Energy in Buildings and Communities Programme

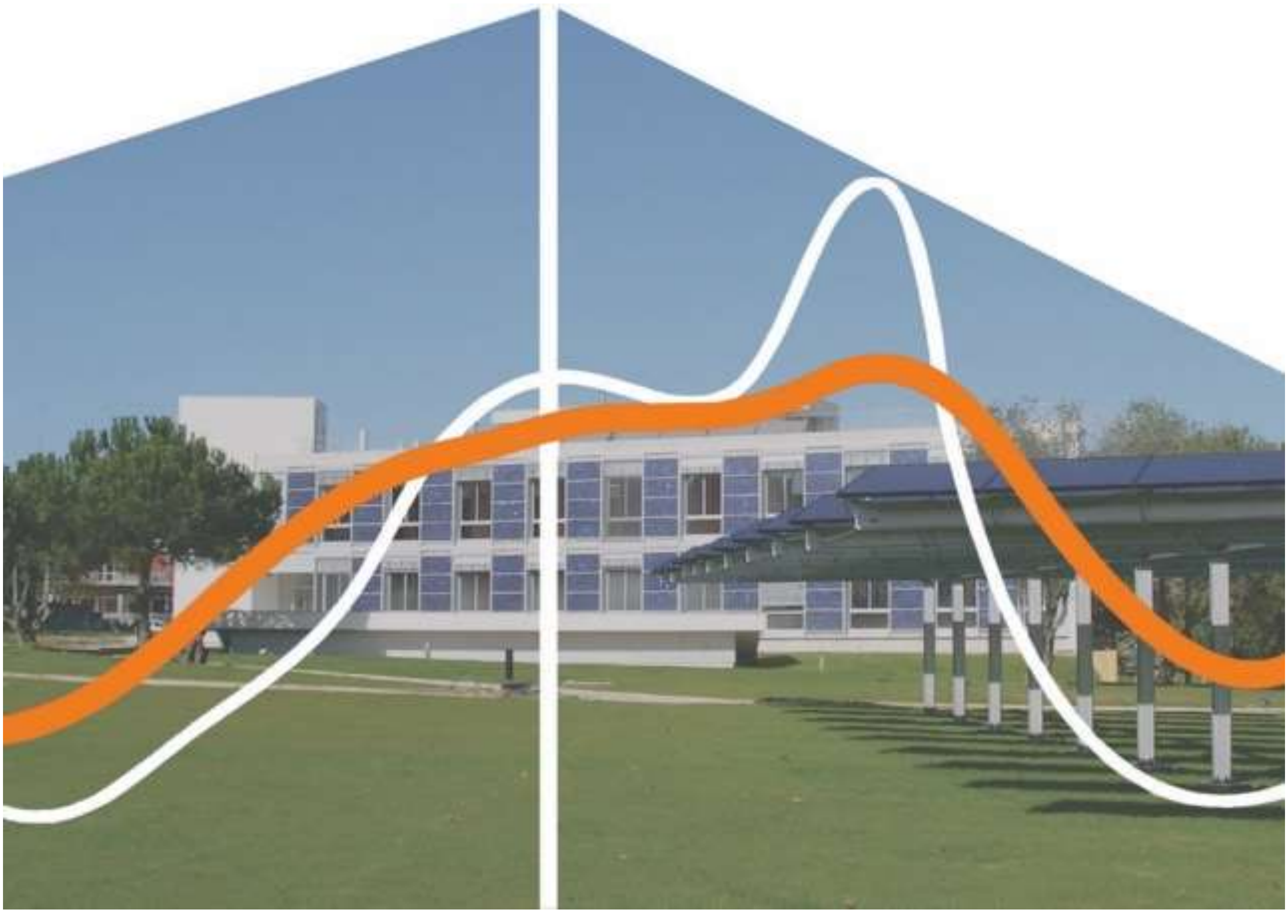
International Energy Agency

Summary report

Energy in Buildings and Communities Programme

Annex 67 Energy Flexible Buildings

December 2019



Technology Collaboration Programme by iea

Project Summary

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 (RES). 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 energy 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) become energy flexible in order to satisfy the generation and/or storage needs of the energy networks, 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. A large part of the energy demand of buildings – such as the energy for space heating or cooling – may be shifted in time and may thereby significantly increase the flexibility of the demand in the energy networks.

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 of the occupants. 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 networks is still in its early stages. 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 many 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 networks. 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 networks.

A building’ potential for energy flexibility depends on many different factors including the type of building, the types of energy service systems in the building, the control system, the state of the storage but also on the climate where the building is situated, the time of day and year, and the acceptance of the users and owners of the building. The value of energy flexibility is further determined by the needs of the surrounding energy networks to which the building may provide flexibility services. There is, therefore, a need for a consistent approach for characterizing the available energy flexibility of any building. In Annex 67 such a methodology has been developed and demonstrated. The methodology is based on a Flexibility Function by which it is possible to estimate the potential energy flexibility of buildings while exposed to a varying Penalty signal (e.g. price signal or CO_2 content of the energy in the energy networks), which describes the conditions in the surrounding energy networks. The result are the Expected Flexibility Saving Index and the Flexibility Index, which 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 networks, it does not matter how energy flexible the building is as the building will not be an asset for any energy networks. 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 networks. 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 Annex 67 been investigated based on sixteen case studies. By systematically studying the motivations and barriers revealed in the sixteen case studies, suggestions on how to strengthen the motivations and how to eliminate or reduce the barriers have been developed. It is shown that, although ‘consumer driven/centred’ approaches have been emphasized in recent years, policy makers are still the lead stakeholders for strengthening opportunities and eliminating barriers for making energy flexibility from buildings available for supporting the future energy systems.

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 practical 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. These types of Hardware-in-the-loop test facilities have been utilized in Annex 67. Heat pumps and other components were for example tested with the energy demand of virtual buildings and exposed to virtual weather and grid conditions. Valuable insights into how to run Hardware-in-the-loop test facilities end a greater understanding of the performance of different types of systems aimed at providing energy flexibility services to the energy networks have been obtained. Subsequently, recommendations on how to test energy flexibility have been outlined.

33 examples (both modelled and measured) on how to obtain energy flexibility from buildings have been documented and this collection of examples is considered to be a unique source of inspiration when considering the energy flexibility of buildings.

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Project Outcomes

1. Background

The development in building technologies has during the last few decades been concentrated on obtaining a sufficient indoor comfort level and on increasing the energy efficiency of buildings including the energy service systems. In many countries this has been forced by continuous strengthening of the building regulations – in e.g. EU regulated via the Energy Performance of Buildings Directive (EPBD). However, up to now, buildings have mainly been considered as passive consumers (and in the later years also passive producers) of energy where the surrounding energy networks (electricity, gas, district heating/cooling) ensure a sufficient energy supply. This has started to change as the stability of the power grids was ensured by central fossil fuelled energy plants, which many countries have decided to phase out and replace with renewable energy sources (RES). Most RES have, however, an intrinsic variability that seriously affect the operation and 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 from RES. In practise this means that the energy consumption needs to become flexible.

Buildings will need to transition from being passive consumers/producers to be active consumers/producers, which are able to adjust their energy consumption according to the actual level of energy in the energy networks. They need to consume more during periods with more renewable energy in the networks e.g. by storing energy, and/or reduce the energy consumption during shortages of energy in the networks. Buildings needs to become energy flexible. As energy flexibility of buildings for most is a new concept, there is a need for a knowledge increase and a knowledge transfer on how to obtain, control and characterize energy flexibility from buildings.

Therefore, the objectives of 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 networks; and
- demonstration of energy flexibility through experimental and field studies.

2. 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 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.

Different ways of obtaining energy flexibility are illustrate in Figure 1. Seen from the right:

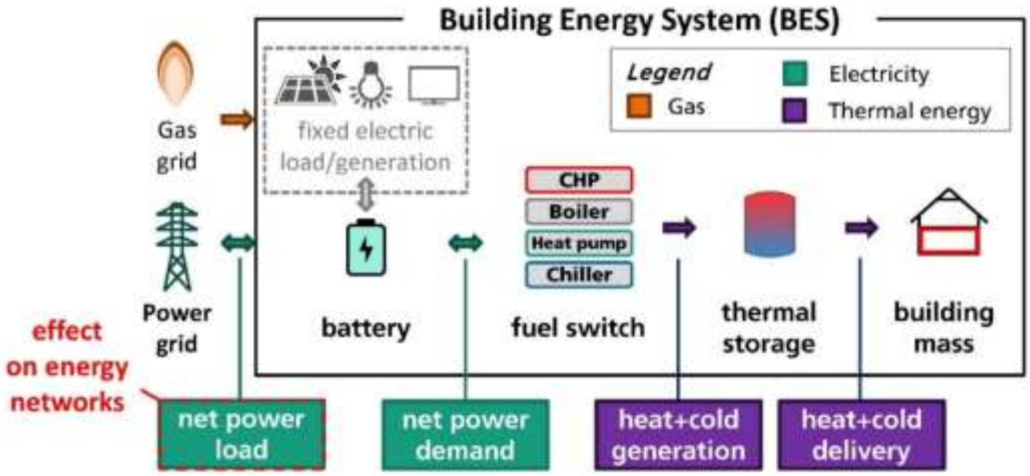


Figure 1 Sources for obtaining energy flexibility [6].

Building mass: walls, floors (especially underfloor heating), ceilings and furniture of buildings contain a certain mass and thereby a certain thermal capacity, which can be utilized to store energy. During a shortage of energy, the heating or cooling system can, therefore, be switched off for a period without decreasing the comfort of the users. The possible duration of such a period depends on the thermal mass and the heat loss of the buildings but can range 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 active storage systems that are not part of the building's thermal mass. 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) as storage medium.

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

Battery: here electricity is directly stored on site. 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.

Generation: many buildings are becoming prosumers – i.e. they no longer only consume energy, they also produce energy through PV, a solar thermal system, a micro wind turbine or a CHP (combined heat and power production) plant (not shown in Figure 1).

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

In order to take advantage of the aforementioned sources for energy flexibility efficiently, there is a need for preferably automated control. Different types of control may be utilized for obtaining energy flexibility from buildings. This control can be very simple like a heat pump being switched off every day during a predefined period, or more complex rule-based control where several constraints are included (e.g. that the heat pump is switched off during high price periods unless the indoor temperature is too low), or be advanced model-based control including forecasts of weather, occupancy behaviour (these two provide a forecast of future demand) and energy prices.

There exist many definitions on energy flexibility in buildings. Annex 67 define energy flexibility in buildings as:

> *The energy flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements.*
>
> *Energy flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding grids.*

3. 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. Having energy flexibility which is actual useful is further determined by the needs of the surrounding energy networks to which the building is providing flexibility services.

The amount of available energy flexibility cannot be expressed with a single number as it can for energy consumption. Therefore, Annex 67 has developed a methodology including key parameters for the characterization of energy flexibility [2].

The methodology, introduced by IEA EBC Annex 67, characterizes energy flexibility by quantifying the amount of energy a building can shift according to an external forcing factor (Penalty signal), without compromising the occupant comfort conditions as well as accounting for the technical constraints of the building and its HVAC system. It acknowledges that the penalty signal acts as a boundary condition for the building. 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 2 further shows the parameters describing the response to the signal.

Consequently, the energy flexibility of a building is not a fixed static value, but varies according to environmental conditions, occupants’ use of the building as well as the penalty signal, which induces a system response (see Figure 2). Hence, a building’s energy flexibility is determined by its ability to shift the instantaneous energy demand to minimize the effect of the penalty signal. The penalty signal could be designed to 1) minimize the energy consumption, 2) minimize the cost, or 3) minimize the CO_2 foot-print of the building – or a combination of those criteria.

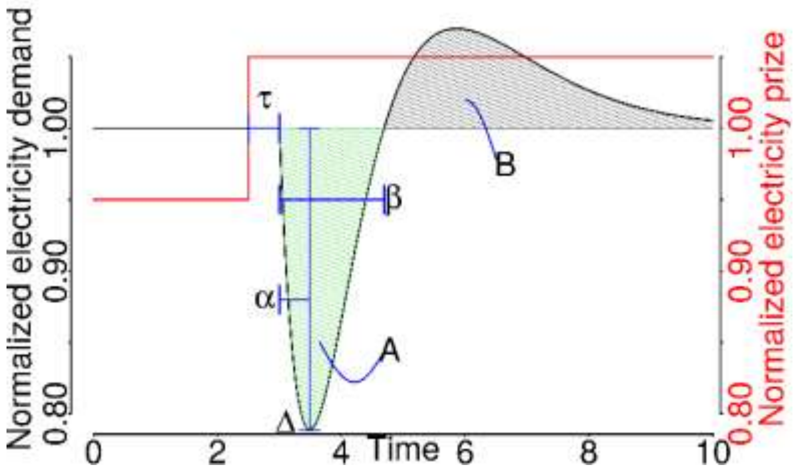


Figure 2. Example of aggregated response when some buildings receive a penalty signal – here a price signal [7]. The parameters in figure are: τ is the time from the signal being submitted to when an action starts, α is the period from the start of the response to the max response, Δ is the max response, 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".

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
- 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 be utilized in simulations to test the capacity of a thermal storage system for example, but may also be utilized for peak shaving in real energy networks. Temporal signals will often 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.

Due to the variation of the conditions for obtaining energy flexibility, the focus of Annex 67 was on a methodology rather than a number. However, using the methodology, numbers may be obtained to characterize the parameters mentioned in Figure 2 and for comparison with a reference case in which no flexibility is obtained. The difference between the case with and without utilization of the energy flexibility (bottom plot of Figure 3) may be used for 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 unaware control.

The energy flexibility of a building can be described by a dynamic Flexibility Function (FF) – e.g. the curved line in Figure 2, which describes how the building reacts 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 and more advanced mathematical methods are necessary in order to derive the FF [2].

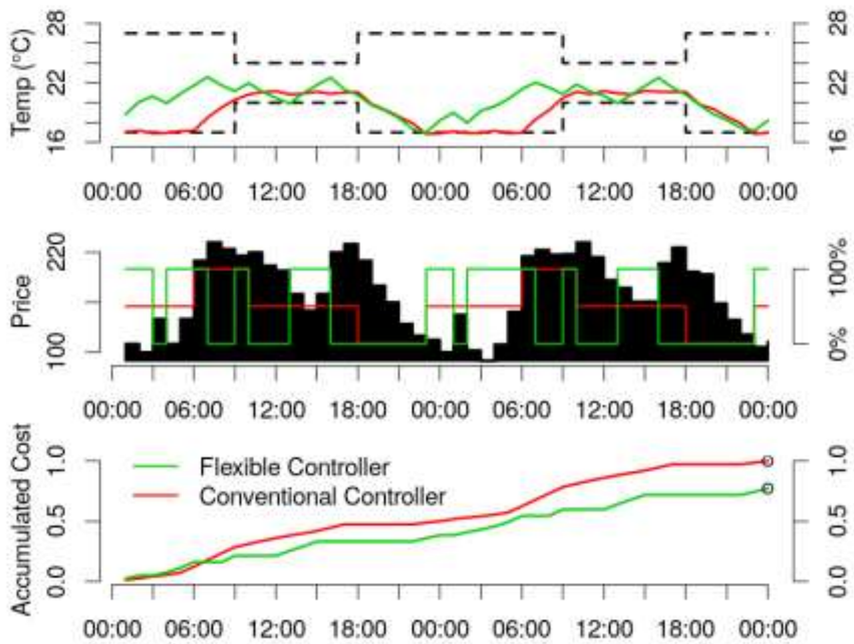


Figure 3. Top plot: the room temperature in a building is controlled by a penalty aware controller (green line) or a conventional controller (red line). Both controllers are restricted to stay within the dashed lines. Middle plot: The black columns give the penalty, while the green and red lines show 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].

Figure 4 shows the FF for three different buildings. Building 1 has a large time constant (e.g. a low energy building with a significant amount of thermal mass), 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.

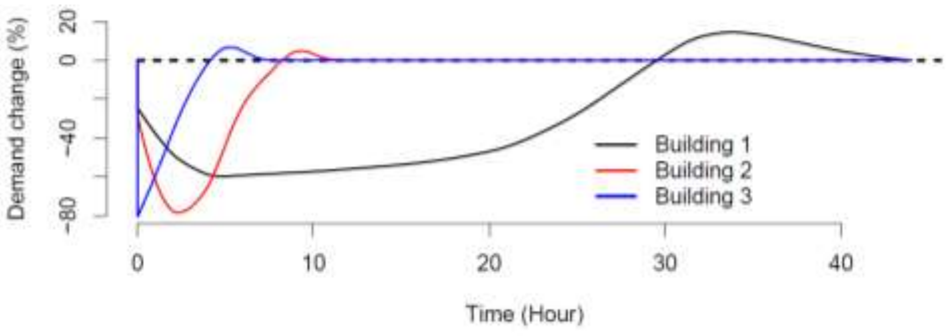


Figure 4. The Flexibility Function for three different buildings [7].

The FF can be used to investigate how a building may support a specific grid. Figure 5 shows three different grids: one with a 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 Expected Flexibility Savings Index (EFSI), which basically states the saving potential (cost or CO_2) of the three buildings when located in different energy networks with different needs. Table 1 shows the EFSI in % savings for the three buildings in Figure 4 when situated in the three grids shown in Figure 5.

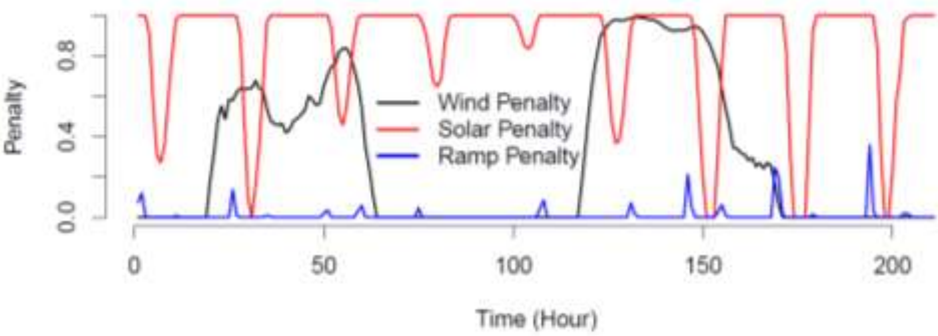


Figure 5. Penalty signals based on wind and solar power production in Denmark during 2017. Ramp penalty based on consumption in Norway during the same period (this situation is also typical for district heating networks) [7].

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 3.6 % and 1.0 % 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 solve. Again based on the FF (Figure 4) and a well-chosen penalty signal similar to those shown in Figure 5, but focusing on solving the problems in the networks, 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 examples.

Table 1. 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. 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. During 35 % of the time, Building 1 is able to help the grid with a fluctuating amount of wind energy, while Building 3 in 71 % of the cases can provide energy flexibility to a grid with ramp problems. It is further seen that the trend of Table 1 and 2 are similar except that the values of Table 2 are approximately 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 actually getting consumers to accept participating in the stabilization of the future energy grids, if there are mechanisms for appropriately compensating building owners for the services they can provide.

During the course of Annex 67 the EU Commission proposed to include SRIs (Smart Readiness Indicators) in the 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 Annex 67. Annex 67 participated as a stakeholder in the first study on SRIs and produced a position paper [8]. The viewpoint of 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 emissions from the overall energy networks than to optimize the energy efficiency of the single energy components in a building.

4. 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 and/or energy consumption. Stakeholder acceptance and behaviour may also be a barrier, but this can be reduced or overcome, if the related stakeholders are informed about flexibility measures and support the measures that are introduced. Knowledge about the acceptance and behaviour of the stakeholders are, therefore, an important outcome of Annex 67 as some solutions, although technically sound, may not be feasible as the consequences for the involved stakeholders may not be acceptable.

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 (Distribution System Operators – both for power and district heating systems) 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. In Annex 67 various methodologies, including questionnaires and interviews, have been utilized to understand stakeholders' acceptance, behaviour, and motivation at different levels of involvement in energy flexible buildings.

The flexibility resources and potentials are different for different types of buildings. 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 the needs of various stakeholders. Shaping stakeholder needs and preferences are a variety of policy and market structures including, incentive programs, national regulations, local policies, and energy and construction market characteristics.

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 flexibility or the promotion of technical solutions such as building energy management systems. Economic instruments can also be deployed to help motivate 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 in many countries, 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.

The European Commission recently proposed new Directives covering measures relating to energy efficiency, renewables, and also 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 Annex 67 been investigated based on sixteen case studies. By systematically studying the motivations and barriers revealed in the sixteen case studies, suggestions on 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' approaches have been emphasized in recent years, policy makers are still the lead stakeholders for strengthening opportunities and eliminating barriers in the energy system.

5. Control of Energy Flexibility in buildings

Since buildings in many cases 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 and energy flexibility.

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 energy 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 ensuring reliability and security in the operating conditions of the system.

In order to achieve an 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 environmental cost. In addition, the sensor information helps to better understand the building performance and the provided services, like air-conditioning, lighting and heating 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] investigate 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, to more complex control of several devices, and further to decision making based on different types of forecast (weather, energy prices, and occupancy).

6. Test of Energy Flexible components and systems

Test and demonstration in real buildings is preferable when evaluating new concepts like energy flexibility in buildings in order to convince the stakeholders of the validity of the concept. 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 can be time consuming and very expensive.

Simulation is, in comparison cheap and fast, so that parametric studies can easily be performed. However, since all inputs and the environment are often specified in a very simple way, this may lead to conclusions that are not applicable 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 inputs 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 represent, 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 environments (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 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 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 Laboratory	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

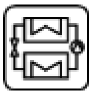
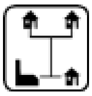
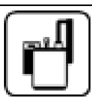
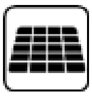
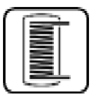
Figure 6. The general layout of the Semi-virtual Energy Integration Laboratory test facility at IREC, Spain [5].

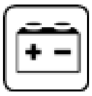
7. Examples of Energy Flexibility from buildings

In order to investigate the different possibilities to obtain and control energy flexibility from buildings the participants of Annex 67 have studied several specific cases either by modelling or by measuring in real buildings or systems. 33 case studies have been documented in [6], [4] and [10]. As energy flexibility from buildings for most is a new concept, well documented examples will often be easier to comprehend than theoretical descriptions of this very complex area.

The 33 case studies covers 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 different ways in the 33 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 33 documented 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 are 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 to store heat
		Thermal storage	Thermal storage are here both DHW tanks, buffer tanks in space heating and cooling systems but also swimming pools or PCM storage

Category	Icon	Technology	Explanation
Source of flexibility		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

8. Conclusion

With respect to the objectives listed under Background, 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 33 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 performs 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.

Annex 67 is, therefore, a major step forward in making energy flexible buildings an important asset for the future energy networks.

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Project Publications

Deliverables from Annex 67

[1] Principles of Energy Flexible Buildings. Jensen, S.Ø., Parker, J. 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., Knotzer, A. and Jensen, S.Ø. (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 annex67.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 www.annex67.org/Publications.

Other relevant Annex 67 publications:

[7] Characterizing the Energy Flexibility of Buildings and Districts. Junker et al., 2018. 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 R., Reynders, G. and Knotzer, A (eds.). A position paper from IEA EBC Annex 67, November 2017. http://www.annex67.org/publications/position-paper/

[9] Laboratory facilities used to test energy flexibility in buildings. Annex 67 technical report. 2. edition. (Péan, T. and Salom, J. (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, R. (ed.). http://www.annex67.org/media/1866/modelling-of-possible-energy-flexibility.pdf