Total energy use in buildings: analysis and evaluation methods

Main findings from IEA EBC: Annex 53

One of the most significant barriers for achieving the goal of substantially improving energy efficiency of buildings is the lack of knowledge about the factors determining the energy use.

Keywords: energy use, monitoring, data collection.

SHUQIN CHEN
Research Center of Green Building and New Energy, Shanghai, China

HIROSHI YOSHINO
Department of architecture and building science, Tohoku University, Japan
yoshino@sabine.pln.archi.tohoku.ac.jp

A limitation of much current research is that it usually focuses on the three factors of climate, building envelope, and building services and energy systems, which have a direct influence on building energy use, while the quantitative influence of building operation and maintenance, occupants' activities and behaviour on energy use is still unknown [1]. Detailed comparative analysis on building energy data, concerning the six factors, would provide essential guidance to identify opportunities to save energy. However, a pivotal problem hindering to realize this is that there is a lack of a scientific method to account for interactions between the six influencing factors and energy use in a clear and thorough way and to predict the expected energy use as well when all influencing factors are taken into account. Aiming at this situation, an IEA EBC (International Energy Agency's Energy in Buildings and Communities Programme) project of "Annex 53: Total Energy Use in Buildings - Analysis and Evaluation Methods" was commenced in January 2009 and completed in a total of five years, intending

IEA EBC

In recognition of the significance of energy use in buildings, in 1977 the International Energy Agency has established an Implementing Agreement on Energy in Buildings and Communities (EBC-formerly known as ECBCS). The function of EBC is to undertake research and provide an international focus for building energy efficiency. Tasks are undertaken through a series of 'Annexes', so called because they are legally established as annexes to the EBC Implementing Agreement.

The largest benefits arising from participation in EBC are those gained by national programmes, such as leverage of R&D resources, technology transfer, training and capacity-building. Countries lacking knowledge can benefit from the experiences of those with more expertise, thereby avoiding duplicated research efforts. In particular, countries can most easily realise the benefits of participation if their own experts have taken part in projects and have assisted in producing deliverables taking into account their national requirements and priorities.

EBC has currently 26 member countries. All member countries have the right to propose new projects, and each country then decides whether or not to participate on a case by case basis. Most EBC projects are carried out on a 'task shared' basis, in which participating organisations arrange for their own experts to take part. Certain projects are 'cost shared' in which participants contribute funding to achieve common objectives.

EBC Secretariat (ESSU)
Mr. Malcolm Orme
+44 (0)121 262 1920
essu@iea-ebc.org

to improve the understanding of how these six factors together can influence the energy use, and also to what extent influence on the building energy use, especially on occupant behaviour.

The main objectives of this annex are to develop and demonstrate the following with respect to energy use:

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

Definition of terms relating to energy use and influencing factors

The inconsistency in the terms related to building energy use is a serious barrier to understanding of the influencing factors and analysis of real energy use. For instance, it is essential that the ambiguity in the meaning of kWh/m² for a building whose energy needs are served by both electricity and fossil fuels be removed by reporting electricity and the different fuel forms separately. Many similar problems exist, related to the terminology of building energy use and the influencing factors, and clear definitions of the terminology is in great need, which can provide a uniform language for the building energy efficiency analysis. In this situation, the consistent definitions related to the building boundary, energy use uses, energy conservation factors, six categories of influencing factors of energy use, and energy performance indicators have been developed. Building boundary is divided to E_b, E_t and E_d, where E_b represents the energy actually required (namely net energy need, or energy demand) within the building space, and E_t is the energy delivered to all the technical systems in the buildings, while E_d captures the energy use of space heating, cooling and hot water in district heating and cooling systems. When the energy carriers have to be combined in order to express the energy consumption through an "aggregated and synthetic" energy parameter, calorific value approach, primary energy approach and electricity equivalent approach are suggested to use [2]. The calorific value approach and primary energy approach traces the heat of on-site energy carriers and the original energy resources respectively. The electricity equivalent approach calculates the maximum ability of electricity generation by each energy carrier, so as to compare the capacity of different energy resources to do work, where it is defined as the heat amount of the energy carrier multiplied by the conversion coefficient of converting the unit energy carrier to the equivalent electricity. Energy performance indicators are defined in three ways to show energy use, that is (1) to list site energy separately, (2) aggregate energy into primary energy, (3) correct energy use by the factors of floor area, number of persons, etc.

As for the influence factors, three-level typologies of definitions have been developed from the simple level, the intermediate level, to the complex level, where the simple level serves large scale statistical analysis, and intermediate level is considered the minimum level for case studies, and the complex level is used for simulation or detailed diagnostics. **Table 1** shows three levels and categories of influencing factors. Aiming at the research subjects of residential buildings and office buildings in Annex 53, the definitions in each level figure out the important items in different kinds of influence factors, the quantitative and qualitative parameters of each item. Moving from Level A to Level C increases the quantity and specificity of the defined parameters and generally goes from large samples of buildings (often thousands) to small numbers (typically one to the low tens).

Definitions of energy-related occupant behaviour and modelling

Energy use in residential and office buildings is influenced by the behaviour of occupants in various ways. In order to achieve better understanding of total energy use in buildings, the identification of the relevant driving factors of energy-related occupant behaviour and a quantitative approach to modelling energy-related occupant behaviour and energy use are required. Energy-related occupant behaviour, as meant here, 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 distinguished into biological, psychological, and social contexts, time, building/installation properties, and physical environment [3-5]. These driving forces can provide a quantitative understanding and allow modelling of energy-related

Table 1. Three level typology definitions for residential buildings and office buildings (Mark Levine & Shuqin Chen). [1]

Typology	Energy use data	Categories of influencing factors			
		I	II	III	+(Optional)
Level A (Simple; for statistics with large scale datasets.) Datasets with small number of data points per building	Annually or monthly	**IF1.** Climate **IF2.** Building envelope and other characteristics **IF3**. Building service and energy system	**IF4.** Building Operation		**IF7.** Indirect factors (for residential buildings)
Level B (Intermediate; for case studies)	Monthly or daily	Same categories as Level A, more detail	**IF4.** **IF5.** Indoor environmental quality	**IF6.** Occupant behaviour	**IF7.** Indirect factors (for residential buildings)
Level C (Complex; simulations or detailed diagnostics)	Daily or hourly				

Note: Levels B and C includes six categories of influencing factors, besides the optional indirect factors, while more extensive set of definitions are covered in Level C.

occupant behaviour and energy use. Generally, the purpose for modelling occupant behaviour in this annex is to reveal the relationship between energy demand and usage, as well as the driving forces for variations. The different reasons for modelling occupant behaviour 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 models include psychological models, average value models, deterministic models, probabilistic models, and agent based models combined with action based models [6-8].

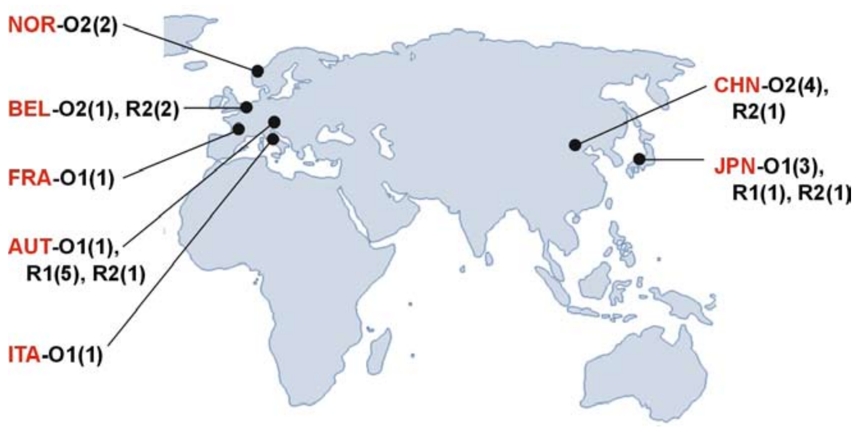


Figure 1. Locations of the 24 case study buildings from the seven contributing countries (Yi Jiang & Qingpeng Wei). [1]

Total energy use for analysis and evaluation

Collecting, reviewing and selecting case studies that document and analyse energy use data is a critical aspect of this annex. 12 office buildings and 12 residential buildings are finally confirmed and collected, as shown in **Figure 1**. The data collection of the 24 case studies follows the office and residential building definitions and typologies of Subtask A and the key results of total energy comparison and occupant behaviour of office and residential buildings are presented.

Table 2 shows the detail information of 10 selected office buildings, and **Figure 2** compares their energy use expressed in the electricity equivalent approach. The office buildings of AUT-01, FRA-01, JPN-01, and JPN-02 has the smallest floor areas of less than 5,000 square meters among the 10 buildings, and the buildings of BEL-01 and NOR-02 have the floor areas around 17,000 square meters, while the four Chinese buildings have the largest area of more than 30,000 square meters. It is found from the figure that there is no obvious relationship with the floor area and energy use intensity. Further analysis indicates that huge differences in electricity uses in the case study buildings are also seen in the following systems: air conditioning, ventilation (including the fans of air-handling-unit, primary air unit, and exhausting fans of toilet, parking

Table 2. Detailed information of 10 office case buildings (Yi Jiang & Qingpeng Wei). [1]

Code	Photo	Basic information	Code	Photo	Basic information
AUS-01		• Location: Melk, Austria • GFA: 4,811 m² • No. 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	**CHN-04**		• Location: Beijing, China • GFA: 54,500 m² • No. of floors: 21 • Construction year: 1980's • AC: VAV, PAU • Cooling source: water-cooled chiller • Heating source: district heating
BEL-01		• Location: Brussels, Belgium • GFA: 18,700 m² • No. of floors: 9 • Construction year: 1970's • AC: AHU, CAV, VAV • Cooling source: water-cooled chiller • Heating source: natural gas boiler	**FRA-01**		• Location: Lyon, France • GFA: 1,290 m² • No. of floors: 2 • Construction year: 1970 • Renovation year: 1993 • Heating source: no heating demand
CHN-01		• Location: Hong Kong, P.R. China • GFA: 30,968 m² • No. of floors: 23 • Construction year: 1998 • AC: AHU, CAV, VAV, FCU, PAU • Cooling source: water-cooled chiller • Heating source: no heating demand	**JPN-01**		• Location: Shimada, Japan • GFA: 2,734 m² • No. of floors: 4
CHN-02		• Location: Hong Kong, P.R.China • GFA: 141,968 m² • No. of floors: 68 • Construction year: 2008 • AC: AHU, CAV, VAV, FCU, PAU • Cooling source: water-cooled chiller • Heating source: no heating demand	**JPN-02**		• Location: Suzuka, Japan • GFA: 3,695 m² • No. of floors: 4
CHN-03		• Location: Beijing, China • GFA: 111,984 m² • No. of floors: 26 • Construction year: 2004 • AC: FCU, PAU • Cooling source: water-cooled chiller • Heating source: district heating	**NOR-02**		• Location: Trondheim, Norway • GFA: 16,200 m² • No. of floors: 6 • Construction year: 2009 • AC: AHU, VAV, FCU • Cooling source: heat pump • Heating source: district heating

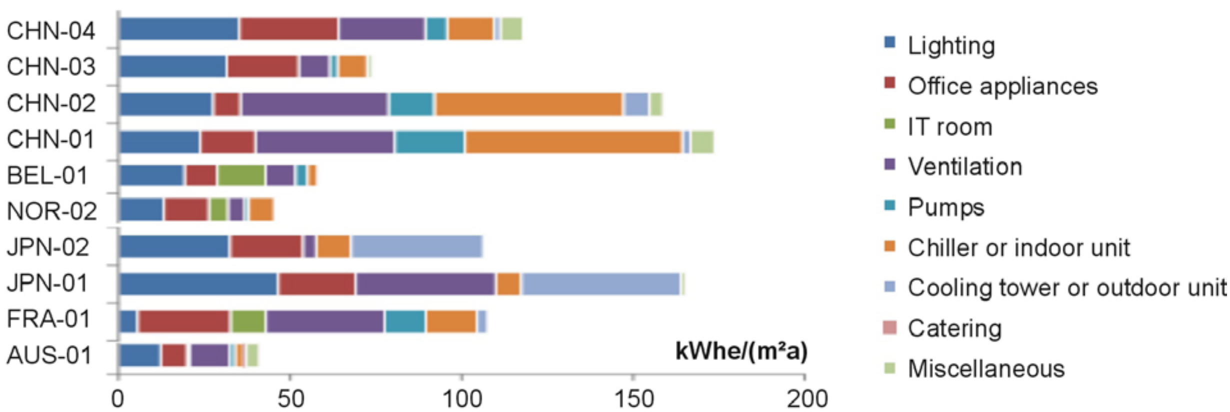


Figure 2. Electricity consumption of case study office buildings (Yi Jiang, Qingpeng Wei & Xiao He). [1]

area, etc), and lighting. The building operator behaviour (i.e. set point temperature, air change rate, control strategy of circulating pumps and fans, etc.) and the architecture design (such as no operable external windows in some large-scaled buildings) are the decisive factor in electricity consumption of AC systems consumption.

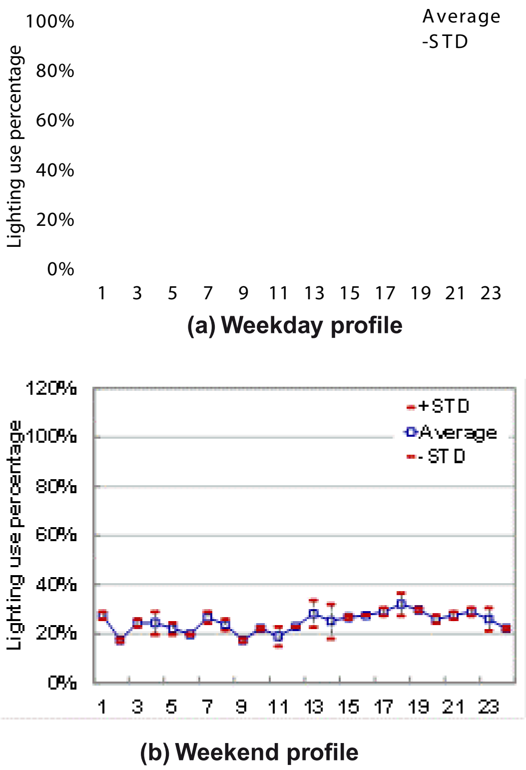


Figure 3. Average lighting profile of weekday and weekend of a case building in Norway (Yi Jiang & Qingpeng Wei).

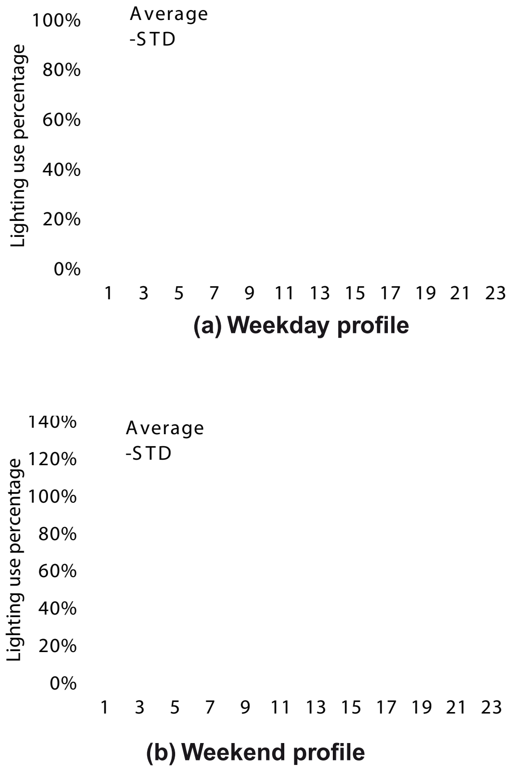


Figure 4. Average lighting profile of weekday and weekend of a case building in China (Yi Jiang & Qingpeng Wei). [1]

Occupant lighting behaviour in office buildings is studied through the comparison of the schedule of artificial lighting in weekdays and weekends in a case building in China and a case building in Norway. As shown in **Figure 3** and **Figure 4**, the impact of occupant behaviour on energy consumption in office buildings shows a weak relationship between external illuminance and the use of artificial lightings. Occupants usually turn on artificial lighting during working hours. Data analysis shows that more than 80% of artificial lighting is on during working hours from 10am to 17pm, and 20% of lighting remains on during unoccupied hours in two cases. There is a small difference that some of the lights are turned off during lunch breaks and turned on gradually in the afternoon in the office building in China.

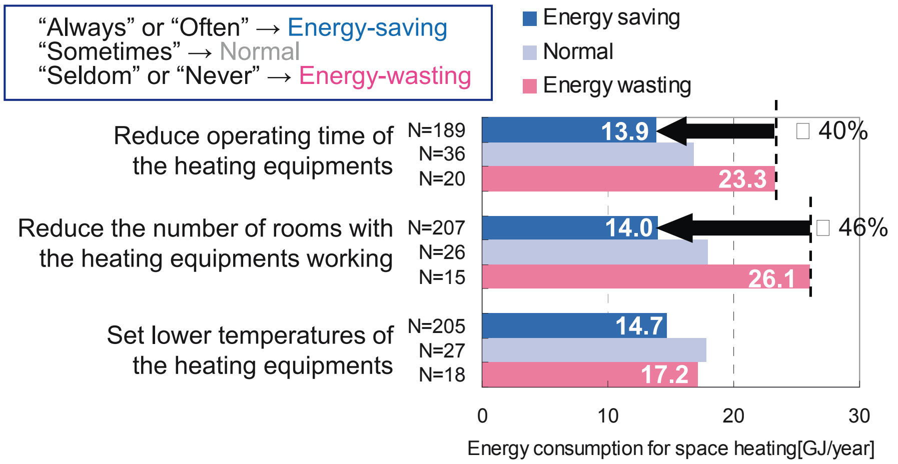


Figure 5. Impact of behaviour on space heating energy use in residential buildings in Japan. [1]

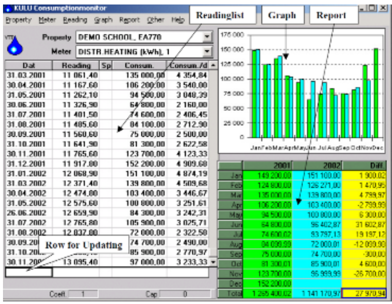
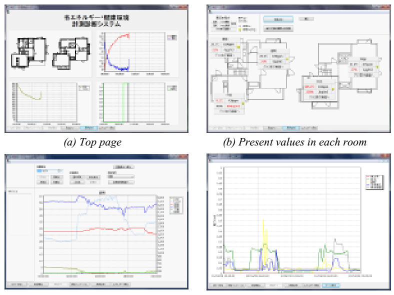
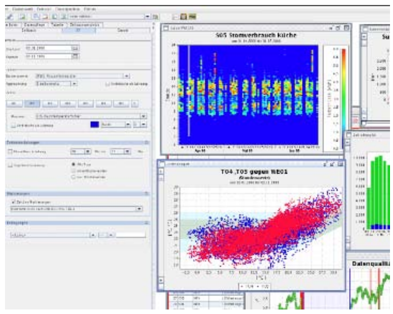
The occupant schedule is the major investigation target that has been surveyed in residential buildings. According to questionnaire surveys, three scenarios named "Energy-saving", "Normal" and "Energy-wasting" are compared. Occupant behaviour in multi-family houses shows that by reducing the operating time or amount of space heating can decrease space heating energy use by 40% to 46% compared to the "energy-wasting" scenario, as shown in **Figure 5**.

Articles

Data collection systems for the building energy system management

Monitoring is fundamental when aiming at better knowledge and understanding of the energy behaviour of buildings. One of the main works in this annex was to review state-of-the-art online data collection systems and technologies, and to analyze a particular Windows application developed by different countries, in order to identify the main features and characteristics of online data collection and monitoring systems. 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 mostly widely used [9]. Data and information provided by smart meters, including energy data and the information about the influencing factors, should be integrated in real time with building automation systems in order to optimize the use of energy in various building systems to capture the full potential for environmental and energy savings. Mass production of sensors often offers cheap and flexible means for measuring both environmental factors and occupation of buildings. So far, five online data collection systems, from Finland, China, Japan, Germany, and Spain, have been reviewed, as shown in **Table 3**.

Table 3. Summary of different on-line data collection systems (Jorma Pietilainen & Guangyu Cao). [1]

	Main features	**User Interface**
Finnish version: VTT Kulu For public buildings	• Versatile monitoring tools in standard web browsers. • No installations - only access to the internet required. • Updating of meter readings, analysis, and reporting can be carried out over the internet. • Readings from smart meters and other data sources can be transferred automatically to the Kulu database.	
Chinese version: Energy Sage 1.0 For public buildings	• Electricity distribution system and energy consumption features of terminal equipment. • Multi-layer data collection system. • Breakdown of HVAC system electricity consumption. • Hourly data in one sub-system of the data collection system.	
Japanese version: For residential buildings	• Real time measurement system that includes information on energy consumption and indoor environment. • • Diagnostic system: Real-time diagnosis and long-term diagnosis.	 (a) Top page (b) Present values in each room (c) Indoor environment of a room (d) Electric consumption by use
German version: MoniSoft monitoring software For all buildings	• Unified, scalable database structure for all buildings. • Automatic interpolation of different measure intervals. • Calculation of specific consumptions with user-definable reference values.	
Spanish version: For multi-family residential buildings	Three-level system: The measured parameters range from overall electric and gas consumption (first level), through sub-metering of main electrical consumption, comfort parameter measurement (second level), to energy for heating, hot water, and solar system energy input (third level).	

Statistical analysis of total energy use

Suitable statistical models are important for building energy use analysis and prediction. In order to carry out a critical examination of the potential and limitations of applying statistical and predictive inverse models to estimating the energy consumption of buildings and exploring the influencing factors, the experiences of the different partners of Annex 53 are collected and shared. A total of 17 contributions that deal with both residential and office buildings were gathered, and the database structure, influencing factors, investigation method and overall judgment of the potential for the investigation method were summarized in each contribution. Examining the contributions, the main goals of the analysis can be synthetically divided into two types: (1) Descriptive analysis, including statistical characterization of the subject, benchmarking, identification of driving variables that contributed to energy use, determination of an accurate profile of user behaviour etc.

Energy Performance Evaluation

In order to get a better benefit from the use of simulation models to analyze total energy use in buildings, a number of specific methodologies were developed considering different phases of the building life cycle. These methodologies complement the use of simulation tools with resources like sensitivity analysis, uncertainty analysis, and model calibration in order to get more reliable results and to adapt the presentation of the results to the specific user of the simulation tools. A more realistic consideration of the impact of the user of the building is also pointed out by the methodologies. The main simulation methodology and the application are as follows:

(1) 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 are identified.

(2) A simulation methodology targeting the design of residential buildings was developed. It is based upon the a priori realization of a large number of simulations of typical cases (generic buildings) followed by the identification of a simplified regression model expressing performance in terms of the dominating parameters. An uncertainty can be attributed to each parameter and the final performance is given as a range around a central value.

(3) Monte Carlo simulation is developed based on performing multiple model evaluations with probabilistically selected model inputs. The results of these evaluations can be used to determine the uncertainty in the model output (prediction) and to perform sensitivity analysis.

Conclusions

This annex contributes 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. The beneficiaries of the annex results and deliverables will be policy decision makers, property developers, energy contracting companies, financers and manufacturers, and designers of energy saving technology, with the following benefits:

(1) Substantially improved understanding of effective energy data on real, long term performance of buildings and building systems in the context of evaluating and developing new energy saving measures and technologies;

(2) Knowledge about the main determining factors of total energy use in buildings and about the specific interactions between them in order to develop new energy saving strategies, technologies, methodologies, and policies;

(3) Opportunities for the development of energy saving technologies that take into consideration building related as well as user related energy use, and the prediction of both expected energy use in new and renovated buildings and the cost-benefit relationship of energy saving measures to increase implementation of energy contracting and management; and,

(4) Support for standardization and benchmarking of total energy use in buildings, so as to establish indicators for energy use in buildings that take occupant related factors into consideration, to achieve better acceptance of energy labelling systems among the public, and to improve the ability to communicate to the public the behaviour that influences energy use in buildings. ■

Acknowledgements

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