Annex 67: Energy Flexible Buildings

Energy Flexibility as a key asset in a smart building future

Contribution of Annex 67 to the European Smart Building Initiatives

Position Paper of the IEA Energy in Buildings and Communities Program (EBC) Annex 67 "Energy Flexible Buildings"

November 2017

Content

Aim of this Paper 3

Energy Flexibility as a key resource in the future energy system 4

European Dimension 5

Characterization and labelling of Energy Flexibility in buildings 8

Conclusion 12

References 13

Editors: Roberta Pernetti (*eurac - IT*), Glenn Reynders (*KU Leuven-Energy Ville - BE*), Armin Knotzer (*AEE INTEC - AT*)

Authors: Søren Østergaard Jensen (*Danish Technical Institute - DK*), Henrik Madsen (*Technical University of Denmark - DK*), Rui Lopes (*New University of Lisbon - PT*), Rune Grønborg Junker (*Technical University of Denmark - DK*), Daniel Aelenei (*New University of Lisbon - PT*), Rongling Li (*Technical University of Denmark - DK*), Susanne Metzger (*TU Wien - AT*), Karen Byskov Lindberg (*Norwegian Water resource and Energy Directorate - NO*), Anna Joanna Marszal (*Aalborg University - DK*), Michaël Kummert (*Polytechnique Montréal - CDN*), Bart Bayles (*CSTC - BE*), Erwin Mlecnik (*Delft University of Technology - NL*), Roberto Lollini (*eurac - IT*), Wilmer Pasut (*eurac - IT*)

Disclaimer Notice: Although this publication is part of the work conducted within IEA EBC Annex 67 Energy Flexible Buildings, the publication only reflects the viewpoints of the authors. The EBC Contracting Parties (of the International Energy Agency Technology Collaboration Program of Research and Development on Energy in Buildings and Communities) make any representation as to the adequacy or accuracy of the information contained herein, or as to its suitability for any particular application, and accept no responsibility or liability arising out of the use of this publication. The information contained herein does not supersede the requirements given in any national codes, regulations or standards, and should not be regarded as a substitute for the need to obtain specific professional advice for any particular application.

Aim of this Paper

The main objective of this Position Paper is to raise awareness about the potential of Energy Flexibility in buildings to support future energy systems and to present the insights gathered from 3 years of work within the IEA EBC Annex 67 [1]. As a general definition proposed within the Annex, 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 and on availability of RES, in order to minimize the CO_2 emissions.**

Annex 67 – Energy Flexible buildings

Project duration: 2016-2019

Operating Agent: Søren Østergaard Jensen

Danish Technological Institute

E-mail: sdj@teknologisk.dk

Website: http://www.annex67.org

Participating countries: Austria, Belgium, Canada, Czech Republic, Denmark, Finland, Germany, Italy, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, UK

Work Program:

Subtask A: Definition and context

Subtask B: Analysis, Development and Testing

Subtask C: Demonstration and Users

Thereby, this document aims to feed into the discussion at EU level and to inform the consortium elaborating the EC-study "Support for setting up a Smart Readiness Indicator for Buildings and related impact assessment" [2] and the interested public about the view of IEA EBC Annex 67 on how to characterize and exploit Energy Flexibility of buildings. In the current state of discussion at EU level, Energy Flexibility is represented as one of three pillars governing the "smartness" of a building since the EC-study defines a "smart building" as *a building that can manage itself, interact with its users and take part in demand response.* In the proposed framework, the "smart readiness level" is evaluated with a qualitative approach according to the number and type of services provided by its components [2]. In contrast, the methodology to characterize Energy Flexibility developed by IEA EBC Annex 67 is based on quantitative and physical indicators. The Energy Flexibility is determined either using measured data or results from simulation studies based on optimization methods including model predictive control. The resulting Energy Flexibility indicators take into account respective individual building components and services, occupant comfort, HVAC systems, and regional climate and energy system conditions. Therefore, rather than providing a qualitative rating of the implementation level of smart technologies, Annex 67 is developing a methodology for obtaining quantitative Energy Flexibility indicators aiming at supporting design decisions on building and clusters of buildings' levels as well as quantifying the available Energy Flexibility in a building or neighborhood during operation. In this regard, the approach defined within IEA EBC Annex 67 provides a quantitative evaluation of the Energy Flexibility of a specific building or building cluster related to a specific target, such as the reduction of CO_2-emissions on a community level [3].

This document is organized in three sections that clarify the approach and position of IEA EBC Annex 67. First, the importance of Energy Flexibility to meet climate and energy policy targets is presented. Thereby, buildings are introduced as an important potential source of Energy Flexibility in future energy systems. In the following section, the importance of Energy Flexibility and the findings of ongoing research in IEA EBC Annex 67 are situated in the context of ongoing discussions on a European Dimension. Finally, the third main section of this paper describes how and why IEA EBC Annex 67 is emphasizing the development of a quantitative framework for Energy Flexibility characterization and labeling.

Energy Flexibility as a key resource in the future energy system

Large-scale integration of decentralized electricity production from renewable energy sources is often suggested as a key technology striving towards a sustainable energy system, mitigating fuel poverty and climate change. In many countries, the growing share of renewable energy sources (RES) goes in parallel with the extensive electrification of demand, e.g. replacement of traditional cars with electrical vehicles or displacement of fossil fuel heating systems, such as gas or oil boilers, with energy efficient heat pumps [4], [5]. At the same time, supporting the operation of (low temperature) district heating grids supplied by different renewable sources. These changes on both the demand and supply side impose new challenges to the management of energy systems, such as the variability and limited controllability of energy supply from renewables or increasing load variations over the day [6], [7]. Consequently, managing the energy transition following the traditional energy system viewpoint would lead to a grid operation closer to its limits, with a possible consequent increase of the energy use at peak periods, requiring more complex control problems with shorter decision times and smaller error margins [8].

Therefore, flexible energy systems are often suggested as an important part of the solution [6] - [13]. Flexible energy systems overcome the traditional centralized production oriented approach, whereby the production follows the demand, by integrating decentralized storage and demand response into the energy market. In this context, strategies to ensure the security and reliability of energy supply involve simultaneous coordination of distributed energy resources (DERs), energy storage and flexible schedulable loads connected to distribution networks[5], [8], [11].

As buildings account for approximately 40% of the annual energy use worldwide [14], they are likely to play a significant role in providing a safe and efficient operation of the future energy system. Hence, they may deliver significant flexibility services to the system by intelligent control of their energy loads, both thermal and electric. Therefore, the research conducted by IEA EBC Annex 67 emphasizes Energy Flexibility and acknowledges that the interactions between buildings and the energy infrastructure in time and scale should be fostered in order to fully benefit from the potential of renewables and mitigate CO_2-emissions on an aggregated level for achieving the intended de-carbonization of energy services until 2050. Consequently, building design and control should also be evaluated beyond that of individual buildings.

To understand and integrate the potential of energy flexible buildings in future energy systems, a holistic approach is needed harmonizing building and energy (both electrical and thermal) system engineering but also energy market design and even occupant interaction. However, extensive review studies carried out within IEA EBC Annex 67 demonstrate that this integration is hampering since a common terminology and methodology for characterization and labeling of Energy Flexibility in buildings is currently missing, both at the single building and at the clusters of buildings level [15]. As building engineers are often not familiar with all technical aspects of energy networks and vice versa, IEA EBC Annex 67 proposes the use of a set of flexibility indicators that are easy to understand by both parties. These indicators should facilitate design and operational decisions on both building and energy system level, taking into account the complex interactions between building, energy system, occupants and other boundary conditions (e.g. RES availability, weather conditions) [16]. The remainder of this document therefore first outlines the position of the IEA EBC Annex 67 approach in the European Dimension and secondly provides a more detailed explanation of the characterization method that is being developed and tested within the Annex 67 project.

European Dimension

With the introduction of the *Winter Package* [17], the concept of smart buildings gained explicit interest in Europe. There are three important aspects of results from work in IEA EBC Annex 67 addressing European discussions at the moment:

1. CO_2-emission efficiency versus energy efficiency

In October 2014, the European Council agreed on the 2030 climate and energy policy targets [18]:

- 40% cut in greenhouse gas emissions compared to 1990 levels
- At least a 27% share of renewable energy consumption

At least 27% energy savings compared with the current use

Following these targets and the COP 21 Paris Agreement of 2015 and changing the approach promoted by other related policy papers and articles ([19] - [21]), IEA EBC Annex 67 envisions Energy Flexibility of buildings and “smartness” more as a mean to promote CO_2-reduction and increasing the share of renewables at the energy system level than to enforce energy efficiency on a building level. Although energy efficiency measures are still to play an important role, an optimal balance needs to be found between energy efficiency and other methods fulfilling CO_2-reduction targets, such as control strategies and demand response.

To support this vision, IEA EBC Annex 67 is working on analyses that focus on exploiting Energy Flexibility in buildings to optimize energy efficiency and CO_2-reductions at an aggregated or community level. A clear example is given in a study on the CO_2-abatement cost of residential heat pumps with active demand response by Patteeuw et. al. [22]. In this study, a large-scale implementation of residential heat pumps – as a measure to gain energy efficiency and reduce CO_2 emissions by replacing traditional gas boilers - is evaluated in a future scenario of the Belgian electricity market assuming a high share of wind (30%) and solar (10%) production. Using a combined optimization of both electricity production and demand response – provided by thermal storage at the building level – the study shows that active demand response can significantly increase the uptake of renewables by matching demand and renewable electricity production. As such, not only total CO_2-emissions decreased, but the societal cost of CO_2-savings was also reduced significantly. While achieving 15% CO_2-savings by including Energy Flexibility into the system compared to a scenario where each building minimized its own energy use, the study reported that the annual energy use on a building level increased by 3-5%.

Similar studies reporting CO_2-emission savings or operational cost savings through harvesting Energy Flexibility in buildings are manifold [23] - [37]. Even though each of these studies may focus on specific services that could be offered by energy flexible buildings, they commonly conclude that offering Energy Flexibility to the grid might increase the local energy use of a building. To compensate this drawback, the technology for creating energy flexibility often also may be utilized for increasing the energy efficiency of the building Anyway, efficiency and/or CO_2-emissions savings as well as a higher uptake of renewables on the aggregated level should compensate this increase.

2. Smart quantitative indicator vs smart qualitative indicator

The Clean Energy Package, launched by the European Commission in November 2016 [38], underlines the need for Energy Flexibility in buildings. The proposed changes of the Electricity Market Directive (EMD) [39] challenges the Distribution System Operators (DSO) to actively take part in and exploit local flexibility, in order to utilize the existing grid more efficiently. Further, it is expected that a flexibility market will be established. Buildings are expected to become "smart" and contribute to user comfort as well as in the flexibility market, which is underlined by the latest proposed amendment of the Energy Performance of Building Directive (EPBD) 2017 [40]. Nevertheless, the currently discussed Smart Readiness Indicator (SRI) differs from the IEA EBC Annex 67 approach. The study on SRI is defining a method for calculating affordably and easily a SRI, mainly rating different smart services integrated in buildings [2]. IEA EBC Annex 67 proposes a physical data- and simulation-based approach with quantitative indicators. As such, the method enables quantification and prediction of the building Energy Flexibility supporting decisions at both building and aggregated level during design and operation. In defining a quantitative and data-driven or simulation-based approach (that could be based also on simulations), IEA EBC Annex 67 acknowledges that Energy Flexibility is not only the result of the available technologies in a building, but depends significantly on the way these technologies are used – i.e. controlled – and their interaction with the surrounding energy network, the occupants and other boundary conditions, such as local climate.

3. Energy performance assessment of clusters of buildings vs individual buildings

Over the last 20 years, the energy performance certificates (EPC) in European countries have been calculated based on a steady state energy balance performed at single building level assuming standard boundary conditions and constant building use. The evaluation of the energy performance of the new generation of buildings, however, requires a transition of the current approach towards a dynamic approach, which takes into account the interaction between buildings and energy systems on the scale of cluster of buildings [41].

On the one hand, assessing the matching between the RES production and building energy demand requires a transient approach representing the actual operation. On the other hand, evaluating the energy performance at aggregated level can lead to several benefits in terms of CO_2 reduction, such as improved storage and load conditions, and compensation of particular constraints of individual buildings - e.g. the poor energy performance of a not-retrofitted historic building can be balanced by the high efficiency of closer new buildings.

In this regards, the modelling activity within IEA EBC Annex 67 and the related Energy Flexibility labelling approach could represent an important reference for the transition from a current single building evaluation, towards a wider perspective that considers building clusters and offers options for extended data processing into the surrounding energy networks.

Characterization and labelling of Energy Flexibility in buildings

As stated in previous sections, IEA EBC Annex 67 is developing a quantitative methodology to characterize and label Energy Flexibility that not only takes into account the technical aspects or services on a building level, but also includes its interaction with the energy system, occupants and other boundary conditions. While studies demonstrating the potential of Energy Flexibility through case studies are manifold, a literature review in the framework of IEA EBC Annex 67 concluded that limited methodologies exist that aim at a direct prediction of the amount of flexibility a building can offer to the grid. Such a uniform and direct quantification method – which starts from what a building may offer rather than how much flexibility is harvested in a specific case study – is a prerequisite to establish a common basis for comparing the flexibility potential of different buildings (and technologies) between studies and applications. Hence, this bottom-up viewpoint, supported by IEA EBC Annex 67, opens the path towards labelling of Energy Flexibility, as a part of smartness, in buildings.

Recognizing that Energy Flexibility is obtained by the level of controllability of the system taking into account its technical constraints, storage options and interaction with its surroundings, it is evident that a direct prediction of the actual, instantaneous, Energy Flexibility that a building can offer to the energy system requires a case specific analysis. Similar to the prediction of the actual energy use of buildings, predicting Energy Flexibility requires a detailed dynamic modelling of the system, its constraints and its boundary conditions, and would result in a flexibility profile that varies in time [41] - [45]. As these profiles or their underlying models are often difficult to communicate – and interpret – between stakeholders at different levels and sides of the energy system, IEA EBC Annex 67 focusses on characterization and labeling of Energy Flexibility by Energy Flexibility indicators. Through an extensive literature review [45], and taking into account the interface between buildings and energy systems when dealing with Energy Flexibility, three general properties return when communicating Energy Flexibility:

I. Capacity (amount of energy that can be shifted per time unit, including the rebound effect as shown in Figure 1)
II. Time aspects (like starting time & duration)
III. Cost (potential cost saving or energy use associated to activating the available flexibility)

These properties generally follow from underlying definitions of Energy Flexibility as a change in power or energy compared to a reference scenario. In other words, the quantification methods formulate the Energy Flexibility of a building by assessing its ability to deviate from a reference standard operation if an incentive would be provided externally, e.g. by an aggregator.

The methodology introduced by IEA EBC Annex 67, represents Energy Flexibility in this manner, by quantifying the amount of energy a building can shift according to external forcing factors, without compromising the occupant comfort conditions and taking into account the technical constraints of the building and of its HVAC system. In that, it acknowledges that forcing factors act as boundary conditions, which can change over the lifetime of a building and with different levels of frequency:

- ✓ **Low frequency factors**: climate change, macro-economic factors, technology improvement, energy costs, use of the building
- ✓ **High frequency factors**: energy mix/RES availability, energy prices, internal/solar gains, user behavior, hourly energy prices, ambient temperature

Consequently, the Energy Flexibility of a building is not a fixed static value, but varies according to such forcing factors and control signals (in the following called **penalty signal**), which induce a system response (see Figure 1). Hence, a building is able to shift and move the instantaneous energy demand minimizing the effect of the penalty signal. The penalty signal could be design to 1) minimize the energy consumption, 2) minimize the cost, or 3) minimize the CO2 footprint of the building – or a combination of those criteria.

Different penalty signals may also represent different (ancillary) services needed by the grid. For example, a penalty signal with a significantly high frequency variability would test the ability to move loads over short distances in time (which is useful for participating on the regulation market), while low frequency variability would test the ability to move loads large distances in time (which is useful for peak-shaving). Although the penalty signal – as shown later – can be a way to deal with specific market conditions in an abstract manner, the penalty signal should as well be tailored for each country to represent actual market conditions and energy system constraints. The factors determining the penalty signals can depend on penetration rates of renewables, grid conditions, the national energy mix, national energy prices or power shortage.

In contrast of using case specific penalty signals, it is possible to think about standardization of these penalty signals in order to harmonize the methodology and increase comparability of different studies. To this end, a more abstract formulation is proposed in IEA EBC Annex 67 whereby the Energy Flexibility potential is quantified according to the building's or system's response to a step change in the (external) penalty signal. As indicated in Figure 1, Energy Flexibility indicators can as such be derived in standardized way that characterize the system and that are easily communicated and interpreted between engineers and other stakeholders.

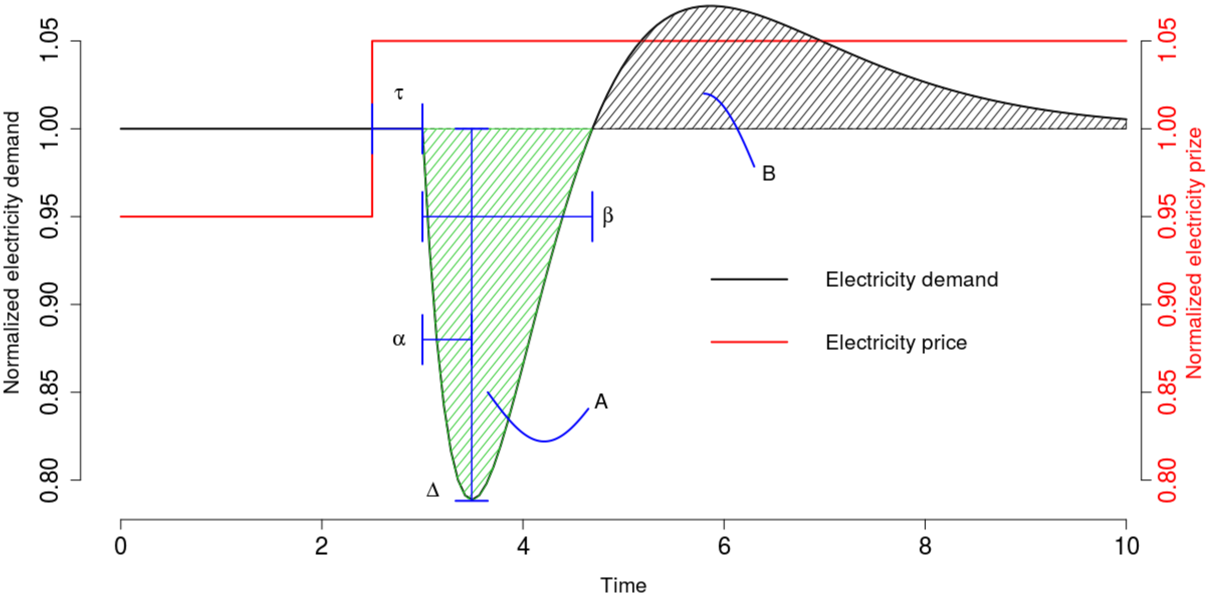

Figure 1 Example of response of a building's electricity demand to a penalty signal, where τ is the time from the signal is submitted to an action starts, α is the period from start of the response to the max response, Δ is the maximum response, β is the duration of the response, A is the shifted amount of energy, B is the rebound effect for returning the situation back to "reference" [12].

As mentioned before, it is however important to note that these parameters will typically change over time according to the variation of the boundary conditions. A detailed case-specific analysis is needed to capture these local and time dependent effects. Annex 67 will address these case-specific issues by investigating a number of well-defined test cases. In addition, the penalty signal can be chosen according to the specific targets of building operation i.e. minimize the energy costs, minimize the CO2 emissions, maximize the RES exploitation. Accordingly, the penalty signal could be a price signal, but can also be a CO2 or a RES production signal. In response to these signals, the controller should minimize the price or CO2 emission, or maximize the utilization of RES (i.e. the resulting penalty), and the capacity of the building to respond to the signal represents the Energy Flexibility. Theoretically, this method can be applied on various levels in the energy system, going from clusters of buildings down to individual technologies. The most important ones are the following: control of heating, cooling, domestic hot water and electricity devices including weather forecast and individual learning system.

Although the direct characterization method for Energy Flexibility in buildings described above gives detailed and quantitative insight into the Energy Flexibility that can be offered by a building or a cluster of buildings, the results are still technical and mostly oriented to researchers and engineers designing, analyzing and operating buildings and energy systems. In parallel, IEA EBC Annex 67 is developing a method for labelling of Energy Flexibility that can be communicated to a broader audience. In this method, the Energy Flexibility potential of buildings will be rated according to 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.

To illustrate this approach, consider an example (Figure 2), that shows the temperature control of a building using two different controllers. The red lines denote a regular controller that seeks to minimize electricity usage on a building level while the green lines denote a controller that minimizes CO_2-emissions. As seen in the top part of Figure 2, the flexibility in this case is generated by recognizing that the occupants accept a limited variation in indoor temperature. As seen in the middle graph, when minimizing the energy use – by tracking the lower comfort temperature – the conservative controller uses a significant amount of electricity during moments when this electricity is produced with high CO_2-emission (as seen by the black bars). In contrast, the *flexible* control is able to move its electricity use away from these periods by increasing the temperature in the building during periods with low CO_2-emission, activating the Energy Flexibility offered by the thermal mass of the building.

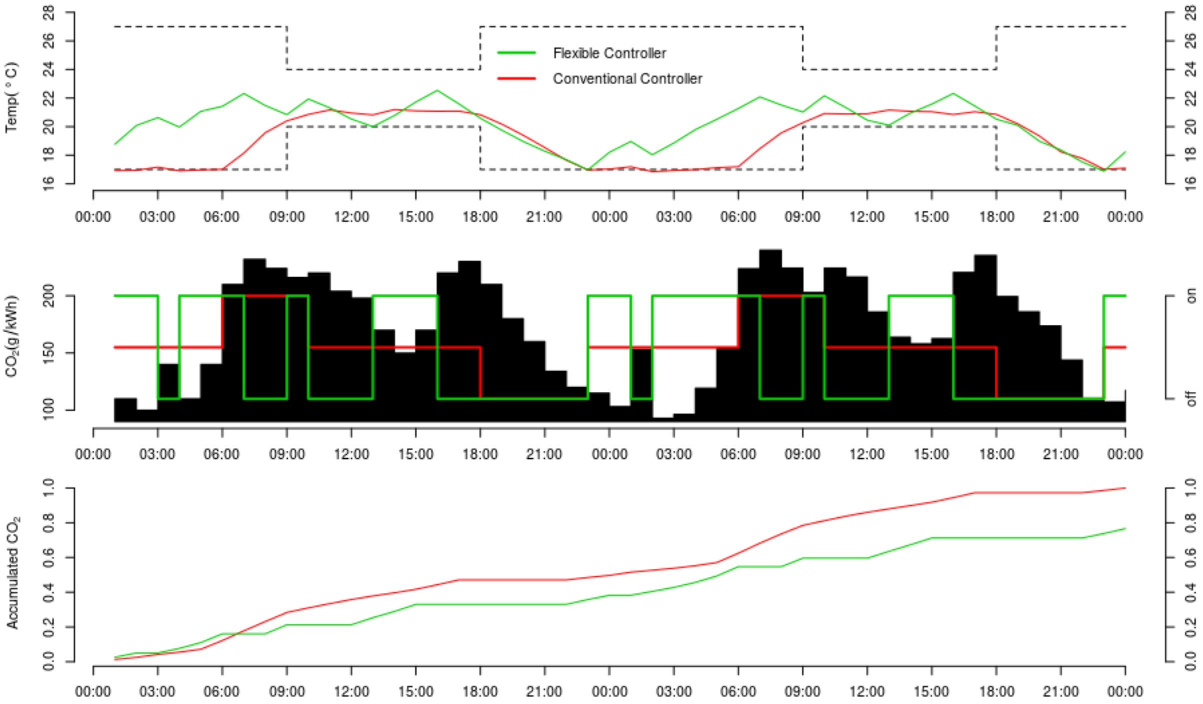

Figure 2 *Example of temperature control using two different controllers. In green is represented the flexible controller and in red the conventional one. In the top figure, the dotted lines represent the boundaries of the comfort conditions. The middle figure, the black rectangles represent the penalty signal, while in the bottom figure is represented the* cumulative CO_2 *emissions. (Source: DTU Compute)*

As expected, the bottom graph shows how the controller that minimizes CO_2-emission ends up causing less emission than the regular one. The y-axis had been normalized with respect to the regular controller, so that the relative amount of saved CO_2-emission can be seen by looking at the end value of the green line. In this case it is approximately equal to 0.8, which means that the flexible controller leads to the emission of around 20% less CO_2 than the regular controller. Thus for this example, a quantification of the flexibility label would be 0.2 or 20% [12].

The methodology for characterization and labelling Energy Flexibility in buildings may be used for design, in order to optimize the available flexibility, based on building simulation, or may be based on monitored data from a building or a cluster of buildings. Therefore, the methodology is expected to be generic, and thus, is applicable to different conditions, especially different penalty signals. As for the characterization method, the results of this method will depend on the system constraints as well as boundary conditions and will hence vary between different regions and times. Therefore, part of the IEA EBC Annex 67 is focusing on methodologies to formulate and standardize these methodologies in order to ensure the comparability of results needed in a labelling method.

Conclusion

By emphasizing Energy Flexibility, buildings are no longer only characterized only by their own energy efficiency. By emphasizing Energy Flexibility, we recognize buildings are able to interact with surrounding buildings and energy systems. By exploiting their intrinsic potential for energy storage and demand response within their technical and comfort constraints and boundary conditions, buildings can provide Energy Flexibility to the surrounding energy networks.

To exploit this potential on a wider scale and stimulate the necessary interaction between different fields (e.g. building and electrical engineering), there is a need to map the Energy Flexibility that different building types and clusters of buildings can offer. Research within IEA EBC Annex 67 shows how the available Energy Flexibility of buildings and cluster of buildings not only relies on technical solutions or available services, but depends on the integration and control of the systems, their interaction with occupants and energy networks as well as local climate and market conditions. To account for these effects, IEA EBC Annex 67 is developing a common methodology and terminology that will allow quantifying and communicate the Energy Flexibility of individual buildings and building clusters.

By doing so, and based on scientific evidence, IEA EBC Annex 67 points out the importance to shift the attention from a static energy efficiency evaluation in single buildings to a dynamic CO_2-efficiency optimization in an enlarged energy network context, using Energy Flexibility and control based energy performance labelling of buildings.

References

[1] IEA EBC Annex 67 “Energy Flexible Buildings”. http://www.annex67.org

[2] Flemish Institute for Technological Research NV (“VITO”) et al.: Support for setting up a Smart Readiness Indicator for Buildings and related impact assessment. Study ordered and paid by the European Commission, Directorate-General for Energy, Contract no. ENER/C3/2016-554/SI2.749248; https://smartreadinessindicator.eu/. Mol/Belgium 2017-2018

[3] RF. Halvgaard, L. Vanderberghe, NK. Poulsen, J.B. Jørgensen; Distributed Model Predictive Control for Smart Energy Systems, IEEE Transactions on Smart Grid, Vol. 7, pp. 1675-1682, 2016.

[4] Eurostat statistics [Online] Available: www.ec.europa.eu/eurostat (accessed Jan. 2017)

[5] Danish Energy Agency (2014) Energiscenarier frem mod 2020, 2035 og 2050 – Energy Scenarios towards 2020, 2035 and 2050. Report of Danish Energy Agency. Copenhagen, Denmark (in Danish)

[6] Denholm, P., & Hand, M. (2011). Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy, 39(3), 1817–1830. http://doi.org/10.1016/j.enpol.2011.01.019

[7] J.M.M. Gonzáles, A.J. Conejo, H. Madsen, P. Pinson, M.Zugno, *Integrating Renewables in Electricity Markets, Operational Problems*, Springer, 429 pp., 2014

[8] Moslehi, K., & Kumar, R. (2010). A Reliability Perspective of the Smart Grid. IEEE Transactions on Smart Grid, 1(1), 57–64. http://doi.org/10.1109/TSG.2010.2046346

[9] Danish Ministry of Climate, Energy and Building (2013). Smart Grid Strategy - The Intelligent Energy System of the Future. ISBN: 978-87-7844-604-6

[10] Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews, 45, 785–807. http://doi.org/10.1016/j.rser.2015.01.057

[11] Baillieul, J., Caramanis, M. C., & Ilic, M. D. (2016). Control Challenges in Microgrids and the Role of Energy-Efficient Buildings [Scanning the Issue]. Proceedings of the IEEE, 104(4), 692–696. http://doi.org/10.1109/JPROC.2016.2532241

[12] H. Madsen, J. Parvizi, R. Halvgaard, L.E. Sokoler, J.B. Jørgensen, L.H. Hansen, K.B. Hilger: Control of Electricity Loads in Future Electric Energy Systems, in Handbook of Clean Energy Systems, Wiley, 2015.

[13] N. O'Connell, P. Pinson, H. Madsen, M. O'Malley, Benefits and challenges of electrical demand response; A critical review. Journal of Renewable and Sustainable Energy Reviews, Vol. 39, pp. 686-699, 2014.

[14] The United Nations, “Environment Program.” [Online]. Available: http://www.unep.org/sbci/AboutSBCI/Background.asp (accessed Jan 2017).

[15] Jensen, S.Ø., Marszal-Pomianowska, A., Lollini, R., Pasut, W., Knotzer, A., Engelmann, P., Stafford, A., Reynders, G. (2017) IEA EBC Annex 67 Energy Flexible Buildings Energy and Buildings, 155, pp. 25-34, DOI: 10.1016/j.enbuild.2017.08.044

[16] R.G. Junker, R. Relan, A.G. Azar, R. Amaral Lopes, K. B. Lindberg, H. Madsen, Characterizing Energy Flexibility for Buildings and Districts submitted to Energy and Buildings

[17] European Commission : An EU Strategy on Heating and Cooling, COM 51/2016

[18] Council, General Secretariat of the Council: European Council (23 and 24 October 2014) – Conclusions, EUCO 169/14.24 October 2014

[19] Buildings Performance Institute Europe (BPIE): Opening the Door to Smart Buildings – Driving the transition with EU-Directives. Brussels, June 2017 – quotation on page 3 "A smart building is highly energy efficient and covers its very low energy demand to a large extent by on-site or district-system-driven renewable energy sources" [

[20] Flemish Institute for Technological Research NV ("VITO") et al.: Support for setting up a Smart Readiness Indicator for buildings and related impact assessment - Background paper for stakeholder meeting 7 June 2017. 1st June 2017 – quotation on page 3 "Smart technologies in buildings have the potential to contribute to increasing the energy efficiency of the building stock,…"

[21] European Commission: A policy framework for climate and energy in the period from 2020 to 2030. COM(2014) 15 final. Brussels, 22.1.2014

[22] Patteeuw, D., Reynders, G., Bruninx, K., Protopapadaki, C., Delarue, D., D'haeseleer, W., Saelens, D., Helsen, L. (2015) CO2-abatement cost of residential heat pumps with active demand response: demand- and supply-side effects. Applied Energy, 156, 490-501, https://doi.org/10.1016/j.apenergy.2015.07.038

[23] Hedegaard, K., Mathiesen, B. V., Lund, H., & Heiselberg, P. (2012). Wind power integration using individual heat pumps – Analysis of different heat storage options. Energy, 47(1), 284–293. http://doi.org/10.1016/j.energy.2012.09.030

[24] Xue, X., Wang, S., Sun, Y., & Xiao, F. (2014). An interactive building power demand management strategy for facilitating smart grid optimization. Applied Energy, 116, 297–310. http://doi.org/10.1016/j.apenergy.2013.11.064

[25] Le Dréau, J., & Heiselberg, P. (2016). Energy Flexibility of residential buildings using short term heat storage in the thermal mass. Energy, 111(8), 991–1002. http://doi.org/10.1016/j.energy.2016.05.076

[26] Arteconi, a., Costola, D., Hoes, P., & Hensen, J. L. M. (2014). Analysis of control strategies for thermally activated building systems under demand side management mechanisms. Energy and Buildings, 80, 384–393. http://doi.org/10.1016/j.enbuild.2014.05.053

[27] Reynders, G., Nuytten, T., & Saelens, D. (2013). Potential of structural thermal mass for demand-side management in dwellings. Building and Environment, 64, 187–199. http://doi.org/10.1016/j.buildenv.2013.03.010

[28] Široký, J., Oldewurtel, F., Cigler, J., & Prívara, S. (2011). Experimental analysis of model predictive control for an energy efficient building heating system. Applied Energy, 88(9), 3079–3087. http://doi.org/10.1016/j.apenergy.2011.03.009

[29] Oldewurtel, F., Ulbig, a., Parisio, a., Andersson, G., & Morari, M. (2010). Reducing peak electricity demand in building climate control using real-time pricing and model predictive control. Decision and Control (CDC), 2010 49th IEEE Conference on, 1927–1932. http://doi.org/10.1109/CDC.2010.5717458

[30] Tahersima, F., Stoustrup, J., Meybodi, S. A., & Rasmussen, H. (2011). Contribution of domestic heating systems to smart grid control. In IEEE Conference on Decision and Control and European Control Conference (pp. 3677–3681). Orlando, FL, USA: IEEE. http://doi.org/10.1109/CDC.2011.6160913

[31] Arteconi, A., Hewitt, N. J., & Polonara, F. (2013). Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. Applied Thermal Engineering, 51(1–2), 155–165. http://doi.org/10.1016/j.applthermaleng.2012.09.023

[32] Kim, Y. J., Fuentes, E., & Norford, L. K. (2016). Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump. IEEE Transactions on Power Systems, 31(4), 3090–3099. http://doi.org/10.1109/TPWRS.2015.2472497

[33] Halvgaard, R., Poulsen, N. K., Madsen, H., & Jorgensen, J. B. (2012). Economic Model Predictive Control for building climate control in a Smart Grid. In 2012 IEEE PES Innovative Smart Grid Technologies (ISGT) (pp. 1–6). http://doi.org/10.1109/ISGT.2012.6175631

[34] Yu Y.J., Morgenstern K., Sager C. (2013) Demand-Side-Management with heat pumps for single-family houses. in: Building Simulation, 13th International Conference of the International Building Performance Simulation Association, IBPSA, Chambery, France

[35] Paatero, J. V., & Lund, P. D. (2006). A model for generating household electricity load profiles. International Journal of Energy Research, 30(5), 273–290. http://doi.org/10.1002/er.1136

[36] Widén, J. (2014). Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings. Applied Energy, 126, 199–212. http://doi.org/10.1016/j.apenergy.2014.04.008

[37] Marszal-Pomianowska A., Widén J., Le Dréau J., Heiselberg P., Bak-Jensen B., Diaz de Cerio Mendaza I. (2017), Low-voltage network performance under different penetration levels of flexible buildings, Energy, (submitted July 2016)

[38] European Commission: Clean Energy for All Europeans – unlocking Europe's growth potential. Press release; Brussels, 30 November 2016

[39] European Commission: Proposal for a Directive of the European Parliament and of the Council on common rules for the internal market in electricity (recast). COM(2016) 864 final/2. Brussels, 23.2.2017

[40] General Secretariat of the Council: Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings. Interinstitutional File: 2016/0381 (COD). Brussels, 27 June 2017

[41] Baetens, R., De Coninck, R., Van Roy, J., Verbruggen, B., Driesen, J., Helsen, L., & Saelens, D. (2012). Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation. Applied Energy, 96, 74–83. http://doi.org/10.1016/j.apenergy.2011.12.098

[42] Stinner, S., Huchtemann, K., & Müller, D. (2016). Quantifying the operational flexibility of building energy systems with thermal energy storages. Applied Energy, 181, 140–154. http://doi.org/10.1016/j.apenergy.2016.08.055

[43] De Coninck, R., & Helsen, L. (2016). Quantification of flexibility in buildings by cost curves – Methodology and application. Applied Energy, 162, 653–665. http://doi.org/10.1016/j.apenergy.2015.10.114

[44] Oldewurtel, F., Sturzenegger, D., Andersson, G., Morari, M., & Smith, R. S. (2013). Towards a standardized building assessment for demand response. In 52nd IEEE Conference on Decision and Control (pp. 7083–7088). IEEE. http://doi.org/10.1109/CDC.2013.6761012

[45] Reynders, G., Diriken, J., & Saelens, D. (2017). Generic characterization method for Energy Flexibility : application to structural thermal storage in Belgian residential buildings. Applied Energy, 198, 192-202. https://doi.org/10.1016/j.apenergy.2017.04.061