# Final report

## 1.1 Project details

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| **Project title** | EUDP17-II: IEA-EBC ANNEX 67 Participation |
| **Project identification (program abbrev. and file)** | J.nr. 64017-0592 |
| **Name of the programme which has funded the project** | System integration |
| **Project managing company/institution (name and address)** | University of Southern Denmark |
| **Project partners** | University of Southern Denmark<br>Technical University of Denmark<br>Aarhus University |
| **CVR** (central business register) | 29283958 |
| **Date for submission** | 19.08.2019 |

## 1.2 Short description of project objective and results

### *1.2.1 English version*

The overall objective of IEA-EBC Annex 67 was to investigate how the energy flexibility of buildings can be incorporated into the future smart energy system, and thereby facilitate the transition towards a fossil free energy system. In addition to the technical investigation, the annex also sought to understand non-technical aspects of energy flexibility from a stakeholders' perspective. This understanding is important when developing business cases for smart energy solutions that can utilize the energy flexibility in buildings to avoid expensive upgrades of the distribution grid. The results of the annex are considered a unique reference for working with energy flexibility in buildings.

### *1.2.2 Dansk version*

Det overordnede mål med IEA-EBC Annex 67 var at undersøge, hvordan bygningers energifleksibilitet kan integreres i det fremtidige smarte energisystem og derved facilitere overgangen til et fossilfrit energisystem. Ud over den tekniske undersøgelse forsøgte annekset også at forstå de ikke-tekniske aspekter af energifleksibilitet fra et interessentperspektiv. Denne viden er vigtig i udviklingen af business cases for smarte energiløsninger, der kan udnytte energifleksibiliteten i bygninger for at undgå dyre opgraderinger af distributionsnettet. Resultaterne af annekset betragtes som en unik reference for arbejdet med energifleksibilitet i bygninger.

## 1.3 Executive summary

The last decades' increasing global energy demand, a foreseen reduction of available fossil fuels and an increasing evidence of global warming have generated a great interest in renewable energy sources. However, energy sources such as wind and solar power have an intrinsic variability that can seriously affect the stability of the energy networks if they account for a high percentage of the total generation. Therefore, future high penetration of variable renewable energy sources forces a transition from generation on demand to consumption on demand in order to match the instantaneous energy generation. In practice, this means that the energy consumption needs to become flexible. Buildings are expected to play a central role in this transition, where consumers and "prosumers" (e.g. buildings with PV) becomes energy flexible in order to satisfy the generation and/or storage needs of the energy grids either as single buildings or as clusters of buildings.

In most developed countries, the energy use in buildings accounts for 30-40 % of the total energy consumption. The energy is used for space heating, heating of domestic hot water, cooling, ventilation, and lighting as well as for appliances used by the occupants. A large part of the energy demand of buildings – such as the energy for space heating/cooling or white-goods – may be shifted in time, and, thus, it may significantly increase the flexibility of the demand in the energy grids.

One option for generating flexibility is to make use of the thermal mass, which is embedded in all building structures. Depending on the amount, distribution, speed of charging/discharging, etc. of the thermal mass it is possible to shift the heating or cooling demand in time for a certain period without jeopardizing the thermal comfort in the building. Typically, the time constant of buildings varies between a few hours to several days depending on the amount and exploitability of the thermal mass together with the heat loss, internal gains, user pattern and the actual climate conditions. In addition, many buildings use different kinds of distributed energy storages (e.g. water tanks, and electrical batteries), which may add to the Energy Flexibility of the buildings. One such typical storage is the domestic hot water tank, which might be excess pre-heated before a low energy level situation. The excess heat may be used for space heating but may also be used for white goods such as hot-fill dishwashers, washing machines and tumble dryers in order to decrease and shift their electricity need.

Although various investigations of buildings in the Smart Grid/Smart Energy context have been carried out, research on the relationship between Energy Flexibility in buildings and future energy grids is still in its early stages. Prior to IEA-EBC Annex 67 - Energy Flexible Buildings, there was no overview or insight into how much Energy Flexibility different types of building and their usage may be able to offer to the future energy systems.

As Energy Flexibility in buildings for most is a rather new research area, there was a need for development of a terminology. On one hand the terminology should be easily understood by the building community, who should provide the Energy Flexibility, and on the other hand it should also allow the grid side to understand how the flexibility may be utilized to stabilize the energy grids. For the latter there is a need for applicable flexibility indicators that characterize the buildings in such a way that it is possible to determine how a building or clusters of buildings may provide flexibility services to the energy grids.

The actual Energy Flexibility potential depends on the type of building, the types of energy service systems in the building, the control possibilities, the climate, the time of day and year, the acceptance of the users and owners of the building, the state of the storage, etc. The actual useful energy flexibility is further determined by the needs of the surrounding energy networks to which the building provide flexibility services. There is, therefore, a need for a methodology for characterization of the actual available energy flexibility. Such a methodology has been developed and demonstrated in IEA-EBC Annex 67. The methodology depends on a Flexibility Function of the considered system delivering flexibility. While exposed to a varying penalty signal (e.g. price signal or CO2 content of the energy in the energy networks) describing the conditions in the surrounding energy networks, the Energy Flexibility

Saving Index and the Flexibility Index states how well the building(s) respond to the requirements of the energy networks seen from the building and network side respectively.

When utilizing the Energy Flexibility in buildings the comfort and economy of the buildings are influenced. If the owner, caretaker and/or users of a building are not interested in delivering Energy Flexibility to the surrounding energy grids, it does not matter how energy flexible the building is as the building will not be an asset for the surrounding energy grids. It is, therefore, very important to investigate and understand which barriers exist for the stakeholders of buildings and how the stakeholders may be motivated to allow their buildings to contribute with Energy Flexibility to stabilize the future energy grids. Strategies to benefit both the total energy system and the customers are, therefore, important. The roles, motivations, and barriers for different stakeholders in energy flexible buildings have in IEA-EBC Annex 67 been investigated based on sixteen case studies. By systematically studying the motivations and barriers revealed in the sixteen case studies, suggestions for how to strengthen the motivations and how to eliminate or reduce the barriers have been developed. It is shown that, although 'consumer driven/centred' has been emphasized in recent years, policy makers are still the lead stakeholders for strengthening opportunities and eliminating barriers in the energy system. To establish and realize the markets for energy flexible buildings, decentralization of the power hierarchy is necessary, especially for international collaboration and trading.

Simulation is a powerful tool when investigating the possible Energy Flexibility in buildings. Simulations make it easy to quickly test many different control strategies, among which some may not be realistic in the real world. Control strategies and the combination of components should, therefore, also be tested in test facilities under controllable, yet realistic, conditions, where the studied systems are real physical components while the boundary conditions (e.g. the weather and occupant behaviour) are virtual. This type of Hardware-in-the-loop test facilities have, therefore, been utilized in IEA-EBC Annex 67, where e.g. a heat pump and other components are tested combined with the energy demand of virtual buildings and exposed to virtual weather and grid conditions. Valuable insight into how to run Hardware-in-the-loop test facilities with regards to gaining knowledge of the performance of different types of systems aiming at providing energy flexibility services to the energy networks have been obtained. Based on this recommendation on how to test energy flexibility have been given.

In total 35 case studies on how to obtain energy flexibility from buildings have been documented (both modelled and measured) and is considered as a unique source for inspiration when dealing with energy flexibility from buildings.

## 1.4 Project objectives

The overall aim of IEA-EBC Annex 67 was to increase the knowledge, identify critical aspects and possible solutions concerning the Energy Flexibility that buildings can provide, plus the means to exploit and control this flexibility. In addition to these technical aims, Annex 67 also sought to understand all stakeholder perspectives - from users to utilities - on Energy Flexibility, as these are a potential barrier to success. This knowledge is crucial for ensuring that the Energy Flexibility of buildings is incorporated into future Smart Energy systems, and thereby facilitating the transition towards a fossil free energy system. The obtained knowledge is also important when developing business cases that will utilize building Energy Flexibility in future energy systems – considering that utilization of Energy Flexibility in buildings may reduce costly upgrades of distribution grids.

The specific objectives of IEA-EBC Annex 67 were:

- development of a common terminology, a definition of 'energy flexibility in buildings' and a classification method,
- investigation of user comfort, motivation and acceptance associated with the introduction of energy flexibility in buildings,
- analysis of the energy flexibility potential in different buildings and contexts, and development of design examples, control strategies and algorithms,

- investigation of the aggregated energy flexibility of buildings and the potential effect on energy grids, and
- demonstration of energy flexibility through experimental and field studies.

The work of IEA-EBC Annex 67 was divided into the following three main areas:

- terminology and characterization of Energy Flexibility in buildings
- determination of the available Energy Flexibility of devices, buildings and clusters of buildings
- demonstration of and stakeholder's perspective on Energy Flexible buildings

### *1.4.1 Terminology for and characterization of Energy Flexibility in buildings*

A common terminology is important in order to communicate a building's or a cluster of buildings' abilities to provide Energy Flexible services to the grid. The available Energy Flexibility is often defined by a set of generally static Key Performance Indicators. However, the useful Energy Flexibility will be influenced by internal factors such as the form or function of a building, and external factors, such as local climatic conditions and the composition and capacity of the local energy grids. There is, therefore, a need for a dynamic approach in order to understand the services a building can provide to a specific energy grid. A methodology for such a dynamic approach has been developed during the course of IEA-EBC Annex 67.

The findings in the area of terminology and characterization of Energy Flexibility in buildings are reported in the deliverable "Characterization of Energy Flexibility in Buildings" listed in section 1.4.4.

### *1.4.2 Determination of the available Energy Flexibility of devices, buildings and clusters of buildings*

Simulation is a powerful tool when investigating the possible Energy Flexibility in buildings. In IEA-EBC Annex 67, different simulation tools have been applied on different building types and Common Exercises have been carried out on well-defined case studies. This approach increased the common understanding of Energy Flexibility in buildings and was useful for the development of a common terminology. Simulations are very effective to quickly test different control strategies, among which some may be more realistic than others. Control strategies and the combination of components were, therefore, also tested in test facilities under controllable, yet realistic, conditions. Hardware-in-the-loop concepts were utilized at several test facilities, where, for example, a heat pump and other components were tested combined with the energy demand of virtual buildings and exposed to virtual weather and grid conditions. The results of the investigations are described in several of the publications by IEA EBC Annex 67.

### *1.4.3 Demonstration of and stakeholders' perspective on Energy Flexible Buildings*

In order to be able to convince policy makers, energy utilities and grid operators, aggregators, the building industry and consumers about the benefits of buildings offering Energy Flexibility to the future energy systems, proof of concept based on demonstrations in real buildings is crucial. Example cases of obtaining Energy Flexibility in real buildings have, therefore, been investigated and reported in reports, articles and papers and as examples in the deliverables of IEA-EBC Annex 67.

When utilizing the Energy Flexibility in buildings, the comfort, economy and normal operations of the buildings can be influenced. If the owner, facility manager and/or users of a building are not interested in exploiting energy flexibility to increase building smartness, it does not matter how energy flexible the building is, as the building will not be an asset for the local energy infrastructure. However, the involvement of utilities, regulators and other stakeholders, for example, building automation providers, can provide incentives and increase awareness of and thereby participation in providing Energy Flexibility. It is, therefore, very important to understand which barriers exist for the stakeholders involved in the Energy Flexible buildings and how they may be motivated to contribute with Energy Flexibility in buildings to stabilize the future energy grids. Investigating the barriers and benefits for stakeholders is, therefore, of paramount importance and work was completed in IEA-EBC Annex 67 to understand these in more detail. Findings from this work are described in the report "Stakeholder perspectives on Energy Flexible Buildings" listed in section 1.4.4.

### *1.4.4 Deliverables from IEA EBC Annex 67*

Many reports, articles and conference papers have been published by IEA-EBC Annex 67 participants. These can be found on annex67.org/Publications.

The main publications by IEA-EBC Annex 67 are, however, the following reports, which all may be found on annex67.org/Publications/Deliverables.

- *Principles of Energy Flexible Buildings* - summarizes the main findings of Annex 67 and targets all interested in what Energy Flexibility in buildings is, how it can be controlled, and which services it may provide.
- *Characterization of Energy Flexibility in Buildings* - presents the terminology around Energy Flexibility, the indicators used to evaluate the flexibility potential and how to characterize and label Energy Flexibility.
- *Stakeholder perspectives on Energy Flexible buildings* - displays the view point of different types of stakeholders towards Energy Flexible Buildings.
- *Control strategies and algorithms for obtaining Energy Flexibility in buildings* - reviews and gives examples on control strategies for Energy Flexibility in buildings.
- *Experimental facilities and methods for assessing Energy Flexibility in buildings* - describes several test facilities including experiments related to Energy Flexibility and draws recommendations for future testing activities.
- *Examples of Energy Flexibility in buildings* - summarizes different examples on how to obtain Energy Flexible Buildings.
- *Project Summary Report* - brief summary of the outcome of Annex 67.

SDU Center for Energy Informatics was editors on the reports *Stakeholder perspectives on Energy Flexible buildings* and *Control strategies and algorithms for obtaining Energy Flexibility in buildings*. In addition, the Center contributed to the reports *Principles of Energy Flexible Buildings* and *Examples of Energy Flexibility in buildings*.

Technical University of Denmark contributed to the reports *Principles of Energy Flexible Buildings*, *Control strategies and algorithms for obtaining Energy Flexibility in buildings* and *Examples of Energy Flexibility in buildings*.

## 1.5 Project results and dissemination of results

The results of IEA-EBC Annex 67 are organized into 6 deliverables and one Project Summary Report as listed in section 1.2.4. The main results from the 6 deliverables are summarized in the following 6 subsections of this section:

- Energy Flexibility in buildings
- Characterization of Energy flexibility in buildings
- Stakeholders perspective
- Control of Energy Flexibility in buildings
- Test of Energy Flexible components and systems
- Examples of energy flexibility from buildings

Dissemination activities of the IEA EBC Annex 67 results are described in subsection 1.5.7.

### *1.5.1 Energy Flexibility in buildings*

Energy flexibility of buildings is typically obtained by decoupling energy demand and energy delivery using storage in the building to shift the energy use e.g. from periods with a high price for the energy (e.g. due to a low amount of energy from renewable energy sources (RES) and, therefore, a high amount of $CO_2$ in the energy network) to periods with a low price. Energy flexibility can also be obtained by peak shaving of the energy demand without a later need of restoring the situation with extra use of energy – e.g. dimming of lights or switching off an appliance.

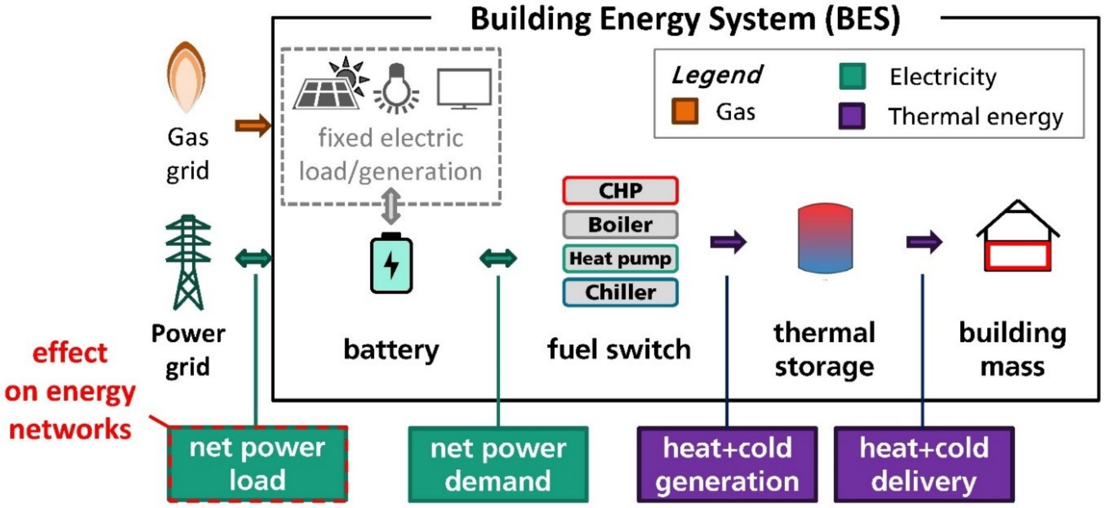



Figure 1 Sources for obtaining energy flexibility [6].

Figure 1 illustrates different ways of obtaining energy flexibility. Seen from the right:

Building mass: walls, floors, ceilings and furniture of buildings contain a certain mass and thereby a certain thermal capacity, which can be utilized to store energy. During shortage of energy the heating or cooling system can, therefore, be switched off for a period without decreasing the comfort of the users. How long a period depends on the thermal mass and the heat loss of the buildings but can be from a few hours up to a couple of days. However, care should be taken, as the storage is directly connected to the indoor climate and the thermal comfort must not be jeopardized.

Thermal storage: this refers to storage outside of the occupied spaces. This can be water in domestic hot water (DHW) storage, buffer tanks between supply and delivery e.g. a heat pump and the space heating system (radiators or underfloor heating) but can also be indoor swimming pools. The storage can, instead of water, utilise PCM (phase change materials).

Fuel switch: if a building utilizes different fuels (e.g. a gas boiler and a heat pump) energy flexibility may be obtained by using the gas boiler during periods where the electricity price is high (or, for example, when the production from wind turbines is low), while using the heat pump when surplus electricity is available in the grid.

Battery: here electricity is directly stored. Batteries can either be the battery of an electrical vehicle or the battery of a PV system. The battery is charged during periods when there is plenty of electricity in the grid and discharged during periods when there is a shortage. The battery can also be used for increasing self-consumption of electricity from a PV system for example.

Generation: many buildings are becoming prosumers – i.e. they no longer only consume energy, they also produce energy through PV, micro wind turbine or CHP (combined heat and power production) plant.

Networks: a building may be connected to one or more energy networks. Buildings are typically connected to a power grid (electricity) but may also be connected to a district heating or gas grid.

In order to utilize the aforementioned sources for energy flexibility there is a need for control. The cases investigated in Annex 67 utilize/investigate different types of control, ranging from very simple control like a heat pump being switched off every day during a predefined period, to more complex rule-based control where several constrains are included (e.g. that the heat pump is switched off unless the indoor temperature is too low and only if the price of electricity is above a certain level), and further to model-based control including forecasts of weather, occupancy behaviour (these two provide a forecast of future demand) and energy prices.

### *1.5.2 Characterization of Energy flexibility in buildings*

How much Energy Flexibility can buildings provide? The quick but correct answer is "it depends". The actual Energy Flexibility potential depends on the type of building, the types of energy service systems in the building, the control possibilities, the climate, the time of day and year, the acceptance of the users and owners of the building, the state of the storage, etc. The actual useful energy flexibility is further determined by the needs of the surrounding energy networks to which the building provide flexibility services.

The amount of available Energy Flexibility can, thus, not be expressed with a single number, as e.g. for energy consumption. Therefore, IEA-EBC Annex 67 has developed a methodology including key parameters for the characterization of Energy Flexibility [2]. Figure 2 shows an example of the aggregated response of buildings when receiving some sort of control signal – in the following called penalty signal. Figure 1 further shows the parameters describing the response to the signal.

The penalty signal can be chosen according to specific conditions: often the penalty signal is a price signal but can also be a signal based on the actual $CO_2$ level or actual level of energy from renewable energy sources (RES) in the networks. For these signals the controller should minimize the price or $CO_2$ emission or maximize the utilization of RES.

The penalty signal can either be a step response (e.g. a sudden change of the price of energy) as in figure 2 in order to test different aspects of the available energy flexibility in a building or clusters of buildings, or it can be a temporal signal varying over the day and year according to the requirements of the energy networks as seen in figure 3. A step response test may e.g. be utilized in simulations to test the capacity of e.g. a thermal storage. Temporal signals will typically be used when utilizing the energy flexibility in an area of an energy network and will concurrently feedback knowledge on the available energy flexibility in this area.

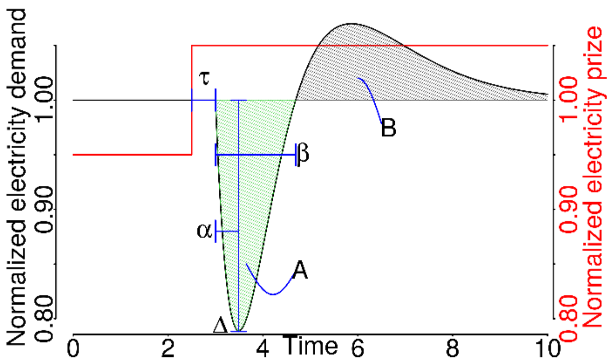



Figure 2. Example of aggregated response when some buildings receive a penalty signal – here a price signal [7]. The parameters in figure are: τ is the time from the signal is submitted to an action starts, α is the period from start of the response to the max response, Δ is the max response, β is the duration of the response, A is the shifted amount of energy, and B is the rebound effect for returning the situation back to the "reference".

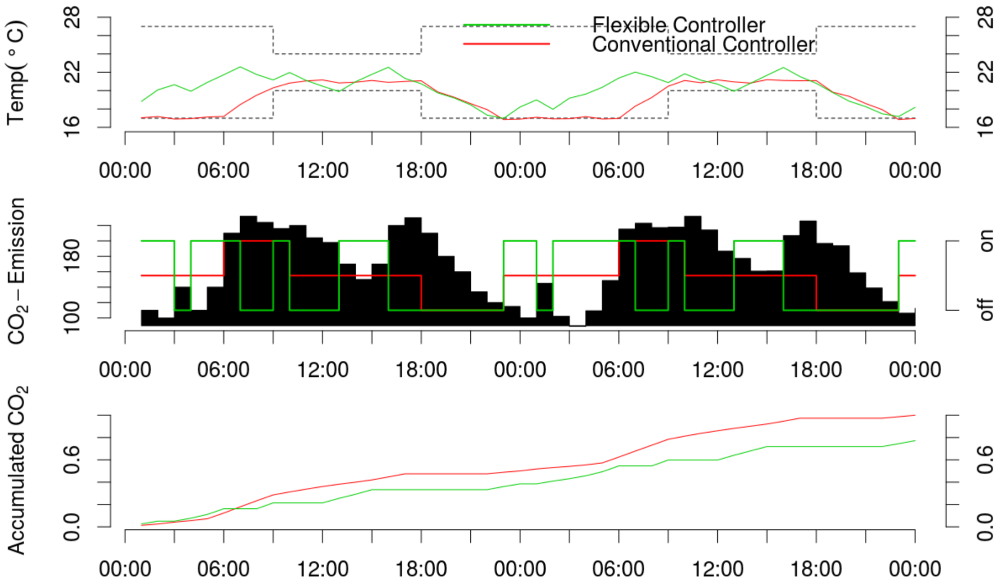



Figure 3. Top plot: the room temperature in a building is controlled by a penalty-aware controller (green line) or a conventional controller (red line). Both controllers are restricted to stay within the dashed lines. Middle plot: The black columns give the penalty, while the green and red lines show when the two controllers calls for heat. Bottom plot: the accumulated penalty for each of the controllers. The penalty-aware controller results, for the considered period, in 20 % less emission of $CO_2$ compared to the traditional controller [7].

Due to the variation of the conditions for obtaining energy flexibility, the focus is on a methodology rather than a number. However, using the methodology, numbers may be obtained for the parameters mentioned figure 2 and for comparison with a reference case, where no flexibility is obtained. The latter refers to labelling, where buildings including their energy systems may be rated by their share of reduction on price/consumption/$CO_2$-emissions etc. (depending on the target of the labelling) when using penalty-aware control instead of penalty-ignorant control.

The flexibility of a building can be described by a dynamic Flexibility Function (FF), which describes how the building react to a penalty signal that may be a price signal, the $CO_2$ content in the grid or the amount of RES in the grid. For simulations the Flexibility Function is found based on the difference between the performance of the penalty aware building and the non-penalty aware building as a function of the penalty signal. For real buildings only the penalty aware performance is measured. For this latter case identification methods are necessary in order to derive the Flexibility Function [2].

Figure 4 shows the FF for three different buildings. Building 1 has a large time constant (e.g. a low energy building), while building 3 has a very low time constant (e.g. a poorly insulated building with resistant heating). Building 2 has a medium time constant.

The FF can be used to investigate how a building may support a specific grid. Figure 5 shows three different grids: one with large amount of wind power, one with much solar power, and one with large peaks (ramps) in the morning and afternoon. Figure 5 shows an example of dynamic penalty signals for such grids, where a penalty of 1 means that there is little or no wind or solar power in the grid or that there are ramping (peak) problems.

Based on the FF for the buildings and the dynamic penalty signal it is possible to calculate an Energy Flexibility Savings Index (EFSI). Table 1 shows the EFSI in % savings for the three buildings in figure 4 when situated in the three grids shown in figure 5.

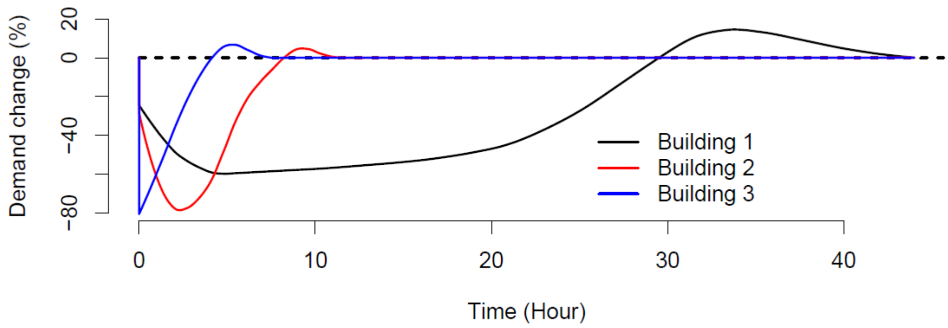



Figure 4. The Flexibility Function for three different buildings [7].

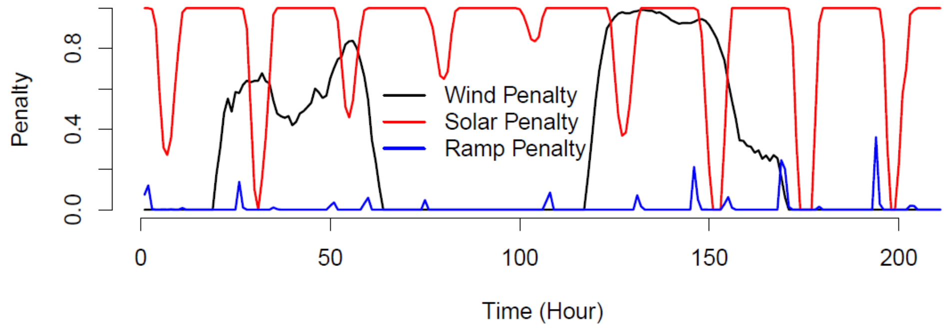



Figure 5. Penalty signals based on wind and solar power production in Denmark during 2017. Ramp penalty based on consumption in Norway during the same period [7].

Table 1 shows that the building with the large time constant is best suited for a grid with much wind power - an EFSI of 11.8 % compared to 4.4 and 6.0 for the two other buildings. The reason is that there often is wind or nearly no wind for several days, so energy needs to be stored for several days. Building 3 with the fast reaction is best suited for a grid with short peak problems, while building 2 with a medium time constant best supports the grid with daily swings in the amount of RES (solar power) in the grid.

Table 1 shows the potential savings in cost or $CO_2$ depending on the applied penalty signal. However, the grid operators are typically more interested in knowing how much of the problems in the grid the buildings may help solving. Again, based on the FF (figure 4) and a well-chosen penalty signal similar to those shown in figure 5, the Flexibility Index (FI) may be calculated for the actual grid, describing the extent to which each of the buildings are able to solve the grid problems. Table 2 gives the FI in % for the considered example.

Table 1. Expected EFSI for each of the three buildings based on the dynamical penalty shown in figure 5.

| Building | Wind (%) | Solar (%) | Ramp (%) |
|---|---|---|---|
| 1 | 11.8 | 4.4 | 6.0 |
| 2 | 3.6 | 14.5 | 10.0 |
| 3 | 1.0 | 5.0 | 18.4 |

Table 2. Expected FI for each of the three buildings based on the dynamical penalty shown in figure 5.

| Building | Wind (%) | Solar (%) | Ramp (%) |
|---|---|---|---|
| 1 | 35.1 | 7.2 | 18.9 |
| 2 | 10.2 | 24.0 | 37.5 |
| 3 | 4.9 | 11.1 | 71.0 |

Table 2 shows how much the buildings are able to correspond to problems in the grid. Building 3 are able during 71 % of the time to help the grid with ramp problems, while Building 1 in 35 % of the cases can provide energy flexibility to a grid with much wind energy. It is further seen that the trend of table 1 and 2 are similar except that the values of table 2 are approx. 3 to 4 times higher than in table 1. This means that if a building performs well from the grid operators' point of view it also gives the highest savings for the customer. This is a very encouraging result for getting the costumers to accept participating in the stabilization of the future energy grids.

During the course of IEA-EBC Annex 67 the EU Commission proposed to include SRIs (Smart readiness Indicators) in EPBD. The aim of SRIs is to rate the readiness of the building to adapt its operation to the needs of the occupant and the grid, and to improve its performance, which is clearly in line with the objectives of IEA-EBC Annex 67. Annex 67 participated as stakeholder in the first study on SRIs and produced a position paper [8]. The viewpoint of IEA-EBC Annex 67 is that there is a need for an approach that takes in to account the dynamic behaviour of buildings rather than a static counting and rating of control devices as proposed by the SRI study. It is more important to minimize the $CO_2$ emission in the overall energy networks than optimize the energy efficiency of the single energy components in a building.

### *1.5.3 Stakeholders' perspective*

Stakeholder acceptance and behaviour are crucial to the success of strategies for energy flexibility in buildings. Without careful design and implementation, introducing energy flexibility has the potential to disrupt occupant lifestyles, building systems for thermal comfort and health, as well as potentially increasing cost or energy consumption. Stakeholder acceptance and behaviour may also be a barrier, but this can be reduced, or overcome entirely, if the related stakeholders are informed about flexibility measures and support any measures that are introduced. Stakeholder acceptance and behaviour is, therefore, an important source of knowledge from IEA EBC Annex 67 as some solutions, although technically sound, may not be feasible as the consequences for the involved stakeholders may not be acceptable to them.

There are a wide range of different stakeholders who may be affected by energy flexibility measures: end-users (occupants of buildings), building owners, facility managers, Energy Service Companies (ESCOs), developers, architects, contractors, and product/system suppliers. The energy flexibility is ultimately useful for aggregators, DSOs (District System Operators) and TSOs (Transmission System Operators). It is important to establish a comprehensive understanding of acceptance, behaviour, and motivation at different levels of involvement for the relevant stakeholders.

To understand stakeholders' acceptance, behaviour, and motivation at different levels of involvement in energy flexible buildings, various methodologies, including questionnaires and interviews, have been utilized in IEA-EBC Annex 67.

The flexibility resources and potentials are different for different types of buildings and building asset managers have different needs and behaviours compared to building owners, end users, electricity providers and energy production stakeholders. Thus, it is essential to understand stakeholders' needs and behaviour, not only regarding comfort and energy requirements, but also regarding their possible position within business models, to develop feasible market access strategies for different types of actors. Meanwhile, incentive programs, national regulations, local policies, and energy and construction market characteristics are important to the stakeholders' activation for continuing the development of business ideas.

Sticks and carrots could enhance stakeholders' participation. General and specific laws and rules, specific exemptions, covenants and agreements can be deployed to engage building stakeholders to comply with energy stakeholders' demands, or vice versa. These could, for example, include energy balancing targets, minimum renewable energy share standards, and requirements for energy efficiency or the promotion of technical solutions such as building energy management systems. Economic instruments can also be deployed, such as to move stakeholders into action: grants, subsidies, beneficial loans, revolving funds and tax incentives for investments are all possible policy instruments that lead to an improvement in the adoption of energy flexible buildings. Also, disincentives might be applied like tariff structures, where higher consumption of energy leads to higher tariffs, a mortgage system or real estate tax system.

In addition, the involvement of governments and regulators in aggregation can provide incentives and increase demand response (DR) awareness and participation. However, the aggregation market is still immature, and the regulations and policies of aggregation markets vary across countries. For instance, in Europe, the countries Belgium, France, Ireland, and the UK have created the regulative framework to enable both DR and independent aggregators, whereas other European countries have not yet engaged with DR reforms, e.g. Portugal and Spain.

Furthermore, the European Commission recently proposed new Directives covering measures relating to energy efficiency, renewables, and changes to reorganize the electricity market and tackle energy poverty. It is expected that the upcoming Directives will support the implementation of energy flexibility. For example, the implementation of the revised European Performance of Buildings Directive already introduced the needed deployment of "smart grid ready" buildings in the Member states. Therefore, the business models exploiting aggregation potentials for buildings need to be based on emerging international policies, national regulations and visions regarding energy market restructuring.

The roles, motivations, and barriers for different stakeholders in energy flexible buildings have in IEA-EBC Annex 67 been investigated based on sixteen case studies. By systematically studying the motivations and barriers revealed in the sixteen case studies, suggestions for how to strengthen the motivations and how to eliminate or reduce the barriers have been listed. The recommendations for related stakeholders are presented in [3]. It is shown that, although 'consumer driven/centred' has been emphasized in recent years, policy makers are still the lead stakeholders for strengthening opportunities and eliminating barriers in the energy system. To establish and realize the markets for energy flexible buildings, decentralization of the power hierarchy is necessary, especially for international collaboration and trading.

### *1.5.4 Control of Energy Flexibility in buildings*

Since buildings are unpredictable consumers of energy, optimization-based control is a key technology in next-generation energy-efficient building systems. Traditional control strategies are still being used even with the development of better alternatives presented over the past years. In addition, the majority of studies focus on independent components of the building rather than building-wide optimization, neglecting the potential efficiency improvements to be exploited for the entire system in order to achieve significant energy savings.

It is necessary to consider important factors such as occupant behaviour patterns, weather conditions, thermal properties and their complex interactions, without compromising the occupants' comfort. In order to use the potential of both commercial and residential buildings as providers of flexibility to the smart energy networks, it is further fundamental to redesign the way a building and its HVAC (heating, ventilation and air condition) system is controlled.

Furthermore, the building-wide optimization is a non-linear and multivariate problem having no unique solution where competitive objectives arise in practice, involving interdependent issues distributed among multiple building climate zones. In this way, the coordinated operation of interconnected subsystems performing autonomous control is essential to achieve the overall system goals.

In this context, where the control process of buildings should be optimized, there is a need to seek new methods and technologies that provide fast and optimized management and control. Appropriate methods must be efficient and robust, performing inter-context considerations among each building zone micro-climate and ensuring reliability and security in several operating conditions of the system.

In order to achieve an emerging overall optimization of the building energy performance, control architectures must be developed, enabling the estimation of weather, occupancy behaviour trends and energy consumption within each building zone. More importantly, control methods are multi-variable systems that can exploit the interactions between states to optimize performance, making buildings more adaptive to system variations and reducing the energy and environment cost. In addition, the sensor information helps to better understand the building performance and the provided services, like air-conditioning, lighting and heating systems and their equivalent parameters, as well as its indoor environmental quality and comfort level in a real-time format.

In order to model/simulate the energy flexibility in buildings it is necessary to define control strategies. Different studies described in [4] investigates algorithms for efficient implementation of strategies for realizing the energy flexibility in buildings, including strategies for storage capacities (thermal and electrical) and local renewables sources, like PV panels. Different control algorithms and strategies are introduced, ranging from simple low-level control of single devices over complex control of several devices to decision making based on different types of forecast (weather, prices, occupancy).

### *1.5.5 Test of Energy Flexible components and systems*

Test and demonstration in real buildings is preferable when evaluation new concepts like energy flexibility in buildings, however, there are many non-controllable variables in a real building, which makes it difficult to draw reliable, significant conclusions - unless the concept is demonstrated in several buildings. Moreover, test and demonstration in real buildings is time consuming and very expensive.

Simulation is on the other hand cheap and fast, so that parametric studies can easily be performed, but it lacks somewhat credibility since all inputs and the environment are often specified in a very simple way, which may lead to conclusions that are not likely in real life.

Many components are exposed to certified tests in order to prove their performance. These tests in laboratories give insight into important parameters of the components, which are necessary input for simulations. However, the tests do not answer the question of how the component will perform in a building under realistic use, as the components are tested under standardized steady-state conditions, which often do not resemble the dynamic conditions the components will be exposed to in real environments.

Hardware-in-the-loop test facilities, where parts of a system are physical components while others are virtual, establishes a bridge between the three approaches described above. Systems and energy flexibility strategies are usually developed through simulations, so there is a need for validation through tests under dynamic, real (or as close as possible to real) operating conditions. Hardware-in-the-loop test facilities represents, therefore, a necessary tool where researchers and industry can test, under controlled conditions, the performance of new systems before they are implemented in real buildings and/or field tests. Compared to field testing, dynamic tests in a controlled laboratory environment with a semi-virtual approach offer the flexibility of imposing well-controlled and repeatable boundary conditions on the equipment, without waiting for given conditions to occur in the real world. The same system can be tested in different environment (e.g. connected to different building types or exposed to different climatic conditions) quickly by reconfiguring the simulation of the virtual parts. Unwanted interferences (e.g. from users) can be avoided and the accuracy of measured data is generally better in a controlled laboratory than in a field study. Of course, field tests are still necessary for a complete performance assessment, but semi-virtual testing allows going further than conventional laboratory tests at a fraction of the cost of a pilot project.

During IEA-EBC Annex 67 nine facilities around the world (Belgium, Canada, Denmark, Finland Germany, Norway, Spain and Switzerland – listed in table 3) specially conceived to test control strategies and the combination of components under controllable, yet realistic, conditions have been documented [9]. Eight out of the nine test facilities use the hardware-in-the-loop concept while the last is a Living Lab being a zero-energy house.

During IEA-EBC Annex 67 experiments for investigation of energy flexibility of components and systems have with success been carried out in six of the test facilities mentioned in table 3 and have been documented in [5]. Valuable insight into how to run hardware-in-the-loop test facilities with regards to gaining knowledge of the performance of different types of systems aiming at providing energy flexibility services to the energy networks have been obtained. Based on this recommendation on how to test energy flexibility have been given in [5]. Figure 6 shows and example of a Hardware-in-the-loop test facility – at IREC, Spain.

Table 3. The test facilities hosted by participants in IEA-EBC Annex 67.

| Name | Managed by | Location |
|---|---|---|
| SEILAB | IREC - Catalonia Institute for Energy Research | Tarragona, Spain |
| Energy Smart Lab | IREC - Catalonia Institute for Energy Research | Barcelona, Spain |
| NZEB Emulator | VTT / Aalto University | Espoo, Finland |
| EnergyVille labs | EnergyVille (VITO, KU Leuven, IMEC) | Genk, Belgium |
| OPSYS test rig | Danish Technological Institute (DTI) | Taastrup, Denmark |
| ZEB Living Lab | NTNU / SINTEF | Trondheim, Norway |
| Semi-Virtual Labora-tory | Polytechnique Montréal | Montréal, Canada |
| Energy Research Lab | Institute Energy in Building, FHNW | Muttenz, Switzerland |
| Test Lab Heat Pumps and Chillers | Fraunhofer Institute for Solar Energy Systems | Freiburg, Germany |

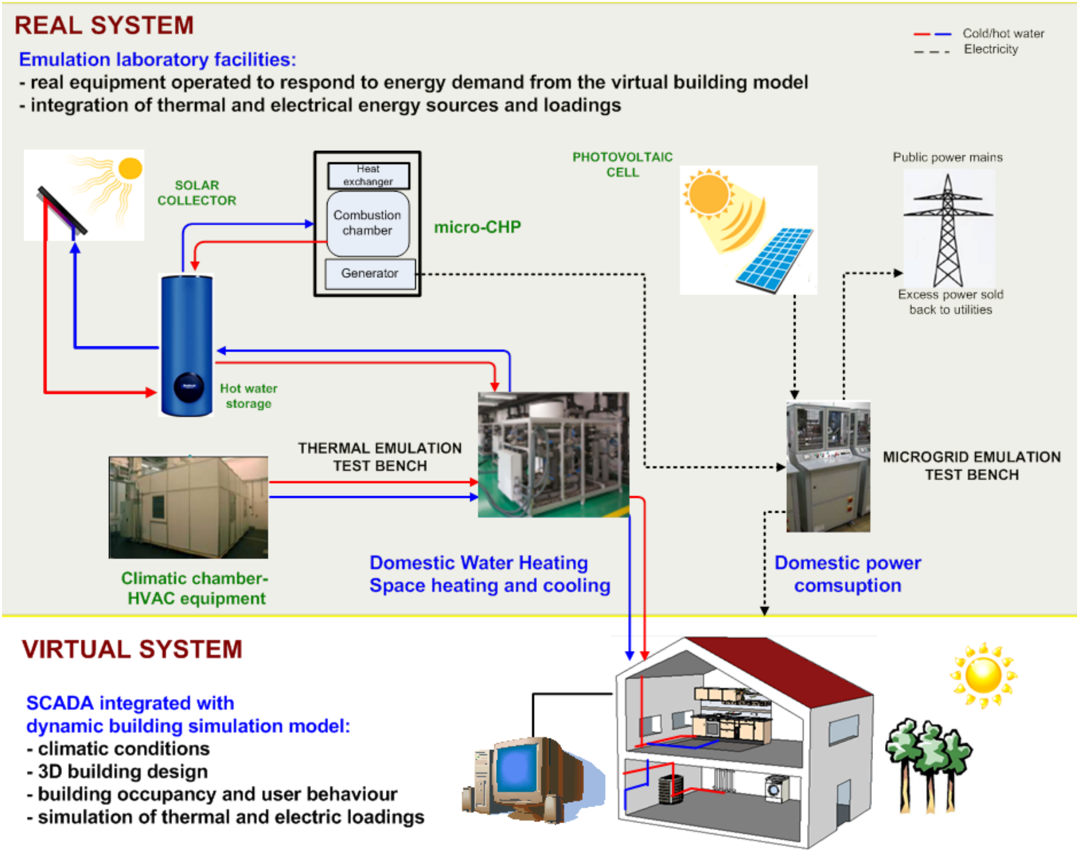


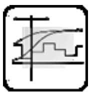

Figure 6. The general layout of the Semi-virtual Energy Integration Laboratory test facility at IREC, Spain [5].

### *1.5.6 Examples of energy flexibility in buildings*

In order to investigate the different possibilities to obtain and control energy flexibility from buildings the participants of IEA-EBC Annex 67 have studied several specific cases either by modelling or by measuring in real buildings or systems. 35 case studies have been documented in [6], [4] and [10]. As energy flexibility from buildings for most is a new area, well documented examples will often be easier to comprehend than theoretical descriptions of this very complex area.

The 35 case studies cover a broad variety of the building typologies, energy systems, sources of flexibility and control strategies highlighted in table 4. The technologies of the four categories in table 4 are mixed in many ways in the 35 case studies, which makes this collection of case studies of energy flexibility in buildings a unique source for inspiration.

Table 4. Brief introduction to the features dealt with in the 35 documented IEA-EBC Annex 67 flexibility case studies.

| Category | Icon | Technology | Explanation |
|---|---|---|---|
| **Building typology** |  | Single-family house | Only one single house or a flat is considered |
| |  | Multi-family house | The considered building is a multi-family building with a number of flats |
| |  | Non-residential building | These buildings are in this report offices or multi-use e.g. university buildings |
| |  | Cluster of buildings | The flexibility of several buildings is considered at an aggregated level. The buildings can either be located physically next to each other or not be physically connected but have the same aggregator controlling their energy flexibility – e.g. buildings with the same type of heating system e.g. a heat pump, and are controlled as a group |
| **Energy system** |  | Heat pump | The utilized heat pumps are located in the buildings and may both be ground source or air source heat pumps |
| |  | District heating | Is considered in the sense, that the building(s) heat demand is covered by district heating via typically a heat exchanger in the building |
| |  | Other HVAC system | This includes any other ventilation and/or cooling systems |
| |  | PV | PV systems located at the building make the building a prosumer, which may put extra stress on the grid when they export electricity to the grid |
| **Source of flexibility** |  | Constructions | The thermal mass of the building (walls, floors, ceilings but also furniture) are utilised for storage of heat |
| |  | Thermal storage | Thermal storage is here both DHW tanks, buffer tanks in space heating and cooling systems but also swimming pools or PCM storage |
| |  | Battery | Batteries may both be a stationary battery in the building (e.g. in connection with a PV system) or the battery of an electrical vehicle owned by the user of the building |
| |  | Fuel switch | Energy flexibility obtained in a building, which has two or more energy systems covering the same demand – e.g. a gas boiler and a heat pump |
| **Control system** |  | Rule based | Traditional control where the energy service systems are controlled by a set of predefined rules. A traditional PI thermostat is a simple rule-based controller |
| |  | Model based | The controller is based on a model of the energy demand of the building in the form of a white box model (e.g. TRNSYS), a grey box model (typically a low order RC (resistance-capacitance) model) or a black box model (where the model is generated from measurements and the parameters of the model give no direct physical meaning). Model based controllers give the possibility of applying forecasts and can thereby make them more efficient but also more complex |

### *1.5.7 Dissemination of IEA EBC Annex 67*

The work in IEA-EBC Annex 67 has been disseminated through working meeting, public seminars, open workshops and publications. The following meetings took place during IEA-EBC Annex 67:

- Definition workshop - spring, 2014, Taastrup, Denmark

- 1st Preparation meeting – autumn, 2014, Basel, Switzerland
- 2nd Preparation meeting – March 19th-20th, 2015, Brussels, Belgium
- 1st Working meeting – September 30th-October 2nd, 2015, Lisbon
- 2nd Working meeting – March 16th-18th, 2016, Trondheim, Norway
- 3rd Working meeting – October 17th-19th, 2016, Bolzano, Italy
- 4th Working meeting – March 15th-17th, 2017, Freiburg and Frankfurt, Germany
- 5th Working meeting – September 27th-29th, 2017, Graz and Vienna, Austria
- 6th Working meeting – March 26th-28th, Barcelona, Spain
- 7th Working meeting – October 10th-12th, 2018, Montreal, Canada
- 8th Working meeting – April 3rd-5th, 2019, Aalborg, Denmark

Each of the working meetings also included a public seminar and open workshop to provide an overview of IEA-EBC Annex 67 deliverables and achievements to a broader audience in the host country, and to give an opportunity to national and international experts to present their activities related to energy flexibility. The public seminars and workshops were scheduled at the last day of each working meeting.

In addition to the series of Annex meetings, the results of the Danish participation have also been disseminated through the research and development projects associated with the Danish participation. One such project was the project: COORDICY - ICT-driven Coordination for Reaching 2020 Energy Efficiency Goals in Public and Commercial Buildings, that was funded by the Innovation Fund Denmark.

The activities and results of IEA-EBC Annex 67 have been published to the general public and the research community through many newsletters and articles. The newsletters are public available at www.annex67.org under Newsletters, and the publications are public available at www.annex67.org under Publications. The main publication deliverables for dissemination of IEA-EBC Annex 67 results are listed in section 1.4.4.

## 1.6 Utilization of project results

The development in building technologies has during the last decades been concentrated on obtaining sufficient indoor comfort and on increasing the energy efficiency of buildings including the energy service systems. This has been forced by an in many countries continuously strengthening of the building regulations – in e.g. EU regulated via the Energy Performance of Buildings Directive (EPBD). However, buildings have up to now mainly been considered as passive consumers (and in the later years also as passive producers) of energy where the surrounding energy networks ensured a sufficient energy supply to the buildings. This has started to change as the stability of the energy networks was ensured by central fossil fuelled energy plants, energy plants which many countries have decided to phase out and replace with renewable energy sources, which have an intrinsic variability that seriously will affect the stability of the energy networks. There is, therefore, a need for a transition from generation on demand to consumption on demand in order to match the instantaneous energy generation. This means in practise that the energy consumption needs to become flexible.

Buildings will, therefore, need to go from being passive consumers to be active consumers, which are able to adjust their energy consumption according to the actual level of energy in the energy networks – i.e. consume more during period with much renewable energy in the networks e.g. by storing energy and opposite reduce the energy consumption during shortage of energy in the networks. Buildings need to become energy flexible. As energy flexibility of buildings for most is a new area, there is a need for a knowledge increase and transfer on how to obtain, control and characterize energy flexibility from buildings.

IEA-EBC Annex 67 has actively contributed to this need by create a better understanding of how buildings' energy flexibility can be controlled and thereby utilized to facilitate the integration of renewable energy resources into the energy system. The Danish participation in IEA-EBC Annex 67 has involved academic staff at all levels, from PhD to Professor level. More specifically from Danish side PhD students, postdocs and assistant professors have contributed to the common annex exercises on energy flexibility in buildings, in addition to the contributions of associate professors and professors to the annex working meetings and deliverable development.

## 1.7 Project conclusion and perspective

With respect to the overall aim and the specific objectives, IEA-EBC Annex 67 has:

- developed a methodology for characterisation energy flexibility from buildings and decided on a common way of referring to energy flexibility in buildings,
- increased the knowledge on the acceptance, motivation and barriers for the involved stakeholders around energy flexible buildings. Knowledge which is important when introducing energy flexibility in real buildings,
- documented 35 cases of different ways of obtaining and controlling energy flexibility in buildings and clusters of buildings and determined the potential available energy flexibility,
- mainly investigated energy flexibility in single buildings, however, the aggregated energy flexibility from clusters of buildings have also been studied in some cases. It has further been shown that different types of buildings perform better in some energy networks than in others depending on the actual mix of renewable energy sources in the actual network,
- tested energy flexibility in Hardware-in-the-loop test facilities and in some field studies.

IEA-EBC Annex 67 is, therefore, considered as a major step forward in making energy flexible buildings an important asset for the future energy networks. The reports of the annex will serve as a unique reference for future work.

## 1.8 References


Deliverables from IEA-EBC Annex 67

[1] Principles of Energy Flexible Buildings. Jensen, S.Ø. and Marzal, A.J. (eds.). Available on www.iea-ebc.org and annex67.org/Publications/Deliverables

[2] Characterization of Energy Flexibility in Buildings. Pernetti, R. and Knotzer, A. (eds.). Available on www.iea-ebc.org and annex67.org/Publications/Deliverables

[3] Stakeholder perspectives on Energy Flexible buildings. Ma, Z. and Parker, J. (eds.). Available on www.iea-ebc.org and annex67.org/Publications/Deliverables

[4] Control strategies and algorithms for obtaining Energy Flexibility in buildings. Santos, A. and Jørgensen B.N. (eds.). Available on www.iea-ebc.org and annex67.org/Publications/Deliverables

[5] Experimental facilities and methods for assessing Energy Flexibility in buildings. Salom, J. and Péan, T. (eds.). Available on www.iea-ebc.org and anex67.org/Publications/Deliverables

[6] Examples of Energy Flexibility in buildings. Jensen, S.Ø., Parker, J., Engelman, P. and Marzal, A.J. (eds.). Available on www.iea-ebc.org and annex67.org/Publications/Deliverables

Other technical reports and links to articles and papers written by Annex 67 participants may be found on: annex67.org/Publications/Deliverables

Other relevant IEA-EBC Annex 67 publications:

[7] Junker et al., 2018. Characterizing the Energy Flexibility of Buildings and Districts. Applied Energy, Volume 225, 1 September 2018, Pages 175–182. www.sciencedirect.com/science/article/pii/S030626191830730X

[8] Energy Flexibility as a key asset in a smart building future - Contribution of Annex 67 to the European Smart Building Initiatives. Pernetti, Reynders and Knotzer (eds.) A position paper from IEA EBC Annex 67. http://www.annex67.org/publications/position-paper/

[9] Laboratory facilities used to test energy flexibility in buildings. Annex 67 technical report. 2. edition. (Péan and Salom (eds.). http://www.annex67.org/media/1708/laboratory-facilities-used-to-test-energy-flexibility-in-buildings-2nd-edition.pdf

[10] Modelling of possible Energy Flexibility in Single Buildings and Building Clusters. Annex 67 technical report. Li (ed).

**Annex**

annex67.org/Publications/