IEA EBC Annex 53: Total Energy Use in Buildings – Analysis and Evaluation Methods

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Abstract

One of the most significant barriers to achieving deep building energy efficiency is a lack of knowledge about the factors determining energy use. In fact, there is often a significant discrepancy between designed and real energy use in buildings, which is poorly understood but are believed to have more to do with the role of human behavior than building design. Building energy use is mainly influenced by six factors: climate, building envelope, building services and energy systems, building operation and maintenance, occupants' activities and behavior, and indoor environmental quality. In the past, much research focused on the first three factors. However, the next three human-related factors can have an influence as significant as the first three. Annex 53 employed an interdisciplinary approach, integrating building science, architectural engineering, computer modeling and simulation, and social and behavioral science to develop and apply methods to analyze and evaluate the real energy use in buildings considering the six influencing factors. Outcomes from Annex 53 improved understanding and strengthen knowledge regarding the robust prediction of total energy use in buildings, enabling reliable quantitative assessment of energy-savings measures, policies, and techniques.

Keywords*:* real energy use; occupant behavior; energy modeling; performance evaluation; energy data definition; energy monitoring

1. Introduction

Globally the building sector consumed more than one-third of the total primary energy. Improving energy efficiency in buildings to reduce energy use and green-house-gas emissions is a proven key strategy to mitigate global climate change. Although building technologies have advanced significantly in last decades, one of the most significant barriers to substantially improving the energy efficiency of buildings is the lack of knowledge about the factors determining the energy use. There is often a significant discrepancy between the designed and real total energy use in buildings. The reasons for this divergence are poorly understood and often have more to do with the role of human behavior than the building design. This discrepancy leads to misunderstanding and miscommunication between the parties involved in the topic of energy savings in buildings.

In fact, building energy consumption is mainly influenced by six factors: (1) climate, (2) building envelope, (3) building services and energy systems, (4) building operation and maintenance, (5) occupant activities and behavior and (6) indoor environmental quality provided. The latter three factors, related to human behavior, can have an influence as great as or greater than the former three [1, 2, 3]. The user-related aspects and behavior effects can be seen from the large spread in energy use for similar or identical buildings, but a distinction between the building-related and the user-related energy consumption cannot be established. It is necessary to investigate all six factors together to understand building energy consumption data. Detailed comparative analysis of building energy data, concerning the six factors mentioned above, would provide essential guidance to identify opportunities to save energy.

Aiming to advance the knowledge in the field and develop and apply methods to analyze and evaluate total energy use in buildings and its driving factors, a group of about 100 researchers from 15 countries gathered together and worked from January 2009 to March 2013 on the Annex 53 project, under International Energy Agency's (IEA) Energy in Buildings and Communities (EBC) Programme. Annex 53 was organized into four subtasks and one taskforce: (1) Subtask A - Definition and reporting, (2) Subtask B - Case Studies and Data Collection, (3) Subtask C - Statistical Analysis, (4) Subtask D - Energy Performance Evaluation, and (5) Task force - Occupant behavior.

Annex 53 employs an interdisciplinary approach, integrating building science, architectural engineering, computer modeling and simulation, and social and behavioral science. The ultimate goal of Annex 53 is to better understand and strengthen knowledge regarding the robust prediction of total energy usage in buildings, thus enabling the assessment of energy-saving measures, policies, and techniques. This annex studies how occupant behavior influences building energy consumption in order to bring occupant behavior into the building energy field so as to develop building energy research, practice, policy, etc. more closely aligned with the real world. The research was performed on two building types: residential buildings (detached houses and multi-family apartments) and office buildings (large scale high rise offices and small scale offices). The main objectives of Annex 53 were to develop and demonstrate the following:

- Definitions of terms related to energy use and the influencing factors of building energy use
- An approach to describing occupant behavior quantitatively and to setting up a model for occupant behavior
- Database of energy use and influencing factors for existing typical buildings in different countries
- Methodologies and techniques for monitoring total energy use in buildings including hardware and software platforms
- A statistical model for national or regional building energy data including the influence of occupant behavior
- Methodologies to predict total energy use in buildings and to assess/evaluate the impacts of energy saving policies and techniques

This paper highlights main research methods, findings, and outcomes of Annex 53, drawing some content from Annex 53's published reports [4-10].

2. Influencing factors on building energy use

Energy use in buildings is mainly influenced by six factors as defined in Annex 53, see Figure 1. These factors may be organized into two groups of factors that can be classified as physical and human influenced. The first group of factors are technical and physical factors, because their origin is related to building envelope, climate, building service systems, and other issues that cannot be easily changed during building operation by humans. Even though they can be changed during building operation, but they are fixed physical parameters. The physical and technical factors give a background for the estimation of building energy performance. Factors that can be changed and are defined by humans and building occupants are classified as human-influenced factors. By adding the human factors into the picture of building energy use, we come to the actual energy use. There are different terms for this building performance, in some literature, this may be called actual or real energy use. The actual energy use is the real building energy performance. When developing a new building, data for the human-influenced factors may be found in standards or required by a new building owner. However, in general, when observing an existing building, these human factors may variate a lot and influence strongly the actual building functioning and actual energy use. Finally, when the building energy performance is calculated considering the standardized input data, the calculated building energy performance is obtained. However, this calculated energy performance is not strictly related to the actual energy use.

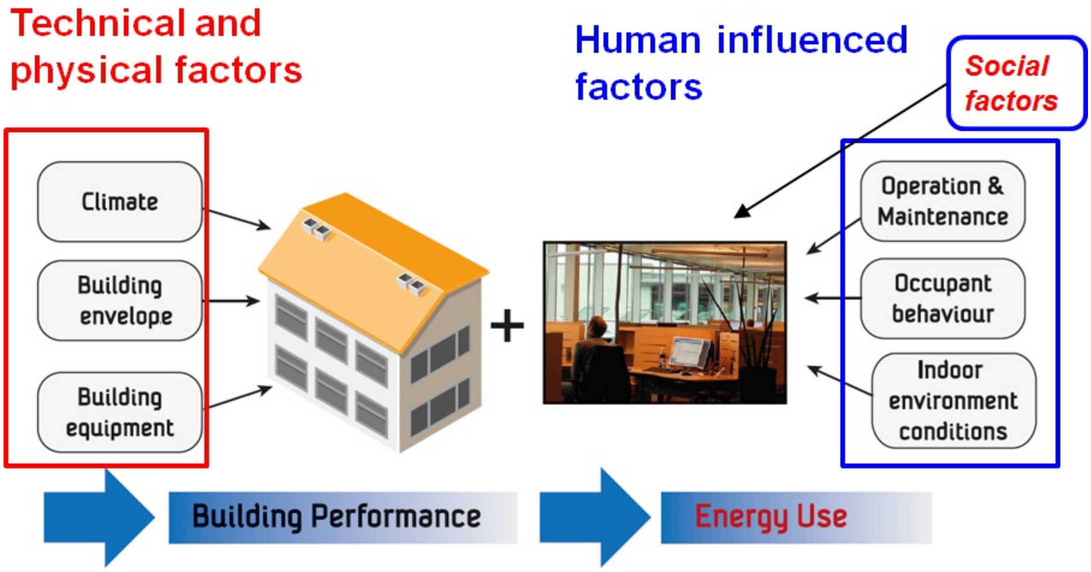


Figure 1 Six influencing factors on building energy use

In addition to the six influencing factors on building energy use given in Figure 1, there is one separate factor called social factor. Social aspects cover a huge field of parameters such as local habits on building use, energy price, dominating energy source in the certain area, the energy-related attitude of occupants, and political conditions. These influence also living standard and possibility of building users to pay energy bills or invest in energy efficiency measures. However, in the cases where it was possible, the social factor has been treated within the Annex 53. Based on the explanation of the social factor it is understandable that it is difficult to define them easily and in a generic way. Therefore, there might be many variations how this factor was treated.

Identification of the occupant behavior as one of the factors influencing the building energy use was one of the most important findings of Annex 53. The influence of the occupant behavior on energy use in buildings has been investigated in various domains: natural sciences and social sciences as well as economics. The literature review resulted in an overview and classification of driving forces that may trigger energy-related occupant behavior. The various classes can be distinguished into biological, psychological, and social contexts, time, building/installation properties, and physical environment. There are two purposes for modeling occupant behavior: (1) to understand driving forces for the behavior itself, and (2) to reveal the relationship between energy demand and usage, as well as the driving forces for variations. Within the framework of Annex 53, the focus was on the second purpose. The different reasons for modeling occupant behavior with respect to total energy use in buildings are design (conceptual, preliminary, and final), commissioning (initial and ongoing), and operation (control).

3. Building energy data definition and energy reporting

Inconsistency in the terminology related to building energy use is a serious barrier to understand the influencing factors on building energy use and to analyze real energy use. Therefore, a starting and highly necessary point with the Annex 53 was definitions of terms to describe total energy use in buildings, energy boundary, conversion factors, and energy performance indicators. This was highly important to enable comparability of datasets and expressions of building energy performance. The work resulted in the definition of energy boundaries for reporting whole building energy performance. The work also defined a variety of key building energy use terms.

Annex 53 deals with office buildings and residential buildings. Office buildings are organized into large and small buildings, as the magnitude of the factors influencing energy use in these two building types are often different from one another. Residential buildings include single detached houses and multi-family apartment buildings. Key terms describing building characteristics will vary among these four building types.

3.1. Definition of energy boundaries

Defining the energy boundaries was very important to enable comparability of the building energy use data. For example, energy used to meet only the cooling load is different from the energy used in air conditioning systems for cooling, as the latter includes energy conversion in the cooling device and the energy loss in air conditioning systems. Within Annex 53, three energy regions with two energy boundaries were introduced as shown in Figure 2. The definition of energy boundary in Annex 53 is a combination of the work in the standards ISO 16346 and ISO 12655 [11, 12]. These three regions present the following terms: energy demand E_B, energy delivered to technical systems in the building E_T, and delivered energy E_D.

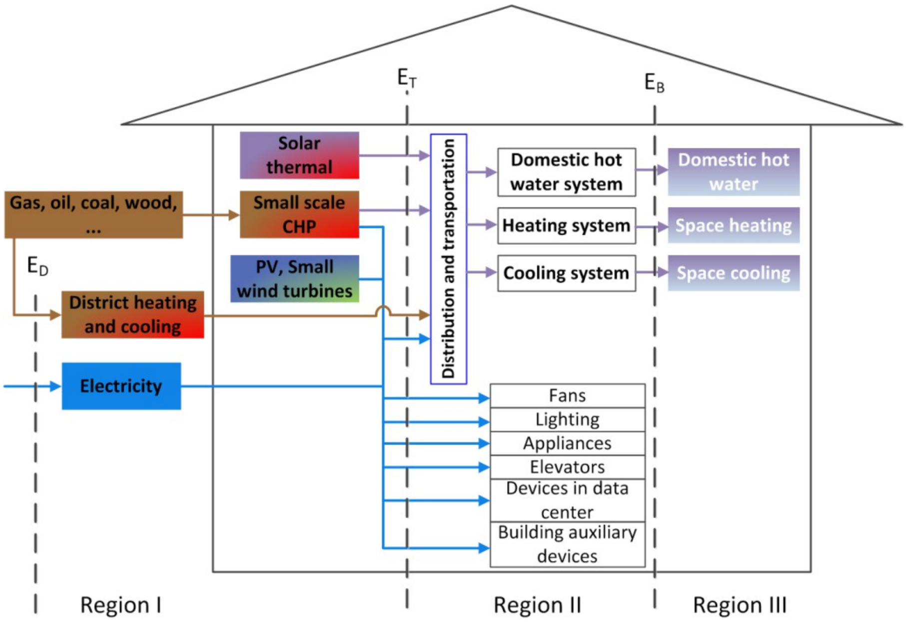


Figure 2 Energy boundaries

Figure 2 will be explained by going from right to left. In Figure 2, E_B presents the energy need within the building space for space heating, cooling, domestic hot water (DHW), lighting, and appliances. E_B is also called net energy need or energy demand. This is theoretically required energy to meet needs of the building occupants. The value of net energy demand will depend on assumptions about thermal comfort, usage, and other factors. It is useful for assessing the potential for energy savings on building envelope and use. In Figure 2, Region II or marked E_T encompasses all energy delivered to all the technical systems in the buildings. The efficiencies of converting the delivered energy to meet the basic needs in Region III are considered within E_T. These efficiencies present one of the six influencing factors of the building energy use called "Building equipment" in Figure 2. Finally, in Region I or E_D is marked delivered energy that presents the energy delivered to the central plant such as boilers, chillers or combined heat and power plants (CHPs) for heating or cooling. E_D also includes district heating and cooling. The electricity energy for running the auxiliary equipment such as pumps and fans in the plant is also considered in E_D.

3.2. Energy reporting

Since one of the aims of Annex 53 was to collect building energy use data from different resources in a critical and reasonable way, it was crucially important and a very extensive work was done to define which and how data should be reported. Quality and frequency of the building energy performance and energy use data can vary significantly, depending on the number of buildings in a sample and the purpose of analysis. For example, for statistical analysis of large numbers of buildings, only a few parameters are usually collected, while for case studies and simulations, detailed data and many parameters need to be defined. There have been noted some examples in between, for which more data are available for large samples of buildings or less for individual case studies. Therefore, three reporting levels for the building energy use have been developed: simple, intermediate, and complex. Each of them may serve different research purposes and covers different categories of influencing factors. The suggested forms for energy use reporting came as a result of analysis and comparison of many case studies and national databases on building energy use [13-16]. Explanation about each reporting level and their possible applications are given in Table 1 and the further text.

Table 1 Definitions for energy reporting

Level	**Energy use data**	**Influencing factors**
Simple • For statistics with large scale datasets • Datasets with small number of data points per building	Annually or monthly	• Climate • Building envelope and other building characteristics • Building service and energy system • Building operation • Social and economic factors (for residential buildings) - optional
Intermediate • For case studies	Monthly or daily	• Climate • Building envelope and other building characteristics • Building service and energy system • Building Operation • Indoor environmental quality • Occupant behavior • Social and economic factors (for residential buildings) - optional
Complex - Simulations - Detailed diagnostics	Daily or hourly	

By analyzing the suggested reporting structure in Table 1, it can be noted that the quantity and detail increase when moving from the simple to the complex level of the energy use reporting. Regarding the number of buildings that can be treated by using some of the reporting methods (see Table 1), the simple level may be suitable for large samples of buildings often thousands, while the complex level may be relevant for one to the low tens of buildings. Regarding the influencing factors, social and economic factors such as family information, the energy-related attitude of occupants, the thermal environmental satisfaction of occupants, and income could be taken into account in any of the three reporting levels for the residential buildings. Please note that the social and economic factors are optional in analyses, because it is difficult to find these data or it may be against rights for personal protection. Regarding the frequency of energy use data on the requirement for the time step is decreasing when moving from the simple level to the complex level. For instance, monthly energy use is preferred for the simple level of reporting, and annual energy use data are acceptable. For an intermediate level of reporting, daily energy use is preferred, while monthly energy use is acceptable. For the complex level of reporting, daily or hourly energy use are preferable. The data requirement given for different energy reporting level in Table 1 is also based on the analysis purpose. For analyses of very large samples of buildings, especially a statistical sample of buildings, the simple level is acceptable. For very detailed analysis of individual buildings, including fault detection and diagnostics (FDD), building performance optimization, and detail simulation, the complex level is acceptable. The above explanation of the energy reporting requirements may be explained through some examples. In the case of FDD, an operator needs detail hourly or minute data to identify fails. A city planner or an agent at an energy efficiency agency who is dealing with thousands of buildings is rather interested in annual energy use. More details about analysis approach and how to handle with the data is given in Section 6 on statistical analysis.

Explanation and suggestion how to collect and organize data for each of the reporting levels and the four of the building types are given in detail in the Annex 53 reports and respective appendixes. A brief explanation about the data requirement for the simple reporting level is given here. Climate as one of the influencing factor (see Table 1) can be quantified with the HDD (heating degree day) and CDD (cooling degree day). Building characteristic may be quantified with the following data: building year, number of floors, building type, etc. Building envelope has to be explained with the following data: U-values ($W/K \cdot m^2$) for walls, roofs, and windows, and window to wall ratio. Building service and energy supply system may be explained with the following data: type of heating system and heating capacity (W), type of cooling system and cooling capacity (W), capacity of the fans in ventilation system (W), type of the lighting system and installed power (W), type of DHW and installed heating capacity (W), and capacity of the other electrical appliances. Building operation data should be explained by specifying the operation hours, week/weekend usage schedule, and length of the heating or cooling season. As can be noted the requirements for the building data are based on the building's physical description, similar as in Figure 1. Building data requirements for all the three reporting level and different building types are organized in tables with the recommendation of their importance in the Annex 53 appendixes.

4. Case studies and data collection

Description and the main findings from the case studies of office and residential buildings are presented here. The main idea in the data collection was to organize information according to the definitions and data framework explained in Section 3. In total data on 13 office and 12 residential buildings from seven countries were collected. The locations of the case studies are given in Figure 3, while the climate data for the corresponding seven locations are given in Figure 4. In Figure 3, the case studies are marked with the country code, building type, and number of the case studies in the parentheses. The building types are marked in the following way: R1 stands for the residential single family house, R2 stands for multifamily apartments, O1 stands for small-scaled office building with the floor area lower than 10000 m^2, and O2 stands for large-scaled office building with the floor area bigger than 10000 m^2.

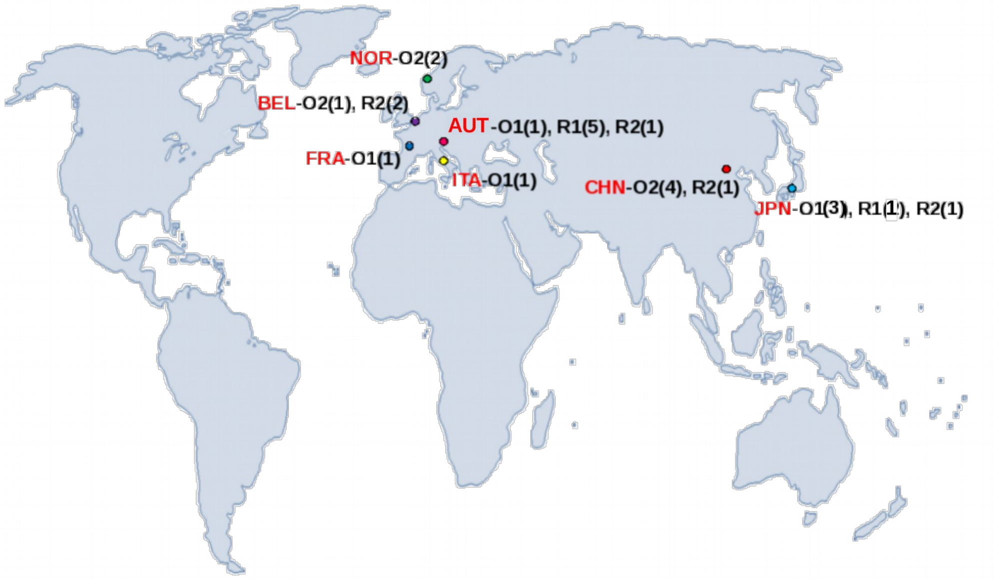


Figure 3 Locations of the 24 case study buildings from the seven contributing countries

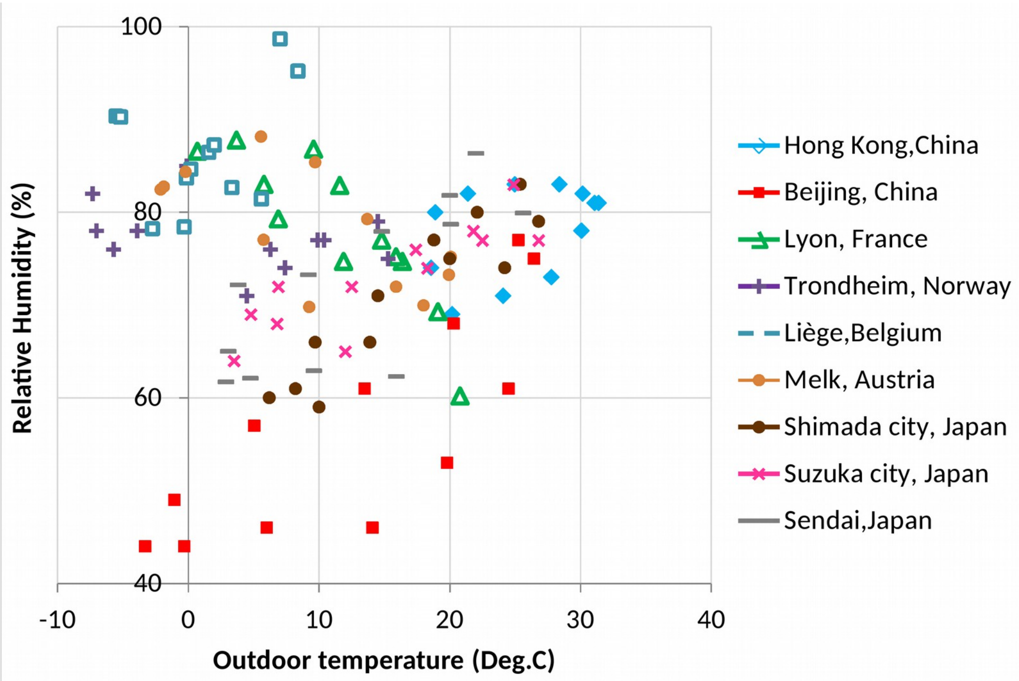


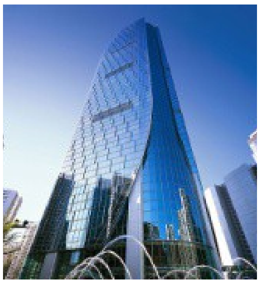
Figure 4 Climate comparison of the seven contributing countries

4.1. Case studies on office buildings

The total floor areas of the office building case studies ranged from 1000 to 150000 m^2. Only two office buildings utilized natural ventilation. Basic information about the office building case studies is given in Table 2. For the effectiveness of presentation, some shortcuts are used in Table 2. GFA is the gross floor area. Building services systems are presented as air conditioning (AC) system. AC system within a building may be air handling unit (AHU), fan coil unit (FCU), and primary air unit (PAU). AHU may deliver constant air volume (CAV) or variable air volume (VAV).

Table 2 General information on 13 case study office buildings

Code	**Photo**	**Basic information**
AUT-01		Category: O1 Data level: Intermediate level Location: Melk, Austria GFA: 4811 m^2 Number of floors: 3 Construction year: 2007 Cooling source: mechanical ventilation with a ground source heat exchanger, decentralized AC for server rooms Heating source: district heating from biomass, mechanical ventilation with a ground source heat exchanger

BEL-01		Category: O2 Data level: Simple level Location: Brussels, Belgium GFA: 18700 m^2 Number of floors: 9 Construction year: 1970's AC: AHU, CAV, VAV Cooling source: water-cooled chiller Heating source: natural gas boiler
CHN-01		Category: O2 Data level: Complex level Location: Hong Kong, P.R. China GFA: 30968 m^2 Number of floors: 23 Construction year: 1998 AC: AHU, CAV, VAV, FCU, PAU Cooling source: water-cooled chiller Heating source: no heating demand
CHN-02		Category: O2 Data level: Complex level Location: Hong Kong, P.R.China GFA: 141968 m^2 Number of floors: 68 Construction year: 2008 AC: AHU, CAV, VAV, FCU, PAU Cooling source: water-cooled chiller Heating source: no heating demand
CHN-03		Category: O2 Data level: Complex level Location: Beijing, China GFA: 111984 m^2 Number of floors: 26 Construction year: 2004 AC: FCU, PAU Cooling source: water-cooled chiller Heating source: district heating

CHN-04		Category: O2 Data level: Complex level Location: Beijing, China GFA: 54500 m^2 Number of floors: 21 Construction year: 1980’s AC: VAV, PAU Cooling source: water-cooled chiller Heating source: district heating
FRA-01		Category: O1 Data level: Simple level Location: Lyon, France GFA: 1290 m^2 Number of floors: 2 Construction year: 1970 Renovation year: 1993 Cooling source: natural ventilation Heating source: no heating demand
ITA-01		Category: O1 Data level: Simple level Location: Vercelli, Italy GFA: 1096 m^2 Number of floors: 5 Cooling source: natural ventilation Heating source: natural gas boiler
JPN-01		Category: O1 Data level: Intermediate level Location: Shimada, Japan GFA: 2734 m^2 Number of floors: 4
JPN-02		Category: O1 Data level: Intermediate level Location: Suzuka, Japan GFA: 3695 m^2 Number of floors: 4

JPN-03		Category: O1 Data level: Intermediate level Location: Sendai, Japan GFA: 4090 m2 Number of floors: 3
NOR-01		Category: O2 Data level: Simple level Location: Stavanger, Norway GFA: 27623 m^2 Number of floors: 6 with underfloor Construction year: 2008 AC: AHU, VAV, FCU Cooling source: water-cooled chiller Heating source: district heating
NOR-02		Category: O2 Data level: Complex level Location: Trondheim, Norway GFA: 16200 m^2 Number of floors: 6 Construction year: 2009 AC: AHU, VAV, FCU Cooling source: heat pump Heating source: district heating

From Table 2 it is possible to note that only in the five cases it was possible to collect the building data according to the complex reporting level. Analysis of the data amount describing each influencing factor produced Figure 5, which shows data frequency that was possible to find though out the case studies.

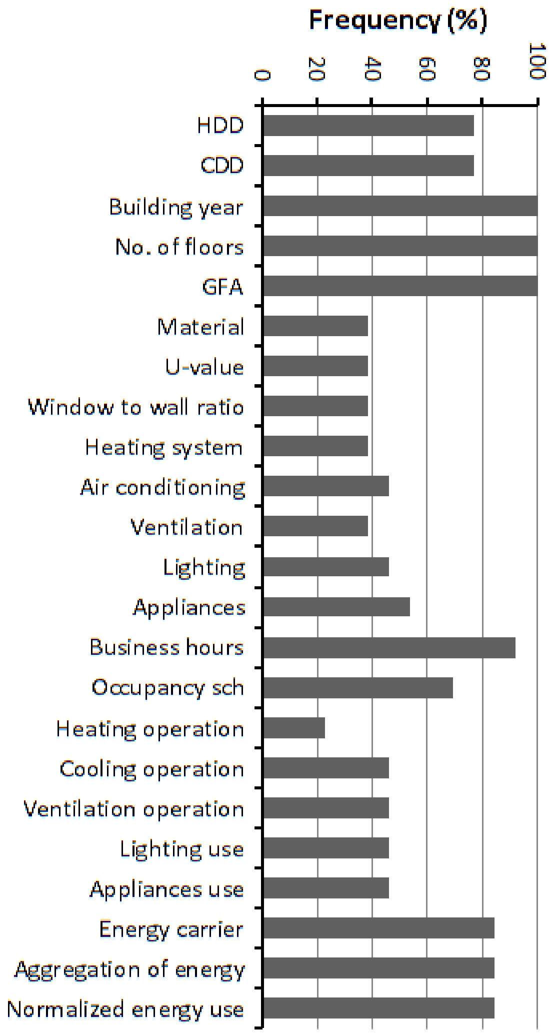


Figure 5 Frequency of data for the case study office buildings

Figure 5 can also be understood as success rate in the building data collection. Figure 5 shows that it is simple to find general building data such as year built and floor area. In about 40% of the cases, it was possible to find the data related to the building service systems and building operation, meaning that in general, it was difficult to find them. Figure 5 shows clearly that it was still partially difficult to fulfill the data required for the complex reporting level as given in Table 1. This is a clear indication that more work on building data standardization and information is necessary.

Since one of the aims of Annex 53 is to understand the building energy use, comparison of the energy use between that case studies was done. Some of the most relevant results are summarized here. Total electricity use divided by usage for buildings lower than 30000 m^2 is given in Figure 6 and for building bigger than 30000 m^2 is given in Figure 7. The results in Figure 6 and Figure 7 are given only for the office buildings where it was possible to obtain electricity use breakdown into end uses.

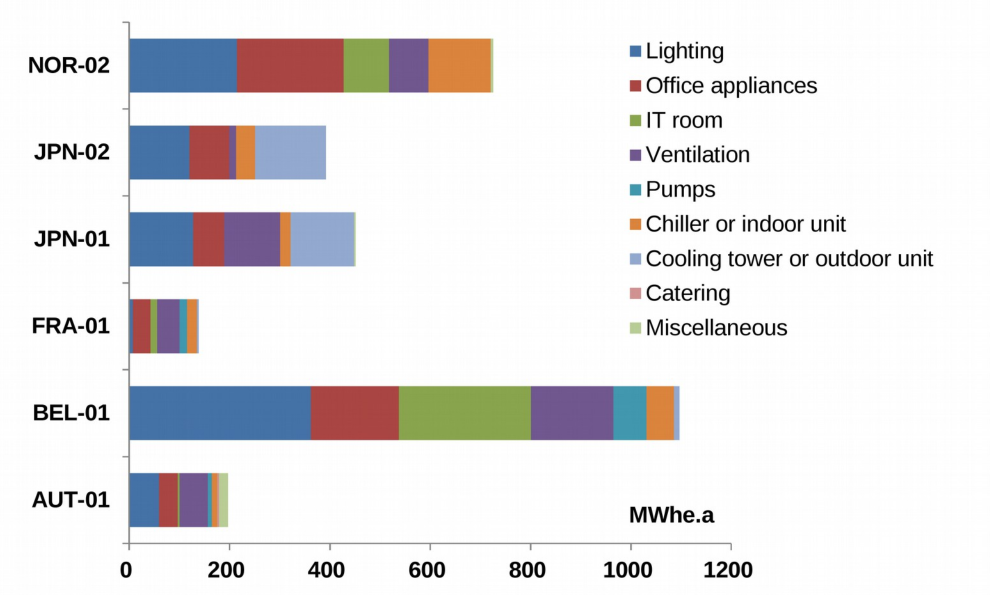


Figure 6 Total electricity use for the office buildings less than 30000 m^2

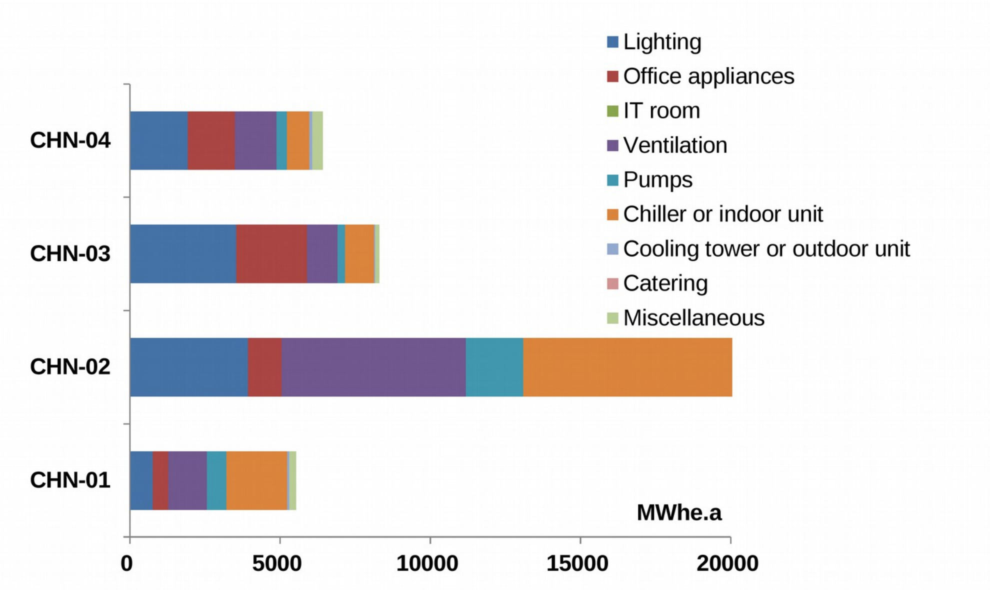
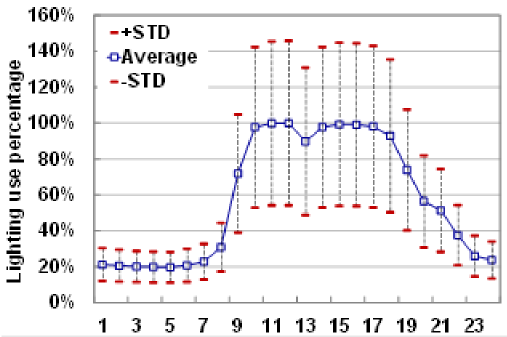
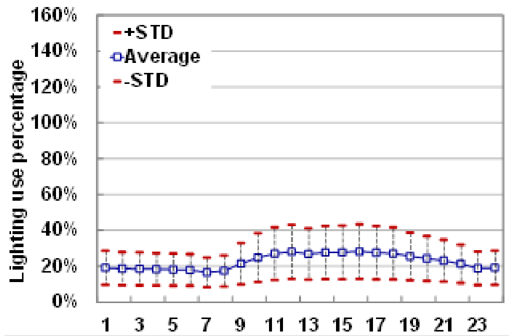
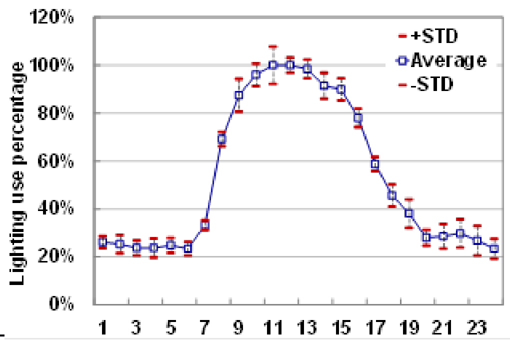
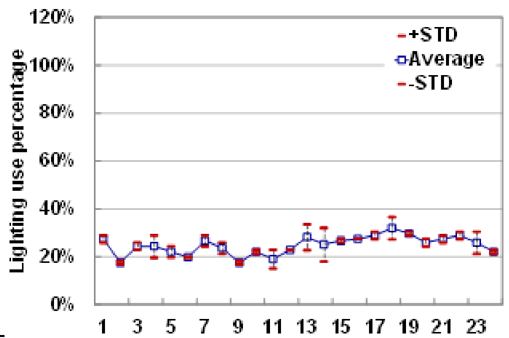


Figure 7 Total electricity use for the office buildings larger than 30000 m^2

Total energy use of the office buildings differs from country to country. For example, heating energy use in Austria, Belgium, Northern China, and Norway are similar, while heating energy use in France is very different. Huge differences in electricity use in the case study buildings are seen in the following systems: air conditioning, ventilation, and lighting. The electricity use for ventilation and cooling systems of large-scaled office buildings are larger than for small offices, by comparing the electricity use per square meter. Large-scaled office buildings consume significantly more electricity than small-scaled office buildings for lighting. Some of the reasons are installed power for lighting and occupant behavior.

Occupant lighting behavior in office buildings is studied through the comparison of the electricity use profiles of artificial lighting in weekdays and weekends in four buildings in China, Norway and Belgium. More than 60% of artificial lighting is on during working hours in the four large-scaled case study office buildings, regardless of the outdoor lighting conditions. 20% of lighting remains on during unoccupied hours in all the cases except the case building in Belgium. A comparison between the lighting use in the two office buildings is given in Table 3. Bigger standard deviation in Table 3 in the lighting use in the CHN-01 case indicates that the light use varies according to the outdoor lighting conditions. In the case of the NOR-02 case, the standard deviation is lower, because the occupants are using the light year around in the same way regardless of the outdoor lighting conditions. In Annex 53 lots of similar and detail comparison about the usage time and scheduling of the appliances and light are made. All the detail graphs on usage can be found in the complete report of Annex 53.

Table 3 Light use in two different office buildings

Code	Weekdays	Weekends
CHN-01		
NOR-02		

4.2. Case studies on residential buildings

Researchers from four countries, Austria, Belgium, P.R. China, and Japan, collected data on twelve residential buildings: six detached houses and six multi-family apartments. Total floor areas of detached houses range from 159 to 389 m^2. Basic information for the case study residential buildings is given in Table 4.

Table 4. General information on 12 case study residential buildings

Code	Photo	Basic information
AUT-01		Category: R1 Data level: Intermediate level Location: Vorarlberg, Austria Number of floors: 2 GFA: 280.6 m^2 Construction year: 1987
AUT-02		Category: R1 Data level: Intermediate level Location: Vorarlberg, Austria Number of floors: 2 GFA: 185.2 m^2 Construction year: 1965
AUT-03		Category: R1 Data level: Intermediate level Location: Vorarlberg, Austria Number of floors: 3 GFA: 164.4 m^2 Construction year: 1957
AUT-04		Category: R1 Data level: Simple level Location: Vienna, Austria Number of floors: 2 GFA: 100 m^2 Construction year: 1930
AUT-05		Category: R1 Data level: Simple level Location: Vienna, Austria Number of floors: 2 GFA:389.4 m^2 Construction year: 2004
AUT-06		Category: R2 Data level: Intermediate level Location: Vienna, Austria Number of floors: 13 GFA: 1330 m^2 Construction year: 2007

BEL-01		Category: R2 Data level: Simple level Location: Hondelange, Belgium
BEL-02		Category: R2 Data level: Intermediate level Location: Arlon, Belgium Number of floors: 6 Heated area: 1330 m^2 Construction year: 2005
BEL-03		Category: R2 Data level: Simple level Location: Belgian coast, Belgium Number of floors: 8
CHN-01		Category: R2 Data level: Intermediate level Location: Beijing, China Number of floors: 20 Construction year: 2000 Data level: B
JPN-01		Category: R1 Data level: Complex level Location: Sendai, Japan Number of floors: 2 Heated area: 285 m^2 Construction year: 2008

JPN-02		Category: R2 Data level: Complex level Location: Fukushima, Japan Number of floors: 15 GFA of case family: 72.3 m^2 Construction year: 2000

Analysis of the successfulness to collect the data describing influencing factors for the residential building from Table 4 gave a similar picture as in Figure 5. Data on general building characteristics and building envelope (material and U-value) were possible to find, while data on the operation and usage were difficult to obtain. In Table 4 it is possible to note that only two case studies could provide complex reporting level.

Since for most of the residential buildings in Table 4 data on energy use were provided, analysis on the energy use was performed. All the twelve case study buildings are located in the cold climate regions. Thus heating demand comprises the largest portion of the energy use. The source for space heating and DHW in the case study buildings varies widely, including gas boiler, oil boiler, wood burning oven, solar panel, gas furnace, air-to-water heat pump, air-to-air heat pump, district heating, direct electric heater, and electric thermal storage heater. Figure 8 compare the heating and electricity use of the twelve buildings. Please note that in Figure 8 due to the effectiveness of presentation, the country code is given only by the first letter of the country name (J for Japan, A for Austria, etc.), see Table 4 for more detail. Electricity use of the buildings in China (in the northern city of Beijing), Austria, Belgium, and Japan is between 17.5 and 44.6 kWh/(m^2.a), while heating energy use of these buildings ranges from 45.0 to 155.4 kWh/(m^2.a). There is no large difference of total energy use for the case study buildings from these four countries. There is no strong evidence that an apartment building consumes less than a residential house.

Figure 8 Electricity and heating energy use of residential case study buildings (Unit: kWh/(m^2.a))

In Figure 8, the difference in the total energy use may be estimated with a factor of three when comparing the lowest and the highest energy use. To understand this difference, occupant behaviors, such as occupancy schedules, window opening, use of air conditioner, use of lights, and use of household appliances, have been studied by questionnaire surveys and onsite measurements. Finally, three major findings came from the analysis:

- Occupancy, heating operation schedule, and set point temperature show large differences and results in large differences in building energy consumption;
- Different countries exhibit large differences in DHW use. Due to different hot water demands (shower, bath, hand washing, etc.), the energy use for DHW per capita in China, Belgium, and Japan shows large variations, see Figure 9. The DHW use in Japan is highest, followed by Belgium, and in China is the lowest. According to the investigation, the Japanese strongly prefer bathing in tubs, while the Chinese often prefer showering, leading to a 7 - 9 time difference in the DHW use.
- Difference in usage patterns of the heating and cooling system induce big different in the respective energy use. This means that in some cases the entire house may be heated entire day, while in some cases only one room is heated for a limited period of the day. For instance, the results show that the measured heating energy use due to different usage patterns differs by a factor of 5 to 20. The same was observed for cooling. The simulated cooling energy use due to different patterns differs by a factor of 3 to 10.

Figure 9 DHW energy

consumption indicator of residential case buildings (Unit: kWh/(ca.a))

The results provide in the section may be used to show how to collect building information, to calibrate building energy use, and to understand undelaying effects of diversities in building energy use.

5. Online data collection systems and technologies

Monitoring is crucial to better understanding the energy behavior of buildings. New automated meter reading technology combined with modern information and communication technologies are overcoming previous data deficiencies. Millions of smart meters are being installed. In addition, fast-evolving sensor technologies with wireless and other communication capabilities offer cheap means for complementing energy data collection with measurements of various environmental factors. However, there are not precise definitions for these different online data collection systems. Thus, the result of this work may also be used as guidelines for different practitioners, such as designers, operators, energy planners, and other businesses to define properly the data framework for the energy use data collection.

This Annex 53 activity reviewed state-of-the-art online data collection systems and technologies and analyzed some applications developed in different countries for monitoring, analysis, and management of energy, water, and other building consumption. Five online data collection systems, from Finland, China, Japan, Germany, and Spain were reviewed to identify the main features and characteristics of various measurement strategies for online data collection and monitoring systems designed for building energy systems and indoor air quality. Key findings from this activity include:

- All online data collection systems normally require five components: measuring, obtaining external data (such as weather information), data transfer, data analysis, and reporting.
- Individual and open access systems are the two types of monitoring systems most widely used. Most of these five elements are implemented by one company, who manages a

closed system where no one else has access; this is called an 'individual' online data collection system. The other type is the 'open access' system, which allows bidirectional data transfer. Open access systems can interact with other systems.

- A monitoring system should be able to apply varying factors to measurements, allow meter replacements and new instrumentation, and even detect instruments automatically.
- Online smart meter systems will create new possibilities for the development of monitoring systems, offering accurate and almost real-time information to various stakeholders.
- Mass production of new-type sensors often with wireless communication capabilities offer cheap and flexible means for measuring both environmental factors and occupation of buildings
- Technologies mentioned above are utilized typically in building automation systems (BAS), which are becoming more popular especially in office and commercial buildings and also include many functions of monitoring systems. Developed and marketed often by big international players, these systems are typically proprietary and closed, however, making integration and common utilization difficult.

These existing online data collection systems provide energy users and other actors with timely information about their domestic energy consumption. Based on this kind of data the energy supplier, customer or service provider can view how much energy is used, when it is used, and identify opportunities for saving energy. On-going smart meter rollouts will create new possibilities for the development of monitoring systems, offering accurate and real-time information for various stakeholders. Smart meters transmit data on the usage of electricity in fifteen-minute intervals, thus motivating consumers to shift energy consumption to the time of day when power is cheapest. For utilities, this can mean better management of the power grid and elimination of the need to develop expensive power generating systems. Data and information provided by smart meters should be integrated in real time with building automation systems in order optimize the use of energy in various building systems to capture the full potential for environmental and energy savings.

6. Statistical analysis and energy performance evaluation

6.1 Statistical analysis

There is great potential for applying statistics in the field of total energy use. A more accurate prediction of both building and user energy-related behavior may result in benefits for energy savings, cost saving, as well as improving the comfort of the indoor environment. The main fields of application for statistical analysis are: (1) Energy diagnosis for individual buildings,

(2) Measuring energy use, targeting, and benchmarking for large building stocks, and (3) Trends in energy policies for analysis at a regional or national level.

This Annex 53 activity assessed the potential application for statistical analysis to predict total energy use in buildings and to identify the most significant influencing factors. First, an extended literature review was conducted, followed by the collection and critical analysis of individual buildings and large building stocks. A deep connection was established between Subtask C and the Taskforce of Occupant Behavior (OB) relating to the explanation of OB through statistical and probabilistic methodologies and Subtask A connects to this subtask regarding the definitions for the structure of the database ("database typologies").

To select a suitable methodology, the understanding of the "scale" of the analysis is essential. To this aim, three main descriptors have to be considered: number of buildings in the data set (from an individual building to very large building stocks), number of items describing each building, and time frequency available for time-dependent parameters (annual to sub-hourly time frequency). This fits with the proposal of the Three Level Database in Subtask A and relates to the different database typologies as explained in Table 1.

Different statistical models have different applications as a function of the final goal of the analysis. Predictive models based on statistical analysis differ in functionality and applicability, depending on the time scale (statistical models dealt with the yearly or monthly time scale, whereas dynamical models are useful tools in case of an hourly time scale). Moreover, the most important factors influencing total energy use have been investigated. The potential in using these models is clear both for individual buildings as well as for the larger building stock. Nevertheless, a pre-condition for the operability of these methodologies is the clear definition of the analysis target and the availability of a suitable database, in which it is possible to detect the influencing factors required for the analysis.

Main findings from this research activity are:

- The availability of suitable databases is a fundamental pre-condition to perform consistent analyses.
- Even when using statistical tools, the physical meaning of the parameters should not be forgotten.
- Energy use can very often be described by a few main influencing factors.
- Among the influencing factors, at present only a few databases contain items related to occupant behavior.
- Among the statistical models, regression models are mainly used for total energy use ranging from simple linear regression to complex neural networks.
- Often, increasing model complexity does not increase the prediction accuracy.

6.2 Energy performance evaluation

Simulation models can provide important added value in the realistic analysis of energy flows in buildings. Such models are developed to compute different aspects of building energy performance: thermal losses through the envelope, HVAC system operation and efficiency, thermal bridges, control features, etc. However, it is frequently observed that the predictions calculated by these tools, although obtained from “detailed” calculations using models submitted to various “validation” exercises, can be quite far from the results of observations realized in actual buildings. There are a number of reasons that may explain this; an important factor being the fact that fixed values are usually entered to represent the human factors related variables. The models embedded in simulation tools are not perfect, because they always provide a simplification of the reality, ignoring certain processes: parameters are fixed according to arbitrary or approximate procedures. Within these parameters, those related to the description of occupant behavior were not, until recently, the object of detailed consideration. Most of the time, simulations use arbitrary and standard user profiles concerning a number of behavioral aspects: selection of set points, control of shading devices, opening of windows, etc.

In Annex 53, this activity is concerned with Energy Performance Evaluation. This includes the use of simulation models in order to improve the evaluation of energy flows in buildings. Simulation models are available to calculate the energy and thermal comfort performance of buildings. Building practitioners use increasingly more sophisticated tools to estimate energy demand (or use) as well as to predict the thermal comfort status. The objective of using simulation models is to improve the knowledge and the understanding of total energy use in buildings. Models increase the possibility of disaggregating the flows of energy and identifying the causal link with the influencing factors that are known to have an impact on those flows.

Three major steps were applied to evaluate the energy performance of the case studies in Annex 53:

1) The first step is, by running simulation models on different case study buildings, to identify the cause and effects relationships between the influencing factors and the energy performance of buildings. Typical case study buildings are defined in each country, corresponding to national standard buildings; the main parameters affecting energy use are identified and quantified, and a large number of simulation runs are carried out in order to estimate the sensitivity of some performance indicators to those factors.
2) In the second step, new indicators are proposed to better capture the building performance, in a standardized way, allowing comparison between two different case studies located in different climates and subject to different occupants’ behavior.

3) In the third step, models are applied to real cases (the case studies of the Annex) in order to characterize the energy flows in those cases and to provide a quantitative method to assess the efficiency (in terms of energy savings) of different energy conservation measures, for either the building envelope or the HVAC system; including its control. This requires calibrating the simulation models to the case studies by comparing the models with the measured performance and adapting some of the sensible model parameters. With calibrated simulation models, the energy savings can be predicted with better accuracy and reliability. This prediction considers all factors shown to influence the performance, including human factors.

When applied to the typical cases in each national context, this methodology allows an extrapolation of the macro-scale (global) impact of some energy conservation measures to a building stock (located in a country or a region) and from there to provide quantified and objective support for energy policies in that country.

Key findings from this Annex 53 activity include:

- To get maximum benefit from the use of simulation models to analyze energy consumption in buildings, specific methodologies have to be developed and applied. These methodologies use specific concepts like sensitivity analysis and uncertainty analysis and highlight the importance of model calibration when analyzing an existing building. Combining these approaches makes it possible to realistically take into account the influence of the building user.
- When using a simulation model, it is important to keep in mind that the results of the calculation greatly depend upon the chosen hypotheses. The output by the calculation is the result of the assumed behavior. Consequently, using simulation models today introduces some traps.
- The presentation of results is very much dependent upon the user being addressed:
    - The *designer* (architect, HVAC engineer, installer, etc.) who tries to optimize the solution he or she is developing. Therefore, some design alternatives are compared;
    - The *building manager* who is seeking the appropriate behavior (sufficient comfort, limited consumption, minimal claims, etc.). The objective is to identify and to apply the best management strategies and to understand why the building does not follow the optimal trajectory;
    - The *policy maker* who is interested in the macroscopic impacts of some energy conservation measures.

7. Occupant behavior in residential buildings and office buildings

Energy-related occupant behavior refers to observable actions or reactions of a person in response to external or internal stimuli, or actions or reactions of a person to adapt to ambient environmental conditions. These actions may be triggered by various driving forces, which can be separated into biological, psychological, and social contexts, time, building/installation properties, and the physical environment. Information on occupant presence and activities can be obtained from individual questionnaires or monitoring by zone. Energy use in residential and office buildings is influenced by the behavior of occupants in various ways. To achieve a better understanding of total energy use in buildings, the identification of the relevant driving factors of energy-related occupant behavior (see Figure 10 and Figure 11) and a quantitative approach to modeling energy-related occupant behavior and energy use are required. For that, around 100 reports and papers have been reviewed in Annex 53. For office buildings, occupant behavior can be classified at three different levels: individual occupants, zone, and building, from a bottom-up perspective. A simplified calculation model of the energy use was developed for a certain item of equipment or system in a certain zone, based on the combination of different behavior types of different kinds of occupants and their equivalent occupied time, which can be used to the rough evaluation of energy consumption for building service systems in office buildings.

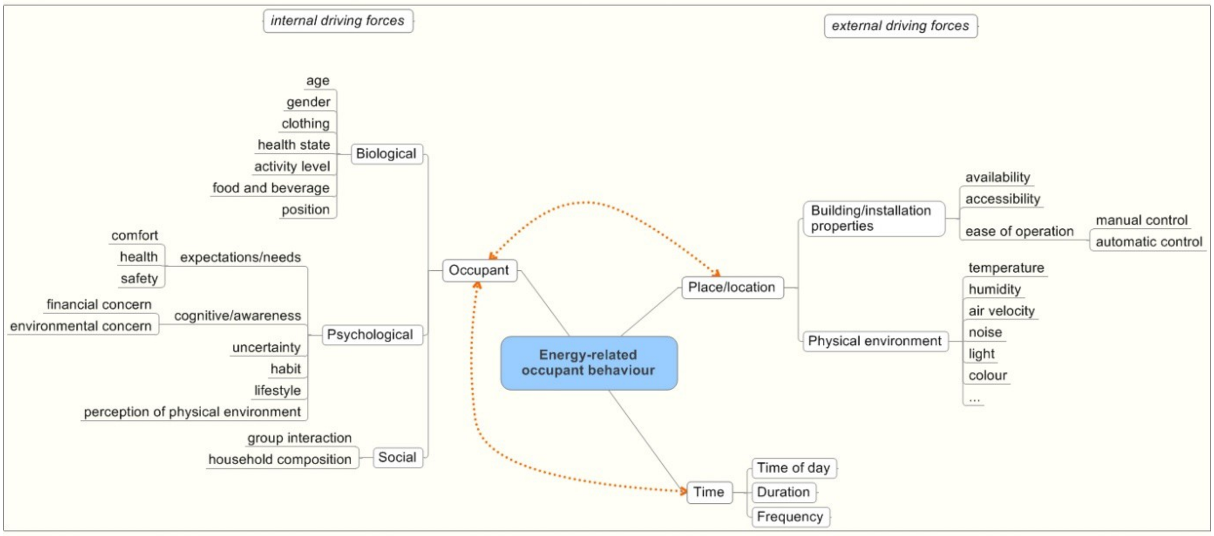


Figure 10 Driving forces of energy-related occupant behavior in residential buildings [4]

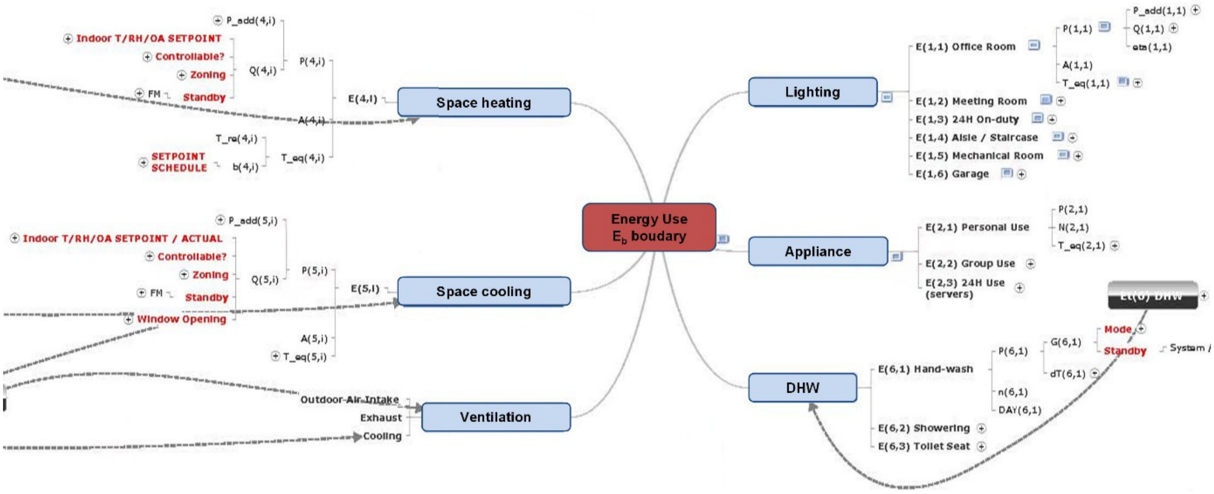


Figure 11 Driving forces of energy-related occupant behavior in office buildings [4]

Annex 53 specifically addressed the segment of building and systems modeling related to modeling user behavior. An extensive state-of-the-art review of the currently available modeling approaches to represent user behavior was performed by the “Task Force” established within the annex and is fully reported in the Task Force report. As a summary, modeling of user behavior in buildings may be tackled by the following approaches: (1) Theory of the planned behavior, (2) MODE model of attitude-behavior process, (3) Modified norm-activation model, and (4) Knowledge-desire-ability-action model. A more detailed description of the characteristics of these modeling issues is given in the Task Force final report. An analysis was carried out to identify the level of detail required for the occupant behavior modeling as a function of the following building life cycle phases: design, commissioning, and operation.

Various driving forces of occupant behavior have a significant influence on energy use. These driving forces can provide a quantitative understanding and allow modeling of energy-related occupant behavior and energy use. However, knowledge of some types of energy-related behavior and corresponding driving forces along with interactions between driving forces is limited and needs further research. Also, future work is needed to validate existing models.

The influence of occupant behavior on energy use in buildings has been investigated in various domains: natural sciences and social sciences as well as economics. The literature review resulted in an overview and classification of driving forces that may trigger energy-related occupant behavior. The various classes can be distinguished into biological, psychological, and social contexts, time, building/installation properties, and physical environment. Generally, the two purposes for modeling occupant behavior are: (1) to understand driving forces for the behavior itself, and (2) to reveal the relationship between energy demand and usage, as well as the driving forces for variations. Within the framework of this Annex, the focus is on the second purpose. The different reasons for modeling occupant behavior with respect to total energy use in buildings are design (conceptual, preliminary, and final), commissioning (initial and ongoing), and operation (control). Based on the aforementioned reasons, model types for the various purposes are defined. The selection of a model type is strongly dependent on the number of buildings, the user profile, and the time scale. The different model types which are discussed here are psychological models, average value models, deterministic models, probabilistic models, and agent based models combined with action based models.

8. Summary of main outcomes and findings

Annex 53 made significant contributions to a better understanding of how to robustly analyze and predict the total energy use in buildings, thus enabling the improved assessment of energy–saving measures, policies and techniques. The definitions of terms related to energy use and the influencing factors of building energy use are developed for office buildings and residential buildings, which provide a uniform language for building energy performance analysis. On this base, database of case buildings in different countries are established, and the building energy use and influencing factors are analysed. The statistical models for national or regional building energy data including the influence of occupant behaviour are summarized, to figure out the ability and limitations of statistical tools to better describe the energy uses in buildings and the main factors that affect the energy end-use in buildings. Methodologies to predict total energy use in buildings and to assess/evaluate the impacts of energy saving policies and techniques are also developed.

Annex 53 advanced the understanding of how the six factors combine to influence building energy use, and developed methods and tools to robustly predict total energy use in buildings. The main outcomes are:

- Developed uniform definitions of building energy use items, including energy boundary, conversion factors, building end use, and energy performance indicators, which provide uniform language for building energy use comparison and benchmarking, as well as three different levels of data collection typologies, that can help in the analysis of energy performance and influencing factors.
- Presented international office building and residential building typologies in the form of case studies. Basic information for twelve office case study buildings including category, data level, location, gross floor area, number of floors, construction years, air conditioning system, cooling and heating sources were outlined. Basic information for twelve residential case buildings including category, number of floors, floor area, construction year, and data level were described.
- Reviewed state-of-the-art online data collection systems and technologies, which included five online systems from Finland, China, Japan, Germany, and Spain. These systems were analyzed to identify the main features and characteristics of various measurement

strategies for online data collection and monitoring systems designed for building energy systems and indoor air quality.
- Highlighted suitable statistical models to apply for energy use analysis: recommendations about the proper application of the different models as a function of the goal of the analysis are offered. The potential to use these statistical models is very high for both individual buildings and large building stocks, but it is important to clearly define the goal of the analysis in advance and the availability of suitable data where the influencing factors required for the analysis are collected.
- Developed and applied specific methodologies to analyze energy consumption in buildings, in order to get the maximum benefit from the use of simulation models. These methodologies used specific concepts like sensitivity analysis, uncertainty analysis, and highlighted the importance of model calibration when analyzing an existing building.

These outcomes support target audience, including building designers, operators, owners, managers, technology vendors, as well as policy makers, to design, operate, and use buildings energy efficiently while meeting needs of occupant comfort and productivity.
Inspired by and built upon the occupant behaviour research done in Annex 53, a new IEA EBC project, Annex 66: Definition and simulation of occupant behaviour in buildings, was established to further advance the science and engineering applications of occupant behavior in buildings.

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