probability that occupants may or may not be at home is accounted for using schedule fractions (see the schedules in Appendix).

Table 1 summarizes the mean preferred thermostat temperatures in winter in the three countries, according to the results of the survey. The results of the survey showed a high heterogeneity among the reported preferred heating temperatures, which suggests a variable range of preferences or a lack of understanding about temperature (Sovacool et al., 2021a). However, when considering the average value in each country, it is shown

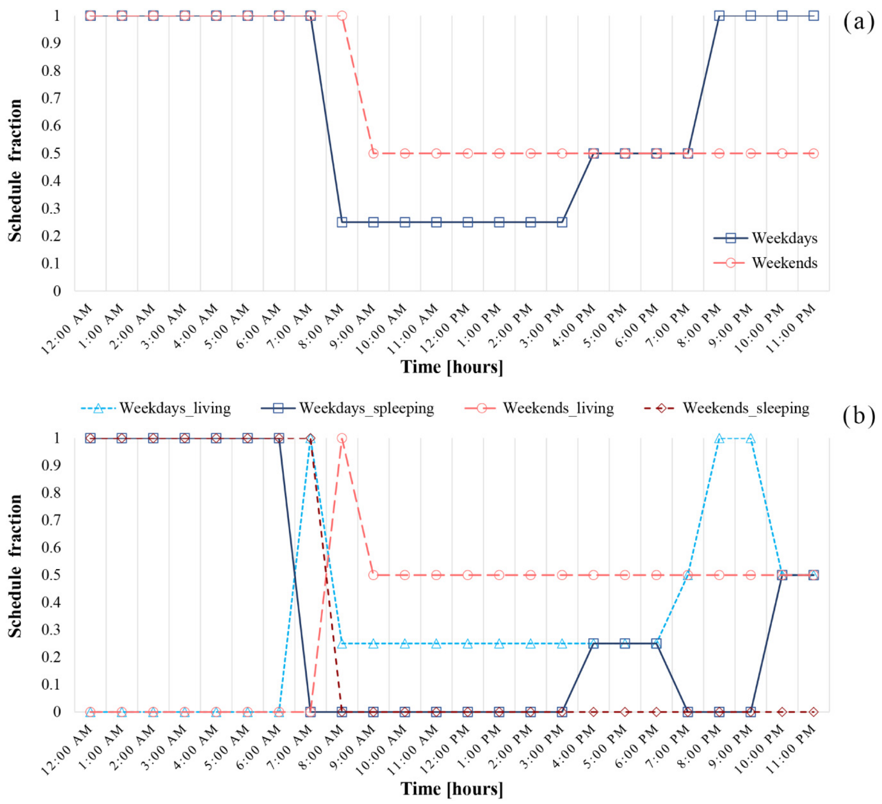

Fig. 1. Occupancy presence profile for (a) the whole building and (b) the living and the sleeping area in a typical weekday and weekend in Spain.

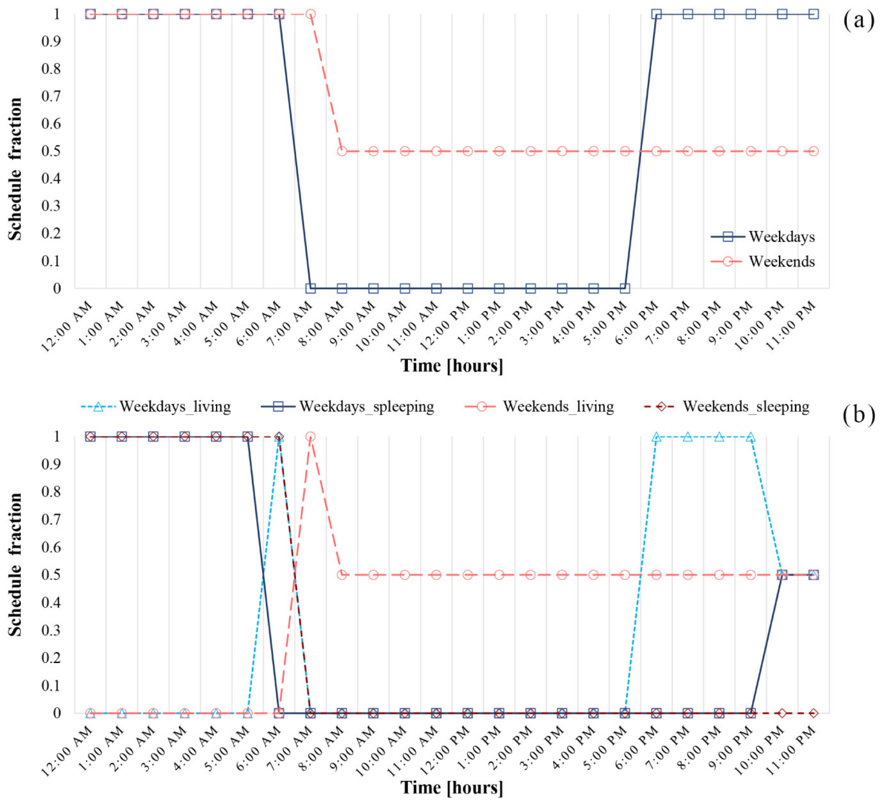

Fig. 2. Occupancy presence profile for (a) the whole building and (b) the living and the sleeping area in a typical weekday and weekend in Germany.

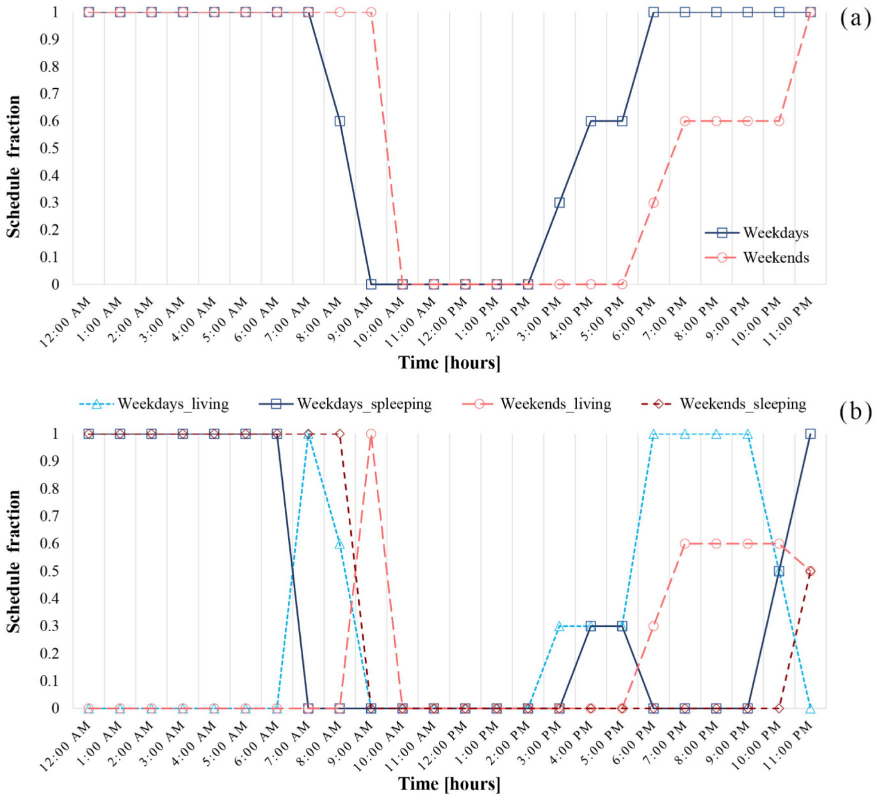

Fig. 3. Occupancy presence profile for (a) the whole building and (b) the living and the sleeping area in a typical weekday and weekend in Sweden.

to progressively decrease when moving from the milder to the colder climate. By the way, the observed average heating set-point temperatures are all quite high for residential buildings. Moreover, the survey allowed to point out different common or acceptable practices of heating use during the year and during the day for the three countries. In particular, in Spain, the heating system is usually switched-on on only during some months, while 35% and 22% of respondents in Germany and Sweden, respectively, seem favorable to leave it switched-on all year round. Moreover, 38% of Swedish respondents switch-on the heating system also for the sake of their pets, given the extreme outdoor temperatures in winter. This outcome suggests that the house could be heated even when people are out of the house. All these insights can be taken into account when modeling the annual and daily schedules of heating use for each country. Although some of those heating practices have been indicated by the respondents as common or acceptable practices – and not as actual practices – they were partially taken into account in the models to assess the worst plausible case.

Additionally, the survey results provide insights about windows opening practices in winter. In Spain, windows are expected to be opened occasionally during winter by the majority of the respondents. Similarly, in Sweden, natural ventilation is mainly used in the cold season to let in fresh air for short periods during the day. On the contrary, in Germany, windows are opened more often and even for long periods, even in the few cases when the building is equipped with mechanical ventilation. These data are used for the development of the natural ventilation control schedule for each country.

The schedules developed for each country based on the results of the survey are reported in their compact format in Appendix attached to the paper. As for DHW use, lighting use, and equipment use since no insight could be inferred from the survey, they will be developed based on the occupancy presence schedule, according to standard practice (Mahdavi et al., 2017). The survey provides no information also concerning windows shading operation. However, indications for the development of the related schedule are gathered from existing knowledge (Piselli et al., 2018). In Spain, window shadings are usually present and used yearly. Common types are blinds and similar. In Germany, these systems are mostly used during summer. Typical window shadings are roller shutters, curtains, and window shutters. In Sweden, they are used sparsely and only in locations where the sun load is disturbing during summer. Finally, regarding mechanical ventilation, the results of the survey only suggest that few households are equipped with this technology in all three considered countries. Therefore, no specific schedule is developed for mechanical ventilation use. To the purpose of building dynamic simulation, it will be modeled according to standard practices.

Table 1
Heating thermostat temperature per-country.

Country	Heating thermostat temperature (°C)
Spain	21.8
Germany	21.3
Sweden	21.0

3.3. User-building interaction models influence on residential building energy performance

Results of dynamic simulation of the two standard residential building typologies in the three considered climate contexts are analyzed in terms of total energy performance for heating. The purpose of this analysis is to assess the influence of implementing tailored user-building interaction schedules on the predicted energy performance of buildings, compared to standard occupancy models. Therefore, the annual heating energy need obtained when using the developed models is compared against

Table 2
Total heating energy needs for standard single-family house and mid-rise apartment building in Sweden, Germany, and Spain with tailored user-building interaction schedules vs. standard occupant behavior model.

Climate context	Building typology	Annual heating energy [kWh/m^2]		% variation
		Standard	*Customized*	
Stockholm, Sweden	Single-family house	177.02	136.83	−22.7
	Mid-rise apartment building	57.64	32.88	−43.0
Regensburg, Germany	Single-family house	143.44	104.59	−27.1
	Mid-rise apartment building	38.63	22.71	−41.2
Madrid, Spain	Single-family house	79.41	59.35	−25.3
	Mid-rise apartment building	13.60	9.41	−30.8

the one obtained with standard occupant behavior models for each residential building typology in each country.

The heating energy performance of the twelve simulated models are summarized in Table 2. As expected, in general, the heating energy needs of both buildings progressively decreases when moving from the coldest climate context of northern Europe to the warmest of southern Europe. Moreover, the total heating energy is significantly different between the two building typologies in all climate contexts. Nevertheless, this finding is not relevant to the purposes of this study, since it is related to the characteristics of the considered ASHRAE standard models, which have not been modified. The relevant outcome of this analysis is the non-negligible variation of the predicted heating energy need between the building model implementing a standard occupant behavior model and the same one implementing tailored user-building interaction schedules that take into account the specific cultural context.

Interestingly, this result is found for both building typologies and in every climate context, up to 43% variation in the coldest climate of Stockholm, Sweden, for the midrise apartment building. The percentage variation decreases when moving to the warmer climates of Regensburg, Germany (about 41%) and Madrid, Spain (about 31%). On the other hand, in the single-family house, percentage variation is similar among climate contexts, i.e. about 23% in Stockholm, 27% in Regensburg, and 25% in Madrid. However, the variation in terms of kWh/m2 is rather different, especially in the mildest climate of Madrid.

In addition, the results of the survey seem to suggest rather energy-intensive behavior on average in the considered countries — some more than others. In other words, while some households reveal elastic patterns to heat demand or practices – changing them based on the weather, the season, or changes in price – others are inelastic, and fail to change them based on any of these factors, especially for homes that prioritize convenience or comfort over cost or sustainability (Sovacool et al., 2020). Some patterns of heating are not influenced strongly by seasonal context or market prices, but instead driven by household preferences.

Moreover, the results of dynamic simulation show lower annual heating energy need in all *customized* models compared to the corresponding *standard* model. This is mainly due to the standard occupancy schedule that tends to overrate occupants' presence at home and, therefore, the operation of the heating system and the other associated schedules that influence building energy performance in winter.

This simple test bed further demonstrated the importance to use tailored occupant-building interaction models embedding not only climate but also culture-related factors of the specific context of application when predicting the energy performance of a building or system. Additionally, the quantification of such variability as primarily imputable to user-building interaction influenced by societal related variables is made possible thanks to the extensive survey, which may be considered as representative of societal attitudes, as already reported in social science publications by partnership of the Horizon 2020 SWS HEATING project (Sovacool et al., 2021b,a).

4. Conclusion

Buildings do not use energy by definition, people do (Janda, 2011). That is why a quantitative assessment of energy final use variability is needed with referring to different societal schemes, norms, and daily energy related attitudes with varying environmental and human-centered boundary conditions. That is why, for the first time, a large-scale survey with more than 6000 participants is used to directly quantify user behavior role in final energy need, with special attention on heating demand.

In this view, within the framework of the H2020 project SWS-HEATING, which has the purpose to design and evaluate the performance of an innovative STES system for heating, this work provides the human-centered boundary conditions to be considered for the assessment of the system, i.e. user-building interaction models. In fact, tailor-made occupant behavior models are developed to more precisely assess the performance and applicability of the proposed system in specific climate and cultural contexts of application. To this aim, these models are newly developed starting from the evidence raised by the results of an extensive survey questionnaire eliciting users' expectations and practices in interacting with heating systems in different European countries, i.e. Sweden, Germany, and Spain.

Different occupant behaviors in the form of occupant-building interaction schedules are selected as able to influence the thermal-energy performance of the building and its heating energy needs. Therefore, deterministic occupant behavior models are developed by combining these schedules to represent three different climate and cultural contexts in south, central, and north Europe, namely Spain, Germany, and Sweden. Given the survey focus on heating preferences and practices, only some among the user-building interaction schedules commonly implemented in dynamic simulation could be inferred from the results of the survey, i.e. thermostat operation and heating switch-on practices and natural ventilation control in winter. The other schedules are defined according to existing knowledge, starting from the profile of occupancy presence in each country.

The outcomes of this study are summarized as follows:

- The survey pointed out relevant differences in terms of occupant behavior among the considered countries, thus providing international comparison as an added value to the existing literature, where studies are often focused on a single country.
- The main results from the survey are the following:
  - the preferred thermostat temperatures in winter decreases when moving from the milder to the colder climate, i.e. from 21.8 °C in Spain, to 21.3 °C in Germany, to 21.0 °C in Sweden. However, the observed average heating set-point temperatures are all quite high for residential buildings;
  - heating switch-on period during the year and during the day varies depending on the context, having less impact in the milder climate context (Spain);

    - the analysis of windows opening practices in winter show that in Spain and Sweden, windows are expected to be opened occasionally and for short periods during the day to let in fresh air. On the contrary, in Germany, natural ventilation is used more often and even for long periods, which is in line with existing studies in literature (Bauer et al., 2021).

- The insights from the survey results are used for the development of the related user-building interaction schedules to form country-representative models. This approach is consistent with few studies presented in the literature review (Section 1), who applied this method in lower scale.
- The results of dynamic simulation of standard residential buildings using the developed tailored user-building interaction models confirmed the importance to use country-specific models:
    - non-negligible variation in terms of predicted heating energy needs is observed when implementing models that take into account cultural factors and their relation to heating practices, compared to standard occupant behavior models, in accordance with the acknowledged literature addressing the role of occupant behavior in building energy performance evaluation (Carlucci et al., 2020a);
    - the percentage difference between *standard* and *customized* models is up to 43% in the coldest climate, 41% in the middle one, and 31% in the mildest climate, demonstrating that the heating performance variation is not only associated to climate peculiarity, but societal norms are also sensitive to other constraints and are intrinsically better variable according to personal preferences;
    - Some heating practices and patterns of demand are inelastic and not strongly shaped by seasonal factors or changes in price.

Future developments of this work will consist in the implementation of the developed models in building dynamic simulation for the assessment of the performance of the innovative STES system for heating developed within the project and other innovative heating systems. Furthermore, the developed user-building interaction models should be validated against experimental data for the different countries in order to assess their effective reliability. Finally, the economics around the developed STES unit need to be investigated, even in connect with its thermal energy performance, towards its marketability.

CRediT authorship contribution statement

C. Piselli: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **A.L. Pisello:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **B.K. Sovacool:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – review & editing, Visualization, Supervision, Funding acquisition.

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.

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Appendix

The user-building interaction schedules developed for each climate context (i.e. Spain, Germany, and Sweden, representing south, central, and north Europe, respectively) based on the results of the survey are reported as follows in their compact format. The occupancy presence schedule is also reported in the compact format.

Spain

(1) Occupancy presence:

Living area	Sleeping area
Schedule:Compact, Fraction, Through: 31 Dec, For: Weekdays, Until: 7:00, 0, Until: 8:00, 1, Until: 19:00, 0.25, Until: 20:00, 0.5, Until: 22:00, 1, Until: 24:00, 0.5, For: Weekend, Until: 8:00, 0, Until: 9:00, 1, Until: 24:00, 0.5, For: Holidays, Until: 24:00, 0;	Schedule:Compact, Fraction, Through: 31 Dec, For: Weekdays, Until: 7:00, 1, Until: 16:00, 0, Until: 19:00, 0.25, Until: 22:00, 0, Until: 24:00, 0.5, For: Weekend, Until: 8:00, 1, Until: 24:00, 0, For: Holidays, Until: 24:00, 0;

(2) Heating thermostat operation:

Living area	Sleeping area
Schedule:Compact, Temperature, Through: 31 Dec, For: Weekdays, Until: 7:00, 18, Until: 24:00, 21.8, For: Weekend, Until: 8:00, 18, Until: 24:00, 21.8, For: Holidays, Until: 24:00, 18;	Schedule:Compact, Temperature, Through: 31 Dec, For: Weekdays, Until: 7:00, 18, Until: 8:00, 21.8, Until: 16:00, 18, Until: 24:00, 21.8, For: Weekend, Until: 8:00, 18, Until: 9:00, 21.8, Until: 22:00, 18, Until: 24:00, 21.8, For: Holidays, Until: 24:00, 18;

(3) Natural ventilation control (in winter months):

Living area	Sleeping area
Schedule:Compact, Air Changes per Hour (ACH), For: Weekdays, Until: 24:00, 0.4, For: Weekend, Until: 24:00, 0.4, For: Holidays, Until: 24:00, 0.3;	Schedule:Compact, Air Changes per Hour (ACH), For: Weekdays, Until: 24:00, 0.4, For: Weekend, Until: 24:00, 0.4, For: Holidays, Until: 24:00, 0.3;

Germany

(1) Occupancy presence:

Living area	Sleeping area
Schedule:Compact, Fraction, Through: 31 Dec, For: Weekdays, Until: 6:00, 0, Until: 7:00, 1, Until: 18:00, 0, Until: 22:00, 1, Until: 24:00, 0.5, For: Weekend, Until: 7:00, 0, Until: 8:00, 1, Until: 24:00, 0.5, For: Holidays, Until: 24:00, 0;	Schedule:Compact, Fraction, Through: 31 Dec, For: Weekdays, Until: 6:00, 1, Until: 22:00, 0, Until: 24:00, 0.5, For: Weekend, Until: 7:00, 1, Until: 24:00, 0, For: Holidays, Until: 24:00, 0;

(2) Heating thermostat operation:

Living area	Sleeping area
Schedule:Compact, Temperature, Through: 31 Dec, For: Weekdays, Until: 6:00, 18, Until: 7:00, 21.3, Until: 18:00, 18, Until: 24:00, 21.3, For: Weekend, Until: 7:00, 18, Until: 24:00, 21.3, For: Holidays, Until: 24:00, 18;	Schedule:Compact, Temperature, Through: 31 Dec, For: Weekdays, Until: 6:00, 18, Until: 7:00, 21.3, Until: 20:00, 18, Until: 24:00, 21.3, For: Weekend, Until: 7:00, 18, Until: 8:00, 21.3, Until: 22:00, 18, Until: 24:00, 21.3, For: Holidays, Until: 24:00, 18;

(3) Natural ventilation control (in winter months):

Living area	Sleeping area
Schedule:Compact, Air Changes per Hour (ACH), For: Weekdays, Until: 18:00, 0.3, Until: 18:30, 2, Until: 24:00, 0.3, For: Weekend, Until: 12:00, 0.3, Until: 12:30, 2, Until: 18:00, 0.3, Until: 18:30, 2, Until: 24:00, 0.3, For: Holidays, Until: 24:00, 0.3;	Schedule:Compact, Air Changes per Hour (ACH), For: Weekdays, Until: 6:00, 0.3, Until: 6:30, 2, Until: 24:00, 0.3, For: Weekend, Until: 7:00, 0.3, Until: 7:30, 2, Until: 24:00, 0.3, For: Holidays, Until: 24:00, 0.3;

Sweden

(1) Occupancy presence:

Living area	Sleeping area
Schedule:Compact, Fraction, Through: 31 Dec, For: Weekdays, Until: 7:00, 0, Until: 8:00, 1, Until: 9:00, 0.6, Until: 15:00, 0, Until: 18:00, 0.3, Until: 22:00, 1, Until: 23:00, 0.5, Until: 24:00, 0, For: Weekend, Until: 9:00, 0, Until: 10:00, 1, Until: 18:00, 0, Until: 19:00, 0.3, Until: 23:00, 0.6, Until: 24:00, 0.5, For: Holidays, Until: 24:00, 0;	Schedule:Compact, Fraction, Through: 31 Dec, For: Weekdays, Until: 7:00, 1, Until: 16:00, 0, Until: 18:00, 0.3, Until: 22:00, 0, Until: 23:00, 0.5, Until: 24:00, 1, For: Weekend, Until: 9:00, 1, Until: 23:00, 0, Until: 24:00, 0.5, For: Holidays, Until: 24:00, 0;

(2) Heating thermostat operation:

Living area	Sleeping area
Schedule:Compact, Temperature, Through: 31 Dec, For: Weekdays, Until: 7:00, 19, Until: 9:00, 21, Until: 15:00, 19, Until: 23:00, 21, Until: 24:00, 19, For: Weekend, Until: 9:00, 19, Until: 10:00, 21, Until: 18:00, 19, Until: 24:00, 21, For: Holidays, Until: 24:00, 19;	Schedule:Compact, Temperature, Through: 31 Dec, For: Weekdays, Until: 7:00, 19, Until: 9:00, 21, Until: 16:00, 19, Until: 23:00, 21, Until: 24:00, 19, For: Weekend, Until: 9:00, 19, Until: 10:00, 21, Until: 21:00, 19, Until: 24:00, 21, For: Holidays, Until: 24:00, 19;

(3) Natural ventilation control and infiltration (in winter months):

Living area	Sleeping area
Schedule:Compact,	Schedule:Compact,
Air Changes per Hour (ACH),	Air Changes per Hour (ACH),
For: Weekdays,	For: Weekdays,
Until: 24:00, 0.4,	Until: 24:00, 0.4,
For: Weekend,	For: Weekend,
Until: 24:00, 0.4,	Until: 24:00, 0.4,
For: Holidays,	For: Holidays,
Until: 24:00, 0.3;	Until: 24:00, 0.3;

References

Abdelkader, O.A., 2020. Impact of perception on willingness and behavior of individuals toward switching to sustainable energy practices in buildings. Energy Rep. 6, 2119–2125. http://dx.doi.org/10.1016/J.EGYR.2020.07.031.

Almeida, L.M.M.C.E., Tam, V.W.Y., Le, K.N., 2020. Quantification of the energy use due to occupant behaviour collected in surveys: a case study of a green and non-green building. J. Build. Perform. Simul. 13, 777–803. http://dx.doi.org/10.1080/19401493.2020.1825529.

Annaqeeb, M.K., Azar, E., Yan, D., Novakovic, V., 2020. Evaluating occupant perceptions of their presence and energy-use patterns in shared office spaces. In: 16th Conference of the International Society of Indoor Air Quality and Climate: Creative and Smart Solutions for Better Built Environments, Indoor Air 2020. International Society of Indoor Air Quality and Climate.

ANSI/ASHRAE/IES, 2016. ASHRAE Standard 90.1-2016 - Energy Standard for Buildings Except Low-Rise Residential Buildings.

ASHRAE, 2001. ASHRAE Standard 140-2001, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Program.

Bauer, A., Möller, S., Gill, B., Schröder, F., 2021. When energy efficiency goes out the window: How highly insulated buildings contribute to energy-intensive ventilation practices in Germany. Energy Res. Soc. Sci. 72, 101888. http://dx.doi.org/10.1016/J.ERSS.2020.101888.

Braulio-Gonzalo, M., Bovea, M.D., Jorge-Ortiz, A., Juan, P., 2021. Contribution of households' occupant profile in predictions of energy consumption in residential buildings: A statistical approach from mediterranean survey data. Energy Build. 241, 110939. http://dx.doi.org/10.1016/j.enbuild.2021.110939.

Carletti, C., Pierangioli, L., Sciurpi, F., Salvietti, A., 2018. Comparison among detailed and simplified calculation methods for thermal and energy assessment of the building envelope and the shadings of a new wooden nZEB house. Sustain. 10 (476), http://dx.doi.org/10.3390/SU10020476.

Carlucci, Salvatore, De Simone, M., Firth, S.K., Kjærgaard, M.B., Markovic, R., Rahaman, M.S., Annaqeeb, M.K., Biandrate, S., Das, A., Dziedzic, J.W., Fajilla, G., Favero, M., Ferrando, M., Hahn, J., Han, M., Peng, Y., Salim, F., Schlüter, A., van Treeck, C., 2020a. Modeling occupant behavior in buildings. Build. Environ. 174, 106768. http://dx.doi.org/10.1016/J.BUILDENV.2020.106768.

Carlucci, S., De Simone, M., Firth, S.K., Kjærgaard, M.B., Markovic, R., Rahaman, M.S., Annaqeeb, M.K., Biandrate, S., Das, A., Dziedzic, J.W., Schlüter, A., van Treeck, C., 2020b. Modeling occupant behavior in buildings. Build. Environ. 174, 106768. http://dx.doi.org/10.1016/j.buildenv.2020.106768.

Chen, J., Wang, X., Steemers, K., 2013. A statistical analysis of a residential energy consumption survey study in Hangzhou, China. Energy Build. 66, 193–202. http://dx.doi.org/10.1016/j.enbuild.2013.07.045.

Crawley, D.B., Pedersen, C.O., Lawrie, L.K., Winkelmann, F.C., 2000. Energy plus: Energy simulation program. ASHRAE J. 42, 49–56.

Cuerda, E., Guerra-Santin, O., Sendra, J.J., Neila González, F.J., 2019. Comparing the impact of presence patterns on energy demand in residential buildings using measured data and simulation models. Build. Simul. 12, 985–998. http://dx.doi.org/10.1007/s12273-019-0539-z.

Da, Y., Hong, T., 2018. IEA-EBC Annex 66 - Definition and Simulation of Occupant Behavior in Buildings: Final Report.

Day, J.K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., O'Brien, W., Rajus, V.S., De Simone, M., Kjærgaard, M.B., Pritoni, M., Schlüter, A., Peng, Y., Schweiker, M., Fajilla, G., Becchio, C., Fabi, V., Spigliantini, G., Derbas, G., Pisello, A.L., 2020. A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort. Build. Environ. 178, 106920. http://dx.doi.org/10.1016/j.buildenv.2020.106920.

Đurišić, V., Rogić, S., Smolović, J.C., Radonjić, M., 2020. Determinants of household electrical energy consumption: Evidences and suggestions with application to Montenegro. Energy Rep. 6, 209–217. http://dx.doi.org/10.1016/J.EGYR.2019.10.039.

EPISCOPE, 2012. IEE Project TABULA: Typology Approach for Building Stock Energy Assessment, 2009-2012 [WWW Document]. URL http://episcope.eu/iee-project/tabula/ (accessed 4.11.22).

Eurostat Statistics Explained, 2017. Archive: People in the EU - Statistics on Household and Family Structures [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:People_in_the_EU_-_statistics_on_household_and_family_structures (accessed 3.26.21).

Feng, X., Yan, D., Hong, T., 2015. Simulation of occupancy in buildings. Energy Build. 87, 348–359. http://dx.doi.org/10.1016/j.enbuild.2014.11.067.

Gaetani, I., Hoes, P.J., Hensen, J.L.M., 2016. Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy. Energy Build. 121, 188–204. http://dx.doi.org/10.1016/j.enbuild.2016.03.038.

He, Z., Hong, T., Chou, S.K., 2021. A framework for estimating the energy-saving potential of occupant behaviour improvement. Appl. Energy 287, 116591. http://dx.doi.org/10.1016/j.apenergy.2021.116591.

Heydarian, A., McIlvennie, C., Arpan, L., Yousefi, S., Syndicus, M., Schweiker, M., Jazizadeh, F., Rissetto, R., Pisello, A.L., Piselli, C., Yan, Z., Mahdavi, A., 2020. What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories. Build. Environ. 179, 106928. http://dx.doi.org/10.1016/j.buildenv.2020.106928.

Hong, T., Chen, Y., Belafi, Z., D'Oca, S., 2018. Occupant behavior models: A critical review of implementation and representation approaches in building performance simulation programs. Build. Simul. 11, 1–14. http://dx.doi.org/10.1007/s12273-017-0396-6.

Hong, T., Yan, D., D'Oca, S., Chen, C. fei, 2017. Ten questions concerning occupant behavior in buildings: The big picture. Build. Environ. 114, 518–530. http://dx.doi.org/10.1016/j.buildenv.2016.12.006.

Janda, K.B., 2011. Buildings don't use energy: people do. Archit. Sci. Rev. 54, 15–22. http://dx.doi.org/10.3763/asre.2009.0050.

Mahdavi, A., Tahmasebi, F., Gunay, H.B., O'Brien, W., D'Oca, S., 2017. IEA-EBC Annex 66 - Definition and Simulation of Occupant Behavior in Buildings. Technical Report: Occupant Behavior Modeling Approaches and Evaluation.

Martinaitis, V., Zavadskas, E.K., Motuziene, V., Vilutiene, T., 2015. Importance of occupancy information when simulating energy demand of energy efficient house: A case study. Energy Build. 101, 64–75. http://dx.doi.org/10.1016/j.enbuild.2015.04.031.

Masrahi, A., Wang, J.H., Abudiyah, A.K., 2021. Factors influencing consumers' behavioral intentions to use renewable energy in the United States residential sector. Energy Rep. 7, 7333–7344. http://dx.doi.org/10.1016/J.EGYR.2021.10.077.

McLoughlin, F., Duffy, A., Conlon, M., 2012. Characterising domestic electricity consumption patterns by dwelling and occupant socio-economic variables: An Irish case study. Energy Build. 48, 240–248. http://dx.doi.org/10.1016/j.enbuild.2012.01.037.

Piselli, C., Pisello, A.L., 2019. Occupant behavior long-term continuous monitoring integrated to prediction models: Impact on office building energy performance. Energy 176, 667–681. http://dx.doi.org/10.1016/J.ENERGY.2019.04.005.

Piselli, C., Pisello, A.L., Cotana, F., Pigliautile, I., Di Grazia, M., Pioppi, B., Landi, F., Cabeza, L.F., Kokorelia, A., Kokorelia, L., Palm, B., Larijani, H.M., Dawoud, B., Brancato, V., Frazzica, A., Karellas, S., Mandilaras, I., Leontaritis, A., 2018. SWS-HEATING Project - Deliverable 2.1: Definition of Climate and Building Typologies Boundary Conditions. Perugia, Italy.

Pisello, A.L., Castaldo, V.L., Piselli, C., Fabiani, C., Cotana, F., 2016. How peers' personal attitudes affect indoor microclimate and energy need in an institutional building: Results from a continuous monitoring campaign in summer and winter conditions. Energy Build. 126, 485–497. http://dx.doi.org/10.1016/j.enbuild.2016.05.053.

Pisello, A.L., Piselli, C., Cotana, F., 2015. Influence of human behavior on cool roof effect for summer cooling. Build. Environ. 88, 116–128. http://dx.doi.org/10.1016/j.buildenv.2014.09.025.

Qadir, S.A., Al-Motairi, H., Tahir, F., Al-Fagih, L., 2021. Incentives and strategies for financing the renewable energy transition: A review. Energy Rep. 7, 3590–3606. http://dx.doi.org/10.1016/J.EGYR.2021.06.041.

Sovacool, B.K., Cabeza, L.F., Pisello, A.L., Fronzetti Colladon, A., Larijani, H.M., Dawoud, B., Martiskainen, M., 2021a. Decarbonizing household heating: Reviewing demographics, geography and low-carbon practices and preferences in five European countries. Renew. Sustain. Energy Rev. 139, 110703. http://dx.doi.org/10.1016/j.rser.2020.110703.

Sovacool, B.K., Demski, C., Noel, L., 2021b. Beyond climate, culture and comfort in European preferences for low-carbon heat. Glob. Environ. Chang. 66, 102200. http://dx.doi.org/10.1016/j.gloenvcha.2020.102200.

Sovacool, B.K., Osborn, J., Martiskainen, M., Lipson, M., 2020. Testing smarter control and feedback with users: Time, temperature and space in household heating preferences and practices in a Living laboratory. Glob. Environ. Chang. 65, 102185. http://dx.doi.org/10.1016/j.gloenvcha.2020.102185.

SVEBY, 2012. Standardization of Household Energy Use in Sweden (Brukarindata Bostäder). Stockholm, (in Swedish), Branschstandard för energi i byggnader.

Umweltbundesamt (UBA), 2017. Richtig Lüften, Schimmelbildung Vermeiden (in German) [WWW Document]. URL https://www.umweltbundesamt.de/themen/gesundheit/umwelteinfluesse-auf-den-menschen/schimmel/richtig-lueften-schimmelbildung-vermeiden (accessed 8.29.18).

U.S. Department of Energy's (DOE) Building Technologies Office (BTO), 2016. EnergyPlus - Weather Data [WWW Document]. URL https://energyplus.net/weather (accessed 11.17.17).

Weissmann, C., Hong, T., Graubner, C.A., 2017. Analysis of heating load diversity in german residential districts and implications for the application in district heating systems. Energy Build. 139, 302–313. http://dx.doi.org/10.1016/j.enbuild.2016.12.096.

Widén, J., 2010. System Studies and Simulations of Distributed Photovoltaics in Sweden. Uppsala University.

Xu, X., Taylor, J.E., Pisello, A.L., 2014. Network synergy effect: Establishing a synergy between building network and peer network energy conservation effects. Energy Build. 68, 312–320. http://dx.doi.org/10.1016/j.enbuild.2013.09.017.