Project Acronym/ Acronimo del progetto:

INTEGRIDS

Project title:

Electric and thermal grids integration with energy flexible building

Titolo del progetto:

Studio dell'integrazione di reti elettriche e termiche con la flessibilità energetica degli edifici

Deliverable name	Linee guida per definire il concetto di flessibilità energetica a livello di singolo edificio
Deliverable N°.	D3.1
Task	3.1
Authors: Approved by:	Ilaria Vigna, Roberta Pernetti, Roberto Lollini David Moser
Due date	28/02/2018

efre · fesr Südtirol · Alto Adige
Europäischer Fonds für regionale Entwicklung
Fondo europeo di sviluppo regionale
EUROPEAN UNION
AUTONOME PROVINZ BOZEN SÜDTIROL
PROVINCIA AUTONOMA DI BOLZANO ALTO ADIGE

Table of contents

Foreword

The increasing penetration of distributed renewable thermal and electrical energy generation and the need of decarbonizing the existing energy infrastructure (both thermal and electrical) has led to a new set of challenges. These will have to be tackled in the next 10 years to make sure that the full potential of renewables can be exploited within electric grids and thermal networks. In the INTEGRIDS projects the concept of integrated energy grids defined as the synergy between thermal and electrical grids to enable high renewable energy penetration in efficient energy buildings and districts is explored.

This is relevant to the local energy landscape of the Province of Bolzano as the energy strategy KlimaLand "Energy South Tyrol 2050" in 2011 set ambitious targets for 2020 and 2050 in terms of CO_2 reduction (4 t/year/person in 2020 and 1.5 t/year/person in 2050) and energy demand covered by renewables (75% in 2020, 90% in 2050). These targets can only be met with a complex mix of energy demand reduction and i) solutions which enable integration of an increasing amount of local and centralized renewable sources in combination with appropriate deployment of active loads (e.g. electric vehicles), electrical and thermal storage, flexible back up generation and virtual power plants and ii) solutions which enable the full exploitation of the flexibility potential provided by a wider range of ancillary services (electricity market frameworks, demand and generation forecasting, balancing or demand side management). Further integration of clean generation entails increasing levels of complexity. It is hence important that cost-effectiveness is also considered together with the security and high quality of supply for customers.

A reduction of the demand of not-renewable energy (and of CO_2 emissions) is thus possible thanks to a better match between energy generation from renewables and loads, exploiting synergies between buildings and the energy grids.

In the INTEGRIDS project the validity of the concept is proven in an innovative laboratory environment.

Challenges covered by this deliverable: Energy Flexible Buildings and District

Energy flexibility in buildings can provide capacity for energy grids where possible solutions for critical aspects in managing such flexibility at building and buildings cluster scale needs yet to be identified. This knowledge is important in order to incorporate energy flexibility of buildings into future integrated energy systems and to better integrate renewable sources in energy systems. An important aspect is represented by the development of design tools and technology solutions for physical and multifunctional integration of PV and Solar Thermal systems towards the demand for nearly zero energy buildings and districts. Such active measures must be coupled with passive ones, user behavior changes, and suitable control strategies for the buildings and grids, to improve load match and optimize grid interaction. Exploitation of natural ventilation, daylighting, and thermal capacity, as well as an adaptive building users' behavior and related electric and thermal load control rules, can define novel business cases for energy efficiency, driven by the overall objective to reduce not-renewable energy use, exploiting flexibility in a very dynamic demand-response concept. It is also important - when developing the business case for using building energy flexibility within future systems - to potentially reduce costly upgrades of energy distribution grids.

Executive summary

Nella pacchetto di misure “Clean Energy for All Europeans” (EC, 2016a), la Commissione Europea definisce le linee strategiche per la transizione energetica programmata per il 2030, con la trasformazione del sistema energetico attuale, centralizzato e basato sui combustibili fossili, in un sistema decentralizzato, efficiente e alimentato da fonti energetiche rinnovabili.

Tuttavia l’aumento della produzione elettrica attraverso fonti energetiche rinnovabili comporta notevoli complessità nella gestione della rete (Whiteman et al., 2016), in particolare legate alla natura intermittente dell’approvvigionamento di tali fonti. Gli edifici possono contribuire ad ottimizzare dal punto di vista funzionale e prestazionale l’integrazione delle energie rinnovabili nelle infrastrutture energetiche, anche considerando che stanno gradualmente passando dal ruolo di consumatori a quello di “prosumers”, cioè produttori e consumatori, tra loro interconnessi e in grado di fornire e immagazzinare energia rinnovabile e contribuire attivamente alla domanda energetica.

Nel percorso evolutivo degli edifici di nuova generazione, si è passati da edifici destinati a minimizzare la domanda di energia attraverso soluzioni passive (edifici passivi), a sistemi finalizzati a minimizzare il bilancio energetico (nZEB - edifici a energia quasi zero), fino ad arrivare agli edifici in grado di interagire con la rete, non solo consumando ma anche producendo e accumulando energia (edifici flessibili).

Lo studio del concetto di flessibilità energetica degli edifici è supportato dall’International Energy Agency nell’ambito del programma “Energy in Buildings and Communities”: il progetto Annex 67 (IEA EBC Annex 67. http://www.annex67.org/) è infatti finalizzato alla definizione di una terminologia e una metodologia per la caratterizzazione e la quantificazione della flessibilità energetica.

La flessibilità energetica è riconosciuta come una questione chiave anche dalla Commissione Europea (EC, 2016a). Considerando la transizione verso l'energia pulita, l'interazione tra edifici e la diffusione di informazioni ai consumatori riguardanti il loro consumo energetico può contribuire alla massimizzazione delle fonti rinnovabili a livello locale. Nella proposta per l’aggiornamento della direttiva europea sulla prestazione energetica degli edifici EPBD (EC, 2016b), viene infatti introdotto quello che è stato definito "Smart Readiness Indicator" (SRI), finalizzato a: (i) valutare la capacità tecnologica di un edificio di adattarsi alle esigenze degli utenti e al contesto energetico; (ii) valutare la potenzialità degli edifici a funzionare in modo più efficiente e (iii) misurare la capacità dell'interazione degli edifici con il sistema energetico, con dinamiche anche molto veloci, in una logica di domanda/risposta (Demand Response – DR).

Definizione di edificio energeticamente flessibile

Secondo la definizione iniziale formulata nell’Annex 67, la flessibilità energetica rappresenta "la capacità di un edificio di gestire la sua domanda e generazione in base alle condizioni climatiche locali, alle esigenze degli utenti e ai requisiti della rete. La flessibilità energetica degli edifici consentirà quindi la gestione della domanda attraverso il controllo dei carichi e quindi la risposta alla domanda in base per ottimizzare l’interazione con le reti eneregtiche".

Da una prospettiva differente, la flessibilità energetica può essere definita come "la capacità di un edificio di reagire a uno o più forzanti, al fine di ridurre al minimo le emissioni di CO_2 e massimizzare l'uso di fonti energetiche rinnovabili". Le forzanti rappresentano un insieme di condizioni al contorno significative che potrebbero cambiare durante la vita di un edificio e avere diversi livelli di frequenza:

- *Fattori a bassa frequenza* (fluttuazioni temporali nell'arco degli anni): cambiamenti climatici, fattori macroeconomici, miglioramento tecnologico, uso previsto dell'edificio e variazione del numero di occupanti, cambiamenti demografici (ad esempio età, reddito);

- *Fattori ad alta frequenza* (fluttuazioni temporali nell'intervallo di tempo di minuti-ore): carichi interni, carichi solari, comportamento dell'utente, prezzi dell'energia.

Gli obiettivi principali degli edifici energeticamente flessibili sono la riduzione delle emissioni di CO_2 e la massimizzazione dell'uso delle fonti energetiche rinnovabili, attraverso il miglioramento della corrispondenza in tempo reale tra consumo e generazione, in modo da mantenere la stabilità della rete in presenza delle forzanti individuate.

Numerosi studi presenti in letteratura analizzano le azioni di gestione della domanda attraverso cui gli edifici possono fornire flessibilità: (i) utilizzo della massa termica delle strutture degli edifici come accumulo termico, (ii) adeguamento dei sistemi HVAC o del funzionamento della sorgente di calore, (iii) modulazione del tempo di utilizzo degli elettrodomestici e (iv) applicazione di un programma di ricarica ottimale dei veicoli elettrici.

L'applicazione di queste strategie può contribuire a ridurre la domanda di energia nei periodi di picco e spostare il consumo di energia da periodi di costo elevato a periodi a basso costo, considerando sempre come vincoli importanti i livelli di comfort dell'ambiente interno, l'accettazione degli utenti e la disponibilità di energia prodotta da fonti rinnovabili e sistemi di accumulo entro un arco di tempo specifico.

Indicatori di flessibilità energetica relativi agli edifici singoli

Nell'ambito dell'Annex 67, è stata condotta una revisione di letteratura per identificare una serie di potenziali indicatori per caratterizzare e valutare l'edificio energeticamente flessibile. Gli indicatori selezionati sono stati classificati nelle seguenti categorie:

- *Indicatori di flessibilità termica*: questo livello comprende indicatori di flessibilità energetica relativi alla possibilità di attivare l'accumulo nella massa strutturale dell'edificio, di altri accumuli dedicati, così come il controllo dei guadagni solari, mantenendo le condizioni di comfort desiderate.

- *Indicatori di flessibilità energetica*: indicatori dedicati alla flessibilità fornita da carichi controllabili per i diversi usi finali dell'energia, senza violare i requisiti di comfort.

- *Indicatori di flessibilità economica*: indicatori riferiti ai sistemi energetici degli edifici con un'implicazione sui costi.

Gli indicatori sono fondamentali per quantificare la Flessibilità Energetica che un edificio può offrire e individuare quali sono gli aspetti architettonici e tecnologici più significativi che possono conferire flessibilità a un edificio. Inoltre, gli indicatori forniscono anche un modo fondamentale per comunicare efficacemente il concetto di flessibilità energetica e verificarla sia in fase di progetto che di certificazione, consentendo la condivisione di un linguaggio comune tra gli attori del settore energetico e il supporto ai responsabili politici nel quantificare l'efficacia delle nuove politiche legate all'energia.

Acronyms and Abbreviations

RES	Renewable Energy Sources
SRI	Smart Readiness Indicator
nZEB	Nearly Zero Energy Building

1 Introduction

The "Clean Energy for All European package" (EC, 2016a) of European commission sets out the energy policy framework going forward to 2030 and it treats buildings as an essential part of Europe's clean energy transition. The principle "energy efficiency first" (EC, 2015) drives the transformation of the conventional centralized energy system based on fossil fuels into an efficient decentralized system powered by RES.

Renewable energy systems are characterized by intermittent generation and their rapid increase challenges the stability of the electrical grid (Whiteman et al., 2016). Buildings are gradually moving from stand-alone consumers to interconnected prosumers (both producers and consumers) able to provide and store renewable energy, actively participate in demand/response (D/R) scheme, while playing a meaningful role in optimising the RES integration in grids.

Despite the Energy Performance of Buildings Directive (EU, 2010) and the Renewable Energy Directive (EU, 2009) have stimulated the deployment of on-site renewable energy systems, the on-site (or nearby) renewable energy production and self-consumption in European countries are not at their full potential, partly due to rigid regulatory frameworks or lack of investments. The instantaneous sharing of produced energy among buildings is allowed or encouraged only in a few Member States and currently the storage technologies are too expansive for massive application. Consequently, the produced renewable electricity is often injected in the public network instead of being used locally. Therefore,

it is necessary to identify solutions aimed to change the relationship between the grid and the consumers and future buildings should adapt their energy demand to the needs of the grid and the renewable production, while maintaining high comfort standards and low operating costs.

In the past recent years, we can observe a deep evolution of the building design approach in terms of targets, technology functions, overall performances and domain. In this regards, the improvement of building resilient behaviour coupled with grid interaction represent the latest step in the evolutionary path of building transformation (Figure 1). The process, started with the minimization of energy demand through passive solutions (passive buildings), then evolved into the nearly Zero Energy Buildings (nZEB) aimed at obtaining an energy balance (consumption-production) through on-site generation from RES, will now find its latest evolution in the energy matching required by smart buildings at cluster/energy infrastructure domain.

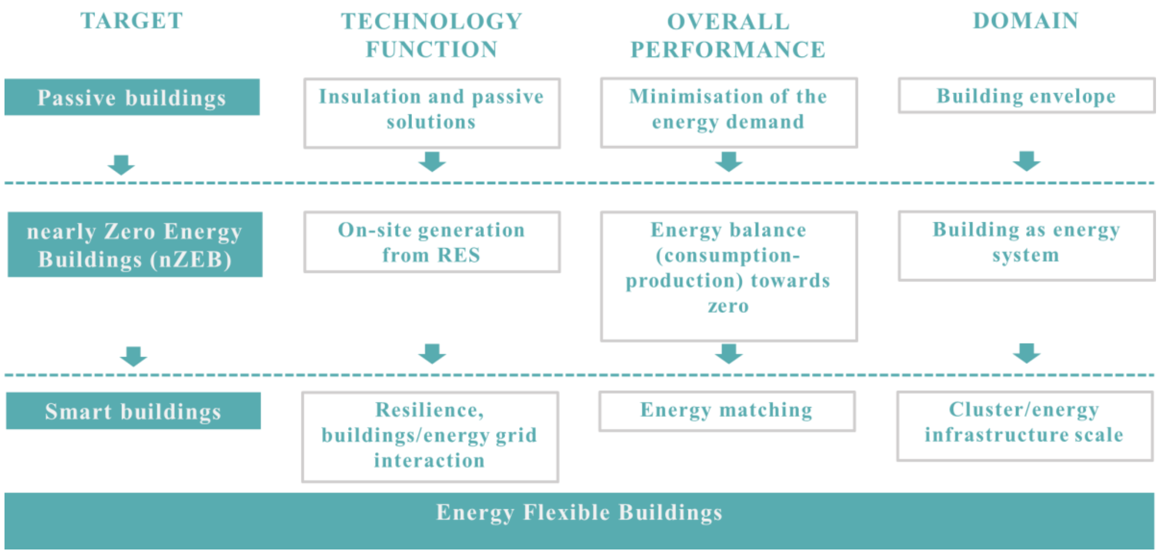

Figure 1 *Evolutionary path of building transformation (Vigna et al., 2018)*

2 Energy flexibility in the European perspective

The International Energy Agency (IEA), in the programme 'Energy in Buildings and Communities' (EBC), introduces the concept of 'Energy Flexible Buildings' with the project 'Annex 67' (IEA EBC ANNEX 67). In addition to being the focus of Annex 67, Energy Flexibility represents a key issue to be addressed also according to the European Commission. Considering the transition toward clean energy, the interaction between buildings and the spread of information to consumers regarding operational energy consumption can contribute to RES maximization at a local level. In this regard, the "Clean Energy for All Europeans" package, the proposal for recasting EPBD (EC, 2016b), introduces a Smart Readiness Indicator (SRI). The "Common general framework methodology for the calculation of 'Smartness Indicator' for Buildings" focuses on the following key functionalities:

(i) the technological readiness assessment of a building's capacity to adapt to user needs and energy environment;
(ii) the evaluation of building readiness in operating more efficiently
(iii) the measurement of the readiness of building interaction with the energy system and the infrastructure with a demand/response approach.

The introduction of such a SRI will increase building users' consciousness of the fundamental role of technologies and ICT solutions, encouraging the spread of healthier and more comfortable buildings with lower energy use and carbon impact, while facilitating RES integration.

The current state of discussion at the EU level evaluates the flexibility according to the number and features of the building components with a qualitative approach, whereas the characterization and methodology defined within the Annex 67 will provide a quantitative evaluation of the flexibility associated with a building, by using measured physical data and results from simulation campaigns. Therefore, the approach being defined within the Annex 67 can be coupled and applied within the framework of the evaluation of Smart Readiness Indicator, providing a quantitative evaluation of the flexibility associated with a building.

In order to properly create the SRI indicator, it is necessary to identify smart services, i.e. services that use smart technologies to facilitate energy management and interact with building occupants' behaviors to fulfil their comfort needs (Verbeke et al., 2017). The concept of 'functionality levels' can be introduced to value the smartness of service implementation, ranging from basic functionality to fully integrated smart solutions (Fig. 2).

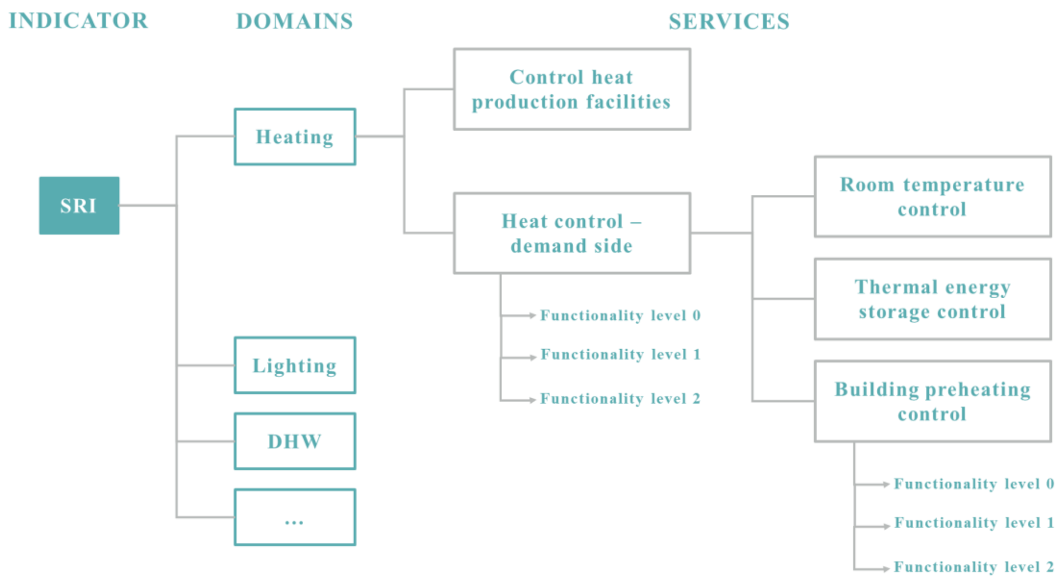

Figure 1 *Excerpt from structure of the service list (Verbeke et al., 2017)*

The review and investigation of Energy Flexible indicators can contribute to defining the proper smart technologies that are able to store thermal and electrical loads, to improve load shifting potential of buildings while maintaining required comfort levels, and support the physical quantification of functionality levels.

3 Energy flexible building definition

According to the initial definition formulated by Annex 67, building Energy Flexibility represents

> **"the capacity of a building 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".**

From a different perspective, Energy Flexibility could be defined as "the capacity of a building to react to one or more forcing factors, in order to minimize CO_2 emissions and maximize the use of RES". The forcing factors represent a set of significant boundary conditions that could change during the lifetime of a building and have different levels of frequency:

- *Low frequency factors* (temporal fluctuations within the years-decades time range): climate change, macro-economic factors, technological improvement, building intended use and variation in the number of occupants, demographic changes (e.g. age, income);
- *High frequency factors* (temporal fluctuations within the minutes-hours time range): internal loads, solar loads, user behavior, energy prices.

Additional Energy Flexibility definitions related to the building context are the following: "ability to deviate from the reference electric load profile (or baseline power consumption, or the business as usual scenario)" (Coninck and Helsen, 2016; Oldewurtel et al., 2013) or "the efficient load of devices in response to real time pricing and reduce peak consumption" (Hong et al., 2015).

The main objectives of Energy Flexible Buildings are **the reduction of CO_2 emission and the maximization of the use of RES** in the building supply, through the improvement of real-time matching of consumption and generation, while also reducing the stress of energy grid.

Many existing studies, even if not fully comprehensive of the building potential flexibility, investigate by which demand-side management (DSM) actions buildings can supply the flexibility service:

(i) usage of the structural thermal mass of buildings as thermal storage (Arteconi et al., 2012; Hedegaard et al., 2012; Hewitt, 2012; Le Dréau and Heiselberg, 2016; Xue et al., 2014),

(ii) adjustment of HVAC systems, e.g. heating system (Arteconi et al., 2014; Oldewurtel et al., 2010; Reynders et al., 2013; Široký et al., 2011; Tahersima et al., 2011) or the operation of the heat source (Arteconi et al., 2013; Halvgaard et al., 2011; Kim et al., 2016; Yu, 2013),

(iii) modulation of time of use of plug loads, primary washing and dishwashing machine and dryer (Paatero and Lund, 2006; Widén, 2014) and (iv) application of an optimal charging schedule of the electric vehicles (Clement-nyns et al., 2010; Mendaza, 2014).

The application of these strategies can contribute to reduce energy demand at peak periods and shift the energy consumption from high-cost periods to low-cost periods, always considering as important constraints the indoor air comfort levels, the acceptance of users and the available capacity of RES and storage systems within a specific time span. In this regard, flexibility can be expressed as "the ability of demand side installations to respond to power systems requirements for ramping up or down using on-site storage capabilities, increasing or decreasing electricity consumption patterns whilst maintaining acceptable indoor comfort bandwidth during a specific time period" (Aduda et al., 2016).

4 Key Performance Indicators for energy flexibility at building level

Indicators are fundamental for quantifying the amount of Energy Flexibility that a building can offer, and measure how different aspects influence the sharing of renewable energies in order to reduce demand peaks in buildings. Furthermore, indicators provide also a fundamental way to effectively communicate the energy flexibility concept, enabling the share of a common language between energy players and supporting policy makers in the quantification of the actual impact of novel energy related policies.

In the framework of Annex 67, a literature review analysis has been carried out to identify a set of potential key performance indicators to characterize and evaluate Energy Flexible Building. The selected indicators have been classified into different categories:

- *Thermal Flexibility*: this level includes indicators of Energy Flexibility related to the possibility to activate the envelope/structural mass of the building.

- *Energy Flexibility*: indicators dedicated in the flexibility provided by controllable loads, without violating the comfort requirements.

- *Economic Flexibility*: indicators referred to energy systems of buildings with respect to costs.

Table 1a reports the list of reviewed indicators specifying their features referred to *Buildings'flexibility source* (Building thermal mass, Loads, Onsite generation system, Energy storage system), *Objective function* (Minimum cost, Minimum energy) and *Constraints* (Temperature, Others).

Table 1b illustrates the list of reviewed indicators with a focus on *Indicator content* (Power, Energy, Time, Cost) and *Duration* (Time unit, Hours, Days, Year).

Table 1a *Reviewed indicators for Energy Flexible Buildings*

	Indicators	**Author**	**Buildings' flexibility source**				**Objective function**		**Constraint**	
			Building thermal mass	**Loads (controllable and shiftable)**	**Onsite generation system**	**Energy storage system**	**Minimum cost**	**Minimum energy**	**Temperature**	**Others**
Thermal Flexibility	Storage capacity (C_{ADR}), storage efficiency (η_{ADR}), power shifting capability (Q_{δ})	(Reynders et al., 2013)	√						√	
Energy Flexibility	Flexible demand ($\Delta p_{k,w}$)	(Aduda et al., 2016)	√	√					√	
	Power Shifting Potential ΔP, Power Shifting Efficiency (PSE)	(Oldewurtel et al., 2013)		√			√		√	air supply, shading
	The time (T) the building fluctuated from maximum to minimum power	(Tahersima et al., 2013)		√			√		√	
	How many points of time sooner or later the energy can be shifted $V(t,E) = (t_{es}, t_{ls})$	(Pollhammer et al., 2011)		√						time-work window of appliances
	Time flexibility tf(f), energy flexibility ef(f), and combined vector $v = (tf, ef)$	(Valsomatzis et al., 2015)	√	√					√	
	The difference between the upper and lower power consumption $Flexibility(k)$	(Maasoumy et al., 2014)	√	√					v	

	Delayed operation flexibility ($\Delta_{Delayed,t}$), forced operation flexibility ($\Delta_{Forced,t}$)	(Nuytten et al., 2013)			√ (CHP)	√				SOC of TES
	Power consumption increase P_{inc}, power consumption decrease P_{dec}	(D'hulst et al., 2015)		√						time-work window of appliances
Economic Flexibility	How much the electricity price would change along with the change in load Φ, Γ, J_{sp}	(Coninck and Helsen, 2016)	√	√	√	√	√	*	√	
	The procurement costs avoid ($flexibility_{pc}$) and the volume shifted ($flexibility_{VS}$)	(Masy et al., 2015)	√	√	√ (heat pump)	√	√		√	

* Minimizing or maximizing energy consumption in certain time intervals

Table 2b *Reviewed indicators for Energy Flexible Buildings*

	Indicators	Author	Indicator content				Duration (Prediction horizon)			
			Power	Energy	Time	Cost	Time unit	Hours	Days	Year
Thermal Flexibility	Storage capacity (C_{ADR}), storage efficiency (η_{ADR}), power shifting capability (Q_{δ})	(Reynders et al., 2013)		√				√	√	
Energy Flexibility	Flexible demand ($\Delta p_{k,w}$)	(Aduda et al., 2016)	√/-				√			
	Power Shifting Potential ΔP, Power Shifting Efficiency (PSE)	(Oldewurtel et al., 2013)	√/+-	√/+-				√	√	√ (with 1 hr)
	The time (T) the building fluctuated from maximum to minimum power	(Tahersima et al., 2013)	√		√		√			
	How many points of time sooner or later the energy can be shifted $V(t, E) = (t_{es}, t_{ls})$	(Pollhammer et al., 2011)		√	√		√			
	Time flexibility tf(f), energy flexibility ef(f), and combined vector $v = (tf, ef)$	(Valsomatzis et al., 2015)		√	√			√	√	√
	The difference between the upper and lower power consumption $Flexibility(k)$	(Maasoumy et al., 2014)	√				√			
	Delayed operation flexibility ($\Delta_{Delayed,t}$), forced operation flexibility ($\Delta_{Forced,t}$)	(Nuytten et al., 2013)			√					√ (with 1 hr
	Power consumption increase P_{inc}, power consumption decrease P_{dec}	(D'hulst et al., 2015)	√/+-		√				√ (with 1 hr)	
Economic Flexibility	How much the electricity price would change along with the change in load Φ, Γ, J_{sp}	(Coninck and Helsen, 2016)		√/+- *		√		√	√	
	The procurement costs avoid($flexibility_{pc}$) and the volume shifted ($flexibility_{VS}$)	(Masy et al., 2015)				√ (unit cost)		√	√	√

* +: power/energy increase flexibility; -: power/energy decrease flexibility

5 Examples of energy flexibility at building level

FLEXIBILITY APPLIED TO BUILDING STRUCTURAL THERMAL STORAGE	
Impact of building design parameters on energy flexibility *(Reynders, 2015)*	
Objective	Parameter study to quantify the impact of the main building design parameters on energy flexibility, considering two types of heat emission systems – radiators and floor heating -.
Energy flexibility indicators	*Available storage capacity*: defined as the amount of heat that can be absorbed by the structural mass of a building without jeopardizing indoor thermal comfort in a specific time-frame and given the dynamic boundary conditions. *Storage efficiency*: defined as the fraction of the heat that is stored during the ADR-event that can be used subsequently to reduce the heating power needed to maintain thermal comfort.
Object of the analysis	Typical Belgian residential semi-detached building, simulated using Modelica IDEAS library.
Expected benefits	Potential to improve the electricity use for heating by active use of structural thermal storage capacity of the building.
a. Impact of interior wall thickness	
Building parameter variation	Interior wall thickness and heat emission system.
Results	The results in Figure 3 (top) show that the impact of increasing the wall thickness on the available storage capacity is non-linear, with a sharper increase when the thickness is varied from 5 cm to 10 cm as compared to an increase from 10 cm to 30 cm. Moreover, it depends on the duration of the ADR-event as for longer durations, the penetration depth of the heat front increases. Nevertheless, the impact is negligible for the high comfort range of 4 ˚C, since regardless of the interior wall thickness the maximum comfort limit (T_{max}) is not reached. Moreover, for the floor heating cases even with a comfort range of 1 ˚C the impact of increasing the interior wall thickness is only visible for event durations longer than 240 min. Again for shorter periods, i.e. less than 2 h and 4 h for respectively the radiator and floor heating systems, the rate of thermal energy storage is thus governed by the difference between the nominal power of the heating system and the heat demand at the minimum comfort range. The corresponding storage efficiencies are shown in Figure 3 (bottom), demonstrating the minimal impact on the efficiency when the thickness of the interior walls increases from 5 cm to 30 cm as long as the storage period is limited to 90 min. For a duration of 480 min (8 h), storage efficiencies of 86 % and 92 % are found for respectively an interior wall thickness of 5 cm and 30 cm in case of radiator heating and respectively 90 % and 94% in case of floor heating. Note again that for an 8 h ADR-event the difference in efficiency between the radiator and floor heating case is strongly reduced.

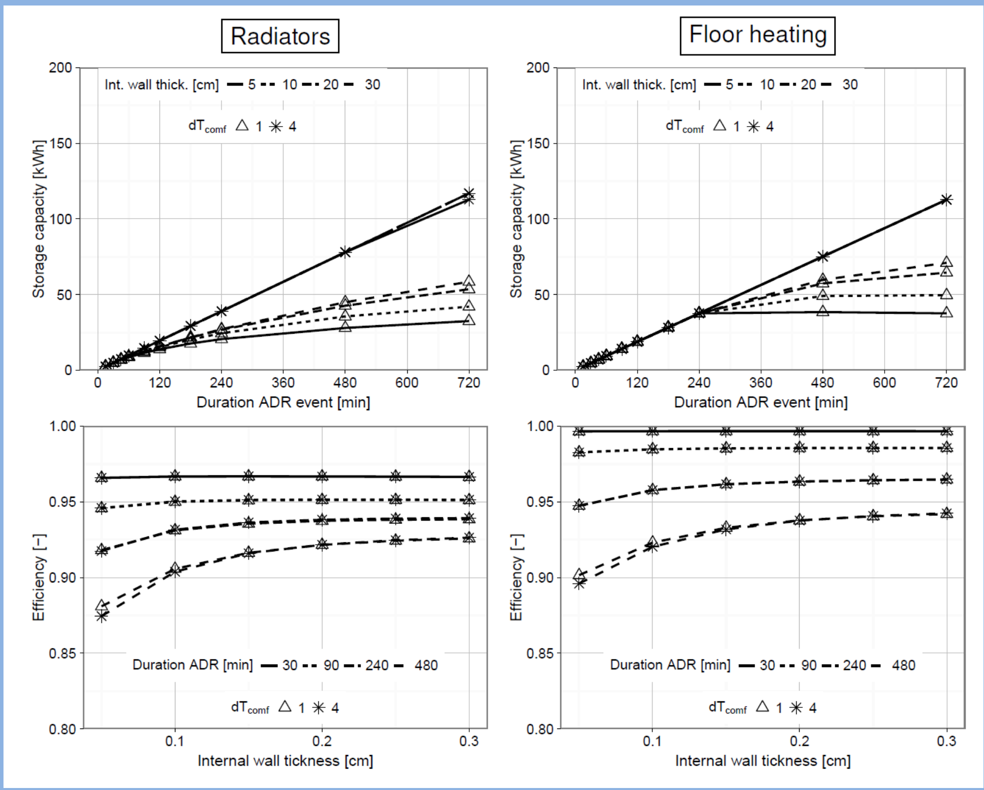

Figure 3 *Available storage capacity (top) and corresponding efficiency (bottom) as a function of the thickness of the interior walls for both the radiator (left) and floor heating system (right). The results are shown for varying duration of the ADR-event, an outdoor temperature of 0 C and a comfort range (dT_{comf}) of 1 ˚C and 4 ˚C (Reynders, 2015).*

b. Impact of building compactness

Building parameter variation	Building geometry (compactness) and heat emission system.
Results	The compactness has a significant effect on the storage efficiency (Figure 4). Changing the compactness from 0.75 m to 2.5 m for the buildings with a radiator system, reduces the storage efficiency from 93 % to 86 % for a comfort range of 4 ˚C and a duration of the ADR-event of 8 h. For the floor heating a similar decrease, from 95% to 89% is found. Both storage efficiency and available storage capacity reduce with increasing compactness: in fact, increasing the compactness results in a reduction of the envelope surface area and in a sharp reduction of the available thermal energy storage capacity. Furthermore, the indoor air temperature and the resulting thermal losses increase more rapidly during the charging process since a higher compactness results in a higher ratio of indoor air to structural thermal mass.

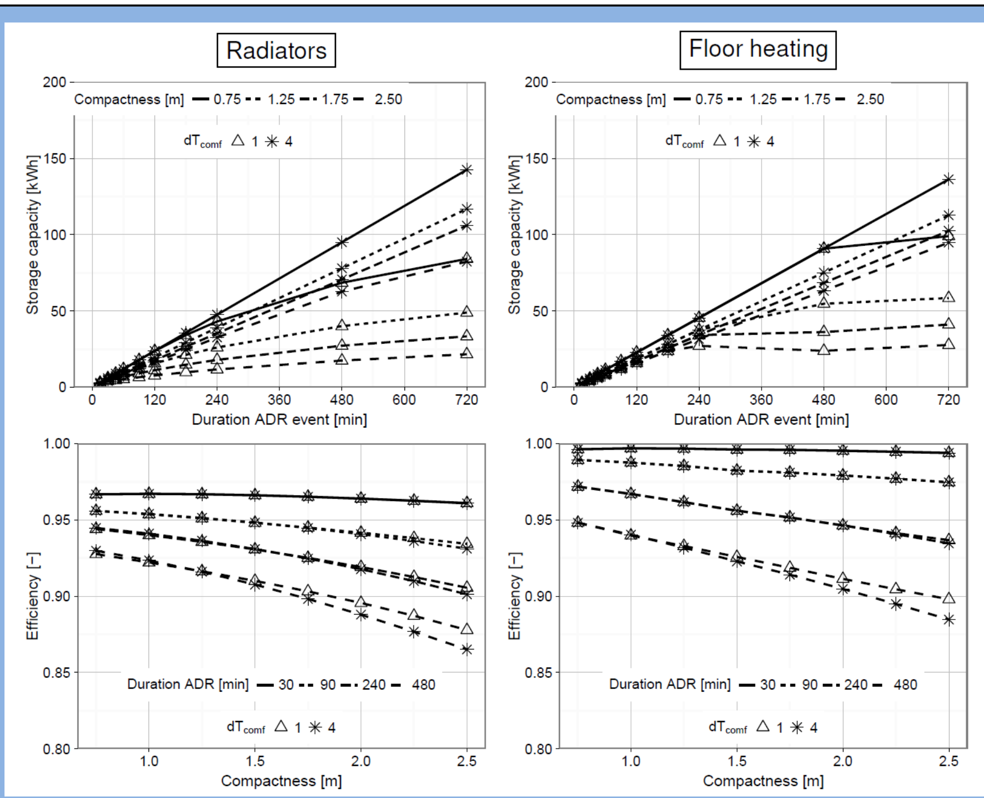

Figure 4 *Available storage capacity (top) and corresponding efficiency (bottom) as a function of the compactness of the building for both the radiator (left) and floor heating system (right). The results are shown for varying duration of the ADR-event, an outdoor temperature of 0 C and a comfort range (dT_{comf}) of 1 ˚C and 4 ˚C (Reynders, 2015).*

FLEXIBILITY APPLIED TO BUILDING STRUCTURAL THERMAL STORAGE	
Impact of building typology and building design parameters on energy flexibility *(Weiß, 2018)*	
Objective	Explore the potential of energy flexibility of domestic thermal loads considering different residential building types.
Energy flexibility quantification	Energy flexibility, defined as "the ability to deviate from the reference domestic heat loads profile", is expressed as power W/m² that can be shifted over a time span – in reaction to an external signal - respecting the indoor comfort band.
Object of the analysis	Four different building typologies representative of the Austrian building stock based on TABULA dataset. Simplified dynamic simulations are performed in IDA ICE.
Expected benefits	Potential of different building typologies to time-shift heating loads away from peak demand periods, to improve grid stabilization, without jeopardizing occupants' comfort.

Building parameter variation	Thermal mass (heavy, medium and lightweight construction), level of insulation based on the year of construction, solar gain control and presence of additional battery storage capacity.
Results	Figure 5 show that old buildings [A,B], in contrast to new and highly efficient buildings [C,D], have shorter delayed operation times due to the lower insulation standard. On the other hand, well-insulated buildings result in high delayed operation times and show the improved ability of modern buildings to retain heat over longer periods. The presence of passive solar gains AND heavy weight construction lead to longer delayed operation times and improve the possibility to shift heating load for much longer time spans. Furthermore, the addition of a battery capacity can drastically extend the load duration curves.

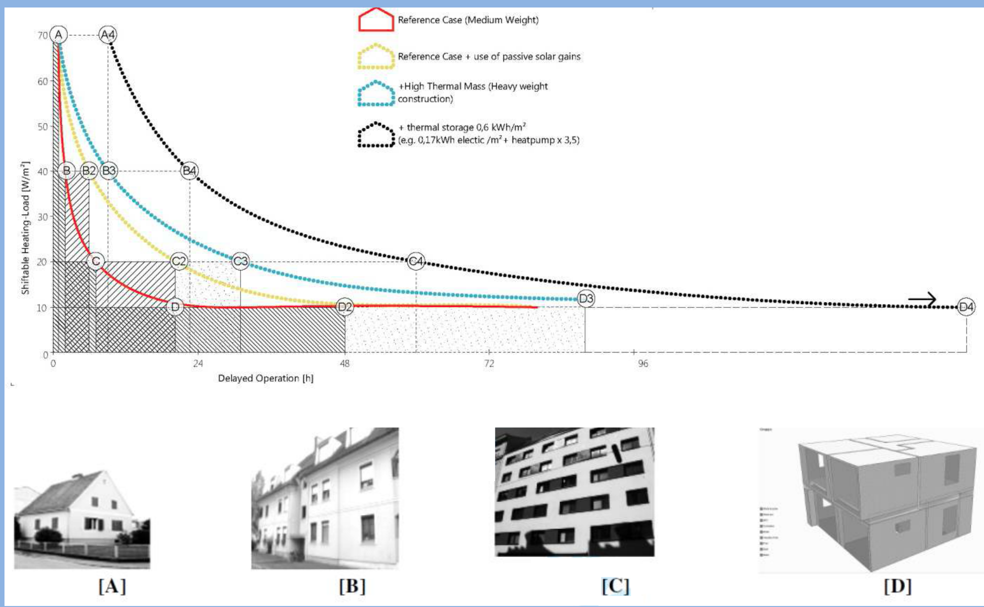

Figure 5 *Load duration curves of different reference buildings showing the potential of shiftable domestic heating load over time – delayed operation (Weiß, 2018).*

Final considerations

Over the last 20 years, the building design and performance assessment in European countries have been 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.

In fact, on the one hand, assessing the matching between the RES production and building energy demand requires a transient approach representing the actual operation with a detailed time frame. On the other hand, evaluating the energy performance at aggregated level can lead to several benefits in terms of CO2 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.

Energy planning at the building cluster scale represents an effective strategy for providing local and low-carbon energy supply, through the enhancement of district energy systems and decentralized energy production. Furthermore, the focus on cluster scale enables the development of a systemic approach in building design that considers, in an economy of scale perspective, factors such as retrofitting and adoption of technologies/strategies for increasing energy efficiency and minimizing CO2 emissions, so as to reduce the unitary cost of investment and reach cost-optimality (Koch & Girard, 2013).

Therefore, the opportunity to enlarge the design at the cluster scale can yield progress toward the aim to reduce carbon emissions.

By emphasizing Energy Flexibility, buildings are no longer only characterized by their own energy efficiency, but we recognize that buildings are able to interact with surrounding buildings and energy systems.

References

Aduda, K.O., Labeodan, T., Zeiler, W., Boxem, G., Zhao, Y., 2016. Demand side flexibility : Potentials and building performance implications. Sustain. Cities Soc. 22, 146–163. https://doi.org/10.1016/j.scs.2016.02.011

Ahmed, K., Akhondzada, A., Kurnitski, J., Olesen, B., 2017. Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS 17772-1 standards. Sustain. Cities Soc. 35, 134–144. https://doi.org/10.1016/j.scs.2017.07.010

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 Build. 80, 384–393. https://doi.org/10.1016/j.enbuild.2014.05.053

Arteconi, A., Hewitt, N.J., Polonara, F., 2013. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. Appl. Therm. Eng. 51, 155–165. https://doi.org/10.1016/j.applthermaleng.2012.09.023

Arteconi, A., Hewitt, N.J., Polonara, F., 2012. State of the art of thermal storage for demand-side management. Appl. Energy 93, 371–389. https://doi.org/10.1016/j.apenergy.2011.12.045

Baetens, De Coninck, Jorissen, Picard, Helsen, Saelens, 2015. OpenIDEAS – an open framework for integrated district energy simulations, in: Proceedings of BS2015. Presented at the 14th IBPSA 2015, Hyderabad, India.

Burhenne, Wystrcil, Elci, Narmsara, Herkel, 2013. Building performance simulation using Modelica: Analysis of the current state and application areas, in: Proceedings of BS2013. Presented at the 13th IBPSA 2013, Chambéry, France.

Clement-nyns, K., Haesen, E., Member, S., Driesen, J., 2010. The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid. IEEE Trans. Power Syst. 25, 371–380.

Coninck, R. De, Helsen, L., 2016. Quantification of flexibility in buildings by cost curves – Methodology and application. Appl. Energy 162, 653–665. https://doi.org/10.1016/j.apenergy.2015.10.114

D'hulst, R., Labeeuw, W., Beusen, B., Claessens, S., Deconinck, G., Vanthournout, K., 2015. Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium. Appl. Energy 155, 79–90. https://doi.org/10.1016/j.apenergy.2015.05.101

EC, 2016a. Clean Energy for All Europeans. COM(2016) 860 final. Brussels, 30.11.2016.

EC, 2016b. Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings. COM(2016) 765 final. Brussels, 30.11.2016.

EC, 2015. Energy Union Package. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy. COM(2015) 80 final. Brussels, 25.2.2015.

Eid, C., Codani, P., Chen, Y., Perez, Y., Hakvoort, R., 2015. Aggregation of demand side flexibility in a smart grid: A review for European market design. IEEE, pp. 1–5. https://doi.org/10.1109/EEM.2015.7216712

EU, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Off. J. Eur. Comm. 53, 13–35.

EU, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union 52, 16–62.

Halvgaard, R., Poulsen, N.K., Madsen, H., Jørgensen, J.B., 2011. Economic Model Predictive Control for Building Climate Control in a Smart Grid, in: 50th IEEE Conference on Decision and Control and European Control Conference. Orlando, Florida, pp. 1–6.

Hedegaard, K., Vad, B., Lund, H., Heiselberg, P., 2012. Wind power integration using individual heat pumps e Analysis of different heat storage options. Energy 47, 284–293. https://doi.org/10.1016/j.energy.2012.09.030

Hewitt, N.J., 2012. Heat pumps and energy storage – The challenges of implementation. Appl. Energy 89, 37–44. https://doi.org/10.1016/j.apenergy.2010.12.028

Hong, S.H., Yu, M., Huang, X., 2015. A real-time demand response algorithm for heterogeneous devices in buildings and homes. Energy 80, 123–132. https://doi.org/10.1016/j.energy.2014.11.053

Kim, Y., Member, S., Fuentes, E., Norford, L.K., 2016. Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump. Power Syst. 31, 3090–3099.

Koch, A., & Girard, S. (2013). Urban neighbourhoods - an intermediate scale for the assessment of energy performance of buildings. *Eceee 2013 Summer Study*, 1377–1385.

Lauster, Fuchs, Huber, Remmen, Streblow, Muller, 2015. Adaptive thermal buildings models and methods for scalable simulations of multiple buildings using Modelica, in: Proceedings of BS2015. Presented at the 14th IBPSA, Hyderabad, India.

Lauster, M., Teichmann, J., Fuchs, M., Streblow, R., Mueller, D., 2014. Low order thermal network models for dynamic simulations of buildings on city district scale. Build. Environ. 73, 223–231. https://doi.org/10.1016/j.buildenv.2013.12.016

Le Dréau, J., Heiselberg, P., 2016. Energy fl exibility of residential buildings using short term heat storage in the thermal mass. Energy 111, 991–1002. https://doi.org/10.1016/j.energy.2016.05.076

Maasoumy, M., Rosenberg, C., Sangiovanni-Vincentelli, A., Callaway, D.S., 2014. Model predictive control approach to online computation of demand-side flexibility of commercial buildings HVAC systems for Supply Following. IEEE, pp. 1082–1089. https://doi.org/10.1109/ACC.2014.6858874

Masy, G., Georges, E., Verhelst, C., Lemort, V., André, P., 2015. Smart grid energy flexible buildings through the use of heat pumps and building thermal mass as energy storage in the Belgian context. Sci. Technol. Built Environ. 21, 800–811. https://doi.org/10.1080/23744731.2015.1035590

Mendaza, I.D.D.C., 2014. Aalborg Universitet An Interactive Energy System with Grid , Heating and Transportation Systems An Interactive Energy System with Grid , Heating and Transportation Systems by A Dissertation Submitted to. Aalborg University.

Nuytten, T., Claessens, B., Paredis, K., Van Bael, J., Six, D., 2013. Flexibility of a combined heat and power system with thermal energy storage for district heating. Appl. Energy 104, 583–591. https://doi.org/10.1016/j.apenergy.2012.11.029

Oldewurtel, F., Sturzeneggert, D., Andersson, G., Morarit, M., Smitht, R.S., 2013. Towards a Standardized Building Assessment for Demand Response, in: 52nd IEEE Conference on Decision and Control. Florence, pp. 7083–7088.

Oldewurtel, F., Ulbig, A., Parisio, A., Morari, M., 2010. Reducing Peak Electricity Demand in Building Climate Control using Real-Time Pricing and Model Predictive Control, in: 49th IEEE Conference on Decision and Control. Atlanta, pp. 1927–1932.

Paatero, J. V, Lund, P.D., 2006. A model for generating household electricity load profiles. Int. J. Energy Res. 30, 273–290. https://doi.org/10.1002/er.1136

Pollhammer, K., Kupzog, F., Gamauf, T., Kremen, M., 2011. Modeling of demand side shifting potentials for smart power grids. IEEE, pp. 1–5. https://doi.org/10.1109/AFRCON.2011.6072110

Reinhart, C.F., Herkel, S., 2000. The simulation of annual daylight illuminance distributions — a state-of-the-art comparison of six RADIANCE-based methods. Energy Build. 32, 167–187. https://doi.org/10.1016/S0378-7788(00)00042-6

Reynders, G., Nuytten, T., Saelens, D., 2013. Potential of structural thermal mass for demand-side management in dwellings. Build. Environ. 64, 187–199. https://doi.org/10.1016/j.buildenv.2013.03.010

Reynders, G., 2015. Quantifying the impact of building design on the potential of structural storage for active demand response in residential buildings. PhD thesis, KU Leuven - Faculty of Engineering Science

Široký, J., Oldewurtel, F., Cigler, J., Prívara, S., 2011. Experimental analysis of model predictive control for an energy efficient building heating system. Appl. Energy 88, 3079–3087. https://doi.org/10.1016/j.apenergy.2011.03.009

Sodja, A., Zupančič, B., 2009. Modelling thermal processes in buildings using an object-oriented approach and Modelica. Simul. Model. Pract. Theory 17, 1143–1159. https://doi.org/10.1016/j.simpat.2009.04.003

Tahersima, F., Madsen, P.P., Andersen, P., 2013. An intuitive definition of demand flexibility in direct load control. IEEE, pp. 521–526. https://doi.org/10.1109/CCA.2013.6662802

Tahersima, F., Stoustrup, J., Meybodi, S.A., Rasmussen, H., 2011. Contribution of Domestic Heating Systems to Smart Grid Control, in: 50th IEEE Conference on Decision and Control and European Control Conference. Orlando, pp. 3677–3681.

Valsomatzis, Hose, Pedersen, Siksnys, 2015. Measuring and Comparing Energy Flexibilities, in: Ceur Workshop Proceedings. Presented at the EDBT/ICDT Joint ConferenceExtending Database Technology, pp. 78–85.

Van Roy, J., Verbruggen, B., Driesen, J., 2013. Ideas for Tomorrow: New Tools for Integrated Building and District Modeling. IEEE Power Energy Mag. 11, 75–81. https://doi.org/10.1109/MPE.2013.2268815

Verbeke, V.S., Ma, Y., Bogaert, S., Tichelen, P. Van, Uslar, O.M., 2017. Support for setting up a Smart Readiness Indicator for buildings and related impact assessment - Catalogue of Smart Ready Services Technical Working Document for Stakeholder Feedback.

Vigna, I., Pernetti, R., Pasut, W., Lollini, R., 2018. New domain for promoting energy efficiency: Energy Flexible Building Cluster. Sustain. Cities Soc. 38C, 526–533.

Ward, G., 1996. RADIANCE reference manual. IEA SHC Task 12.

Weiß, T., Fulterer, A.M., Knotzer, A., 2018. Energy flexibility of domestic thermal loads – a building typology approach of the residential building stock in Austria. Adv. Build. Energy Res. 1–16.

Whiteman, A., Rinke, T., Esparrago, J., Elsayed, S., 2016. Renewable Capacity Statistics 2016.

Widén, J., 2014. Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings. Appl. Energy 126, 199–212. https://doi.org/10.1016/j.apenergy.2014.04.008

Xue, X., Wang, S., Sun, Y., Xiao, F., 2014. An interactive building power demand management strategy for facilitating smart grid optimization. Appl. Energy 116, 297–310. https://doi.org/10.1016/j.apenergy.2013.11.064

Yu, Y.Y., 2013. Demand-Side-Management with heat pumps for single family houses, in: 13th IBPSA Conference. Chambéry, France.

IEA EBC Annex 67. http://www.annex67.org/

IEA EBC Annex 60. http://www.iea-annex60.org/