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	Energy flexible district concept: load profiles at district level, also coming from technology solution shared at district scale.
Deliverable N°.	D3.2
Task	3.2
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Due date	30/04/2019

Europäischer Fonds für regionale Entwicklung
Fondo europeo di sviluppo regionale
EUROPEAN UNION
AUTONOME PROVINZ BOZEN SÜDTIROL
PROVINCIA AUTONOMA DI BOLZANO ALTO ADIGE

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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

Nell'evoluzione dell'attuale sistema energetico verso modelli di decarbonizzazione e generazione distribuita, l'incremento della produzione elettrica da fonti rinnovabili di tipologia intermittente mette alla prova la stabilità delle reti termiche ed elettriche.

Come parte integrante della soluzione, (i) la flessibilità energetica degli edifici può consentire di gestire la domanda e la generazione di energia in base alle condizioni climatiche locali, le esigenze degli utenti e i requisiti della rete e (ii) la gestione energetica a scala di distretto può rappresentare un modo efficace per migliorare la contemporaneità tra la produzione locale e il consumo di energia.

Il concetto di flessibilità energetica, introdotta dall'International Energy Agency nell'ambito del progetto Annex 67 (IEA EBC Annex 67), è definita come la "*capacità di un edificio di reagire ad una o più forzanti, al fine di ridurre al minimo le emissioni di CO_2 e massimizzare l'utilizzo di fonti energetiche rinnovabili*" (Vigna et al., 2018a). Le forzanti rappresentano un insieme di condizioni al contorno significative, che possono cambiare durante la vita di un edificio e avere diversi livelli di frequenza.

Gli edifici di nuova generazione interagiscono con l'infrastruttura energetica non solo più come consumatori, ma anche producendo e accumulando energia. La gestione della domanda energetica a scala di cluster di edifici (quartiere o distretto) consente di fornire maggiore flessibilità alla rete, massimizzando l'utilizzo di risorse naturali e applicando logiche di accumulo energetico a livello locale. Inoltre, il focus sulla scala del cluster consente lo sviluppo di un approccio sistemico nella progettazione degli edifici che consideri, in una logica di economia di scala, fattori come l'adozione di tecnologie/strategie per aumentare l'efficienza energetica e ridurre al minimo le emissioni di CO_2, in modo da ridurre il costo unitario dell'investimento e raggiungere l'ottimizzazione dei costi (Koch & Girard, 2013).

Definizione di cluster di edifici

In letteratura non è presenta una definizione univoca di 'cluster', ma sono riportati diversi termini per descrivere il concetto di cluster in base a diversi punti di vista: la parola *quartiere* è riferita alla dimensione spaziale (Galster, 2001), la parola *comunità* indica la dimensione delle relazioni sociali che caratterizzano lo spazio (Managan & Controls, 2012) e infine in riferimento alla dimensione energetica emergono i concetti di *Net Zero Energy Communities* (He, Huang, Zuo, & Kaiser, 2016) e *Net Zero clusters (Li, Wen & Wu, 2014).*

A partire dalle precedenti accezioni, una nuova definizione di cluster è proposta e adottata nell'ambito del progetto INTEGRIDS: "*gruppo di edifici interconnessi alla medesima infrastruttura energetica in modo tale che il cambiamento nel comportamento/performance*

energetica di ciascun edificio abbia influenza sia sull'infrastruttura energetica che sugli altri edifici del cluster" (Vigna et al., 2018a).

La *connessione fisica* tra edifici collegati alla stessa rete consente uno scambio di energia tra edifici del cluster (ad esempio l'energia prodotta dai pannelli fotovoltaici installati su un edificio può essere anche utilizzata dagli altri edifici) o da una sorgente centrale agli edifici del cluster (nel caso del district heating).

La presenza di una possibile *aggregazione di mercato* (Eurelectric, 2014) indica invece una gestione energetica condivisa di diversi edifici appartenenti ad un unico proprietario/gestore (anche non localizzati nella stessa area geografica), che può contrattare con il Distribution System Operator (DSO) per ottenere tariffe energetiche più vantaggiose, offrendo in cambio una riduzione dei consumi energetici quando viene richiesto dalla rete.

Definizione di flessibilità energetica a scala di cluster

La mancanza di una definizione consolidata di cluster di edifici energeticamente flessibile richiede l'analisi di alcuni concetti ausiliari adottati in letteratura per descrivere la sinergia tra edifici energeticamente efficienti e utilizzo di fonti rinnovabili a livello aggregato; ciascuno di tali concetti contiene importanti parole chiave che confluiranno nella definizione finale di flessibilità energetica a scala di cluster, elaborata nell'Annex 67.

I concetti ausiliari identificati sono i seguenti: (*i*) *Smart Building Cluster* e (*ii*) *Zero Energy Neighbourhood* pongono l'accento sull'importanza del ragionare a scala aggregata nell'interazione tra edifici intelligenti e reti energetiche; il concetto di (*iii*) *Micro Energy Hub* definisce l'edificio come nodo del sistema energetico, capace di consumare, produrre e accumulare energia per ridurre i picchi di domanda e lo stress delle reti; (*iv*) *Virtual Power Plant* è una strategia di aggregazione delle risorse energetiche per alleggerire il carico sulla rete distribuendo in modo intelligente la potenza generata dalle singole unità durante i periodi di carico massimo; (*v*) *Collaborative Consumption* descrive l'accordo sociale da parte degli utenti per condividere le loro fonti di energia; (*vi*) *Local Energy Community* è il concetto introdotto dall'Unione Europea (EU, 2018) per definire gli edifici come nuovi attori del mercato dell'energia.

Modellazione di cluster di edifici e quantificazione della flessibilità energetica a scala di cluster

La natura complessa del cluster di edifici necessita di uno strumento di modellazione multi-dominio. Considerando come requisiti fondamentali dello strumento (i) la possibilità di studiare l'interazione tra edifici e sistema energetico, (ii) l'opportunità di simulare un gruppo di edifici in un singolo modello e (iii) la facilità di costruzione e riutilizzo del modello e in accordo con la revisione di Allegrini (Allegrini et al., 2015) sugli approcci per la modellazione a scala di distretto, Modelica (http://www.iea-annex60.org/) è selezionato come linguaggio di modellazione olistico adatto per il cluster di edifici.

La strategia di modellazione del cluster è sviluppata basandosi sull'analogia elettrica resistenza-capacità e utilizzando i componenti della libreria IDEAS (Jorissen et al., 2018).

Una metodologia per valutare la performance energetica e la flessibilità del cluster è elaborata, implementando la strategia definita nell'Annex 67. La flessibilità del cluster è valutata come la quantità di energia che un edificio può spostare in base alle forzanti. In questo studio, l'energia prodotta da un impianto fotovoltaico è scelta come forzante e la flessibilità è quantificata come riduzione della domanda energetica non coperta da fonti rinnovabili, ovvero come il miglioramento dell'utilizzo di energia durante i periodi di disponibilità di rinnovabili.

L'approccio è applicato a due diverse configurazioni di cluster caratterizzate da differenti livelli di massa termica (pesante in calcestruzzo e leggera in legno). Entrambe le configurazioni, impiegando un sistema di controllo intelligente, consentono di migliorare l'utilizzo delle rinnovabili, con una conseguente riduzione della domanda che deve essere coperta da combustibili fossili.

Negli sviluppi futuri, la metodologia verrà applicata considerando altre forzanti (ad esempio il prezzo dell'energia o l'intensità di CO_2 nel mix energetico) e ulteriori variazioni delle caratteristiche del cluster (profilo di utilizzo dell'edificio, tipologia di edificio, sistema costruttivo).

Acronyms and Abbreviations

DSO	Distribution System Operator
FI	Flexibility Index
H	Heavy configuration
L	Light configuration
nZEB	Nearly Zero Energy Buildings
R	Reference operation
RC	Resistance-Capacitance
RES	Renewable Energy Sources
ROM	Reduced-order model
S	Smart operation
SFH	Single Family House

1 Introduction

In an evolving energy system, shifting from single energy efficient units to interconnected active players that manage the energy flows, the relationship between the buildings and the grid significantly changes. Smart buildings are able to both consume and produce energy and they increasingly interact with the energy infrastructure by acting as micro energy hubs (D'Angiolella, De Groote, & Fabbri, 2016).

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. In the European context, the combination of energy efficiency improvement with renewable energy integration at the cluster scale has been investigated in a considerable number of strategically selected case studies (e.g. the BedZED eco-community in London, Vauban in Freiburg, Hammarby in Stockholm (Williams, 2016)). The results reveal that the management of a shared distribution network powered by solar thermal or combined heat and power (CHP) plants can bring several benefits to individual buildings in terms of increased efficiency, higher possibilities of storage and load complementarity due to building usage differences (e.g. commercial and residential) (IPCC, 2007).

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 CO_2 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.

The present report presents an overview of the definitions of building cluster and the auxiliary concepts available in literature dealing with energy flexible cluster. Starting from this reference background, it presents the modelling approach for the building cluster, with the results of the simulation activity on a sample cluster.

2 Definition of energy flexible building clusters

The concept of cluster

Finding a common definition for 'building cluster' concept is the starting point necessary for setting common rules and specific characteristics -e.g. size, composition, owner, type of connection with other buildings. Indeed, in the literature it is possible to find several terms and definitions related to the cluster concepts according to different perspectives, even if there is not a univocal description of clusters' features.

In particular, urban social scientists introduce the concept of *neighborhood*, focusing on its spatial attributes - geography, infrastructure and buildings - and on the social collective relations that characterize the space. (Galster, 2001). The term *community* could identify, on the one hand, a group of buildings located in the same area and, on the other hand, a "portfolio of buildings" geographically far but owned by a single person or set of occupants (Managan & Controls, 2012). . Moreover, the definition of cluster can be linked to the concept of *Net Zero Energy Communities*, characterized by a null or positive value in the difference between annual delivered energy and on-site renewable exported energy (He, Huang, Zuo, & Kaiser, 2016). The community can be considered the crucial scale for reaching the target of net zero energy, for improving energy interdependency and reducing maintenance and life-cycle costs. In fact, compared to a single building, the community level ensures a larger accommodation of RES supply systems and an easier flattening of load profiles due to highly varying occupancy patterns.

Thus, the building cluster concept will fundamentally transform the energy system by shifting on-site energy generation from a single Net Zero building to a system of "*Net Zero clusters*", able to freely share distributed power generation and storage devices, in order to achieve maximum energy efficiency (Li, Wen, & Wu, 2014). Starting from the previous reviews, a new definition of cluster is suggested (Vigna et al., 2018a) and adopted within the project INTEGRIDS: ***a building cluster identifies a group of buildings interconnected to the same energy infrastructure, such that the change of behaviour/energy performance of each building affects both the energy infrastructure and the other buildings of the whole cluster***. This definition does not assign fixed dimension and boundaries to the building cluster scale, but it is based on building interconnection that could be physical and/or virtual/market related (Figure 1)

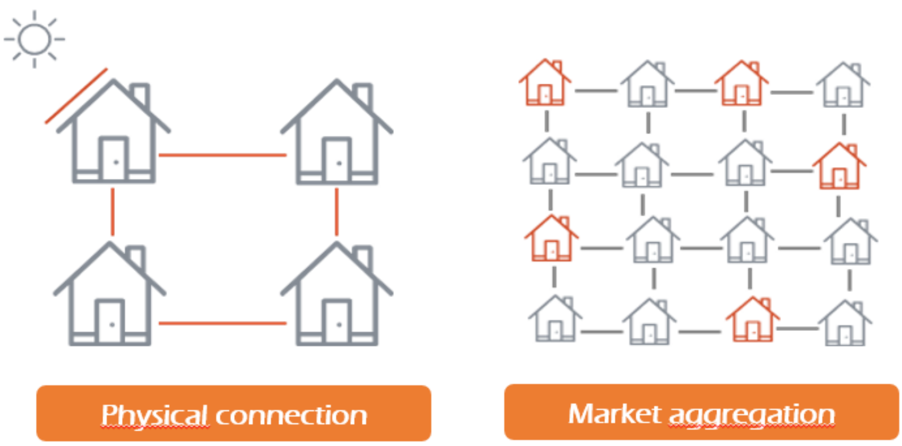

Figure 1. Scheme of the possible connections among buildings within a cluster.

The *physical connection* to the same grid of building clusters allows the exchange of energy between buildings (e.g. PV panels installed in one building produce energy that can be used also by the other buildings) or from a central source toward the buildings (e.g. district heating).

The possible presence of *market aggregation* (Eurelectric, 2014) enables the management of the building cluster by a common agent or company who can potentially exploit the Energy flexibility of the whole cluster (Langham, Cooper, & Ison, 2013; SF Environment, 2013). In general, different buildings can be treated as elements of the same cluster although they are not located in the same area (multi-site aggregation), e.g. different buildings with the same owner that can negotiate better energy tariffs with the DSO, offering in exchange a reduction of the energy consumption when required by the grid.

First steps towards the Energy Flexibility at building cluster scale

The International Energy Agency (IEA), in the programme 'Energy in Buildings and Communities' (EBC), introduces the concept of 'Energy Flexible Buildings' within the project 'Annex 67' (IEA EBC ANNEX 67). The aim of IEA EBC Annex 67 is to increase the knowledge, identify critical aspects and possible solutions concerning the Energy flexibility that different types of building and their usage may be able to offer to the future smart and fossil free energy systems.

One of the specific objectives of Annex 67 is the development of a common definition of 'Energy Flexible Building Cluster', in order to create a common basis for the work and to explain what Energy Flexibility is and how it can be evaluated.

As a general definition, starting from the approach set out for single buildings and reported in the introduction, Energy Flexible Building Clusters should demonstrate the capacity to react to forcing factors in order to minimize CO_2 emissions and maximize the use of Renewable Energy Sources (RES).

Nevertheless, the absence of a consolidated definition requires as a starting point the analysis of some auxiliary concepts adopted so far in the literature used to describe the synergy of energy efficient buildings and renewable energy utilization at an aggregated level; all of these concepts contain important keywords that will be included in the final definition elaborated during the Annex 67 work.

The auxiliary concepts identified are the following: (*i*) *Smart Building Cluster* and (*ii*) *Zero Energy Neighbourhood* concepts stressing the role of smart interaction between buildings and grid and underlining the importance of reasoning at an aggregated level to reach the aim of Zero Energy Buildings; (*iii*) *Micro Energy Hub* concept, representing the future behaviour of buildings, that will be able to consume, produce and store energy and will increasingly interact to reduce peak demand and grid stress; (*iv*) *Virtual Power Plant* concept as a strategy for aggregating heterogeneous Distributed Energy Resources (DERs) to relieve the load on the grid by smartly distributing the power generated by the individual units during periods of peak load; (*v*) *Collaborative Consumption* concept as a social agreement by users to share their energy sources; (*vi*) *Local Energy Community* concept introduced by the European Union as new market players with the right to generate, consume, store and sell renewable energy.

It is important to refer to such auxiliary concepts, further detailed in the following sections, since they represent an expression of the market stakeholders and players involved in the ongoing energy transition towards the ambitious 100% RES target. Policy makers should start from these auxiliary concepts in order to effectively promote energy efficiency in the current crucial transformation of market, building and infrastructure technologies, as well as EU legislative framework.

I. Smart Building Cluster

The concept of Energy Flexibility at an aggregated level can be linked to the definition of "*Smart Building Cluster*", indicating "a group of neighboring smart buildings electrically interconnected to the same micro-grid" (Ma et al., 2016). Considering the Smart Building Cluster scale, it is possible to obtain an improvement of the local use of renewable energy, a decrease in the cost of electricity consumption, and a larger load shift in time due to different occupancy patterns and varying load profiles within a cluster composed of mixed-use buildings.

II. Zero Energy Neighborhood

The "Zero Energy Building" concept still considers the individual buildings as autonomous entities and neglects the importance of reaching energy efficiency at a larger scale. In the future shift to nZEB 2.0 (D'Angiolella et al., 2016) the *Zero Energy Neighborhood* scale will take into account the numerous interactions between urban form, building energy needs and on-site production of RES (A.-F. Marique &

Reiter, 2014), in order to balance annual building energy consumption and individual transportation by the local production of renewable energy (A. Marique, Penders, & Reiter, 2013).

III. Micro Energy Hub

In the framework of an Energy Flexible Building Cluster, buildings will increasingly interact with the energy systems and have the potential to take up an important role in the energy-supply-system stability by acting as *micro energy hubs* i.e. "multi hubs-generation systems, providing renewable energy production, storage and demand response" (Geidl, Koeppel, Klockl, Andersson, & Frohlich, 2007).

The key concept of the energy hub approach is the possibility to jointly manage the energy flows from multiple energy sources in order to improve the renewable energy sharing between different interconnected buildings (Darivianakis, Georghiou, Smith, & Lygeros, 2015; Orehounig, Mavromatidis, Evins, Dorer, & Carmeliet, 2014).

IV. Virtual Power Plant

It is possible to make an analogy between Energy Flexible Building Clusters and virtual power plants: in fact, Virtual Power Plants are "collective generators of renewable energy sources that can store and adjust energy output on demand and at will" (Carr, 2011). An aggregator can group different distributed energy resource systems into a Virtual Power Plant in order to provide more Energy Flexibility than a single system and, in parallel, Energy Flexible buildings have the possibility to co-generate with current grids or operate solely to produce energy in a cost-effective way, while adapting/shifting the electricity consumption profile in time (De Coninck & Helsen, 2013).

V. Collaborative Consumption

In the current market, end-users hold only the role of final consumers and are not involved in the energy supply side. The community engagement to reach a suitable energy management framework represents an opportunity to increase social acceptance of distributed generation in smart grids (Ahmadi, Rosenberg, Lee, & Kulvanitchaiyanunt, 2015). Collaborative consumption is "a social-based agreement framework", in which different consumers cooperate to share their resources and to create valuable services for the benefit of the whole community (Belk, 2010). Therefore, an active participation of residents into the energy market improves their inclination towards cooperation in order to reschedule their consumptions and generate more renewable energy so as to minimize energy cost, carbon emissions and primary energy consumption (Dai, Hu, Yang, & Chen, 2015).

VI. Local Energy Community

The European Union Directive on the promotion of the use of energy from renewable sources (recast) (EU, 2018) establishes a framework for Local Energy Communities aimed at improving energy management at the community level and empowering local participants. In such a geographically confined network, all consumers can have a direct involvement in energy consumption, storage and/or the sale of self-generated electricity to the market, and the up-take of new technologies and consumption patterns, including smart distribution grids and demand response, will get easier.

3 Modelling environment

Modelica and RC-network approach

The complex nature of the building cluster imposes the need for multi-domains modelling tools. In order to identify the most suitable tool for energy flexibility simulation at cluster scale, the selecting criteria considered were: (i) *interaction* (possibility to study the interaction between buildings and energy systems, including interconnection by thermal and electrical networks, the use of renewable energy systems and storage systems); (ii) *modelling scale* (opportunity to simulate a group of mixed-use buildings in just one model); *scalability* (possibility to model a cluster of buildings considering the proper detail related to both the two scales of project, from technological component and building envelope for single building to district plants and layouts at cluster scale); (iii) *balancing* (easy model construction, exchange and reuse). As results of this analysis and according to the review of Allegrini (Allegrini et al., 2015), Modelica has been identified as one of the proper holistic modelling language to address district-level energy system for evaluating the whole potential of sharing/exchange energy between interconnected buildings.

Modelica is an equation-based object-oriented modelling language able to decompose complex physical systems into structured hierarchies of elementary components (Fritzson, 2004). Modelica adopts an acausal modelling approach (Elmqvist & Mattsson, 1997) and the physical construction of the model is enhanced by a graphical interface (Elsheikh, Widl, & Palensky, 2012). The advantages that the employment of Modelica brings are the multidisciplinary modelling using standardized libraries (http://www.iea-annex60.org/) and the support of fast prototyping of physical models by encouraging the implementation of reusable, independent and extensible components.

A detailed physical model of a building cluster requires consistent computational resources to perform both the simulation and the optimization (Lauster et al., 2014). To overcome this issue, model simplification techniques, such as resistance-capacitance (RC) networks, seem promising since they represent a good compromise between reasonable accuracy, parameters requirement and computational effort (Kämpf & Robinson, 2007).

The electric analogy of RC networks has been extensively used in literature, representing the conductivity of materials as electric resistance and the thermal mass as electrical capacity (Achterbosch et al., 1985; Fraisse et al., 2002; Kämpf & Robinson, 2007; Nielsen, 2005; Ramallo-González, Eames, & Coley, 2013). Moreover, many authors have made use of the electric analogy in Modelica language to represent heat transfer in a building cluster. Lauster (Lauster et al., 2015) describes a low order thermal network model for multiple buildings using Modelica AixLib (Müller et al., 2016). The number of RC elements for wall has been varied in order to test dynamic behaviour of components and related calculation times. The building envelope model proposed by Burhenne (Burhenne et al., 2013) is also based on equivalent circuit model made of resistors and capacitors using components of Modelica Standard Library (https://github.com/modelica/Modelica). The Buildings Library developed at LBNL (Wetter, 2009) has been used to predict HVAC load dynamic of building districts by He (He et al., 2015). The Integrated District Energy Assessment by Simulation (IDEAS) library (Baetens et al., 2015; Van Roy, Verbruggen, & Driesen, 2013) has been applied by Reynders (Reynders, Diriken, & Saelens, 2014) with the aim to identify suitable RC models for whole set of dwellings.

According to this brief review, in this work a simplified model for building clusters has been adopted, based on RC-elements and Modelica libraries' components, in order to properly describe the features and the energy performance of the cluster and the building interactions with the grid.

Model description

This section describes the main features of the simulated building cluster.

3.1.1 Building cluster configuration

The buildings adopted for this study are referred to the archetypes presented in the IEE-Project TABULA database for the Italian building stock typology of the detached Single Family House (SFH) (Corrado et al., 2011) of the construction period after 2006. Such construction period has been selected with the aim to investigate the flexibility performance of new buildings (nZEB) with local integrated renewable energy sources. Based on the archetypes of Italian building stock presented in the TABULA database (webtool.building-typology.eu), the geometrical and thermal properties of the selected buildings were translated into reduced-order Modelica models using the Python package TEASER developed by RWTH Aachen (Remmen et al., 2017).

The geometrical properties of the building typology used in simulations are summarised in Table 1. As assumption, the internal walls and floor had the same surface area as respectively the outer walls and the ground floor. The thermal transmittance values of the building envelope components were set accordingly to NZEB Italian requirements defined in D.M. 26.06.2015 (Decreto del Ministero dello Sviluppo Economico, 2015): *U-value* of 0.22 W/m^{2}K for the opaque elements (exterior walls, ground slab, roof) and *U-value* of 1.1 W/m^{2}K for the transparent elements.

A variation of the building components' thermal mass was carried out to investigate its impact on cluster energy and flexibility performance. For the exterior walls, roof, internal walls and internal floor, two different levels of thermal mass -heavy (H) and light (L)-, respectively referred to two different structural cores (concrete and laminated timber) were considered. The main thermal properties are reported in Table 2.

Table 1. Geometrical properties of the building typology used in simulations.

Single Family House SFH	
Volume	607 m^3
Gross heated area	174 m^2
Number of floors	2
Component area	
Exterior walls	225.3 m^2
Ground slab	96.4 m^2
Roof	96.4 m^2
Window area	21.7 m^2
Internal walls	225.3 m^2

Internal floor	96.4 m^2

Table 2. Thermal properties of building components for different cluster configurations.

	Heavy configuration (H)	**Light configuration (L)**
Structural core	Concrete	Laminated timber
Thermal transmittance U-value [W/m^{2}K]	0.22	0.22
Heat capacity [MJ/K]	68	25
Periodic thermal transmittance Y_{ie} [W/m^{2}K]	0.014	0.068

In each configuration, the cluster was composed of four residential detached buildings with four different stochastic occupant behaviour, connected to a district heating system that allowed thermal energy exchange between buildings (Figure 2).

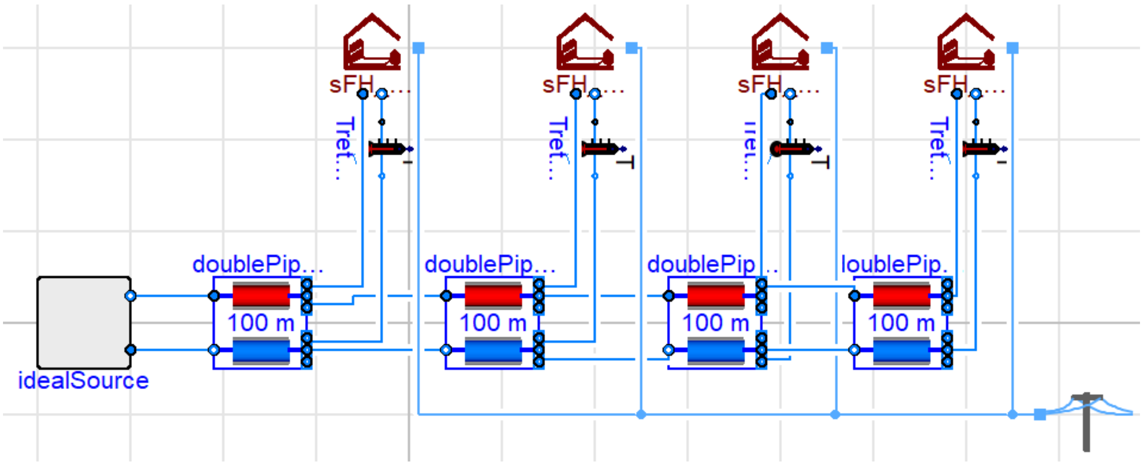

Figure 2. Model of the building cluster integrated with thermal and electric grid in Dymola environment.

The building cluster models were set out following a series of methodological steps reported in the following subsections.

3.1.2 Translation of geometrical and thermal properties of buildings in Modelica language

To automatically generate the reduced-order models, the open-source Python package TEASER (Remmen et al., 2017) was employed, although in a slightly adapted version. The original version of TEASER imports a CityGML model, containing the building geometry, construction year, the number of floors and their height as well as the building height, enriches these data with material layers for all building elements based on the German TABULA project and exports Aixlib or IBPSA Modelica models. For this work, as no CityGML model of the buildings was available, an additional import feature was implemented in TEASER, more in particular import from a csv-file. The csv-file contained the same data as required for the CityGML file, but considered only 8 possible orientations for the building elements (N, NE, E, SE, S, SW, W and NW) (De Jaeger et al. 2018) and only one tilt for all the pitched roof parts of a particular building. Additionally, the German data, used for the data enrichment, were replaced by Italian data. Finally, the export of IBPSA reduced-order models to the IDEAS Modelica library (Jorissen et al., 2018) was implemented.

3.1.3 Definition of the main boundaries and district heating system

The IBPSA reduced-order model for the thermal zone is included in the IDEAS building model. The cluster was modelled in IDEAS library and simulations were performed in Dymola environment. The IDEAS-Integrated District Energy Assessment Simulations (https://github.com/open-ideas/IDEAS) library allows simultaneous transient simulation of thermal and electrical systems at both building and feeder level. The main items included in the model are described below.

- Boundary conditions

The weather data conditions were referred to the city of Bolzano, Italy. A Typical Metereological Year (TMY) file was obtained from the Meteonorm database (www.meteonorm.com).

- Building envelope

To reduce computational effort and keep an adequate level of accuracy, the building envelope was described through a Reduced-Order Model (ROM), shown in Figure 3. The distributed thermal mass of building envelope components was defined as a model of resistance-capacitance (RC) network analogue to electric circuits, as described in Lauster et al. (2015). The thermal masses of each building envelope component (external walls, ground slab, roof and internal walls) were represented as a vector of capacitances. Solar gains, internal gains and heating were distributed over the capacities. Additionally, for each envelope component a vector of resistances was defined, representing the radiative heat transfer between building components and the convective heat transfer between building components and both the outdoor and the inner air of the zone. All the values of the resistances and capacitances were automatically calculated within TEASER, before generating the IDEAS building models.

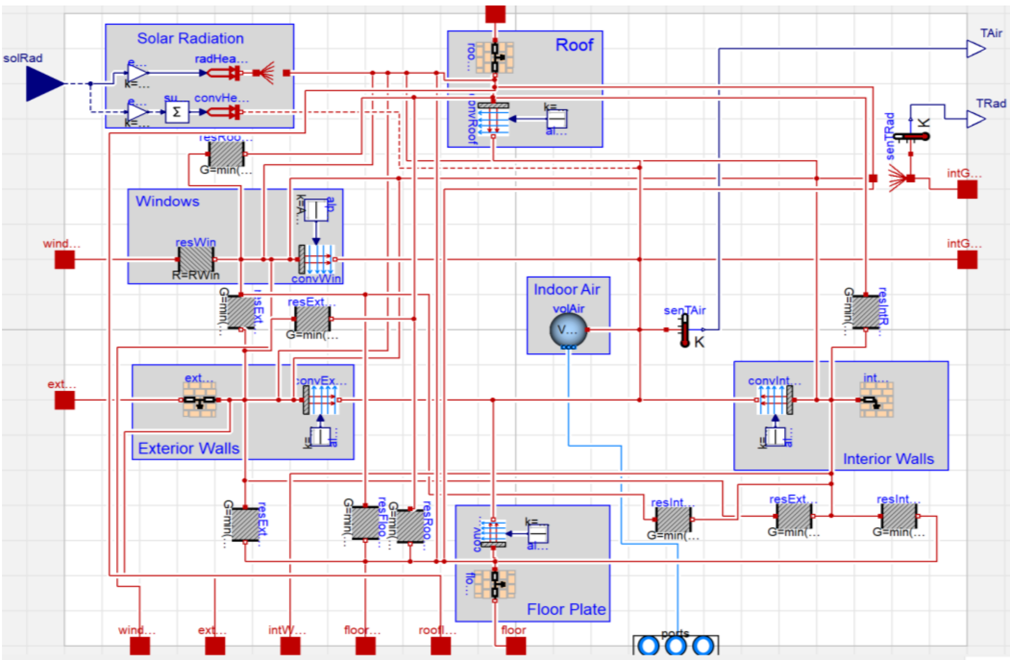

Figure 3. Reduced-order model of the structure of each building forming a cluster, using resistors and capacitors components of the library IDEAS.

- Systems

The buildings were equipped with radiators as heat emission system, connected to the district heating network through a heat exchanger. As the focus of this work is on the heating period, no cooling system was included. The domestic hot water circuit was modelled as a hot water storage system. The mechanical ventilation system was set with a constant ventilation rate of 0.5 1/h, with recuperation efficiency of 84%.

- Occupancy and appliances

The residential occupancy and appliances use profiles were stochastically defined using the Load Profile Generator tool (https://www.loadprofilegenerator.de/). Four different load profiles were created:

- Profile #1: Family consisting of 2 adults (both workers) and 3 children;
- Profile #2: Couple of adults (1 worker);
- Profile #3: Family consisting of 1 adult woman (worker) and 2 children;
- Profile #4: Single adult man (worker).

The stochastic data referred to heat flows from occupants and appliances have been imported in the model as a matrix. The temperature set-points were not influenced by the stochastic occupant behaviour, as they were specifically designed and used as inputs, as described in the *Flexibility assessment* section.

- District heating

The district heating network was represented through a succession of distribution double pipe models (van der Heijde et al., 2017), supplied by an ideal source. For the purpose of this analysis, aimed to implement the methodology to evaluate the flexibility of clusters correlating the heating energy demand to the PV production as a forcing factor, we adopted as an ideal source, a large-scale heat pump electrically driven. This technological system is in line with the limited size of the cluster and with proven experiences across Europe of large scale heat pumps (https://www.ehpa.org/fileadmin/red/03._Media/03.02_Studies_and_reports/Large_heat_pumps_in_Europe_MDN_II_final4_small.pdf, http://www.cooldh.eu/demo-sites-and-innovations-in-cool-dh/osterby-hoje-taastrup/).

3.1.4 Definition of the renewable energy production profile of the local installed cluster PV system

The photovoltaic design software POW tool was used to define a reference PV system capacity and solar collectors' position for the cluster according to an energy optimization, as described in Vigna et al. (2018b) and Lovati et al. (2018). The resulting renewable energy production profile served as a forcing factor (i.e. an external signal to which the building cluster was supposed to react) for the energy flexibility assessment of the cluster, as explained below. The monthly values of the production from the PV plant are reported in Figure 3. The PV capacity installed in the cluster was of 14.33 kWp. The modules dimensions were 1.989x1.63 m, the static performance ratio coefficient was of 0.8 and the efficiency assumed was of 17%.

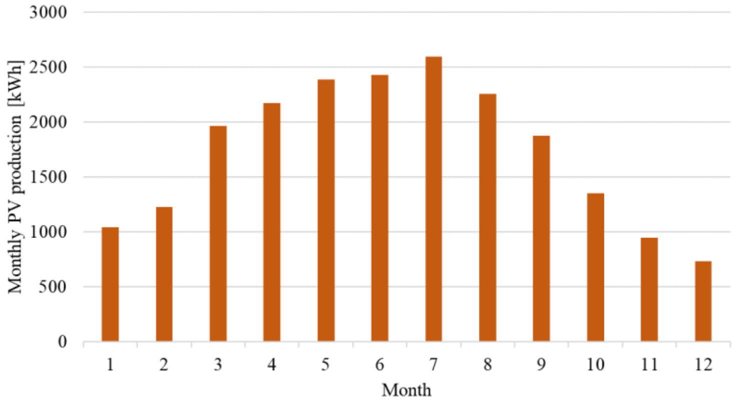

Figure 4. Monthly renewable energy production from the cluster PV plant.

4 Flexibility assessment

In line with the energy flexibility characterization methodology set out in Annex 67 project (Grønborg Junker et al., 2018), energy flexibility can be calculated as the measure of the cluster reaction to external forcing factors. In other words, the flexibility is the difference in terms of net energy use, between the cluster managed by a control system that is not aware of the forcing factor (reference operation), and the control sharpened according to the forcing factor (smart operation). In the present work, the availability of local RES production from a PV system is settled as forcing factor.

The modulation of the temperature set-point is used as strategy for affecting the timing operation and the power requested by the heating system. For the heating period (January-April and October-December), two different temperature set-point controllers of the heating system are defined (an example is illustrated in Figure 6a-b and Figure 7a-b):

- for the reference operation (R) of the heavy weight (H) and of the light weight (L) clusters, a set-point of 20 ˚C is set during the day (7AM-11PM) according to the standard EN15251 (CEN, 2007), while a set-back of 16 ˚C is fixed for the night hours (11PM-7AM).

- for the smart operation (S) of the heavy weight (H) and of the light weight (L) clusters, a forcing factor-aware controller is designed based on the monthly available RES produced by the PV system. First, a forcing factor signal is defined: for each month of the heating period, the maximum value of the renewable energy produced is sorted; this value is associated to the upper limit of the forcing factor signal of +2 ˚C (time intervals with high renewable production), while the lower limit of the signal of -2 ˚C is referred to time intervals with no renewable production. The limits of comfortable conditions of 20 ˚C ±2 ˚C are chosen in accordance to Category III–Acceptable, moderate level of expectation defined in the standard EN15251 (CEN, 2007). Then, in order to define a proper signal for controlling the building set-point temperature according to the PV production, we subdivide the range between the null and maximum production in nine intermediate intervals. Each interval indicates a variation of the set-point of ±0.5 °C respect to the adjacent intervals. During the night hours, no signals are applied and the temperature set-point is kept the same as the reference operation building (16 °C).

In this study, the energy flexibility is defined as the ability of the building to minimize the heating energy usage during the absence of renewable energy sources (RES) production and maximize it during periods of available renewable production. Therefore, the final objective of the energy flexible cluster is to maximize the use of RES and reduce the use of non-renewable energy. The flexibility of each cluster configuration is quantified considering the Flexibility Index FI, expressed as the difference between the residual demand of the reference cluster q_{match}^{REF} and the residual demand of the smart cluster q_{match}^{SMART} divided by the reference heating demand $q_{consumed}^{REF}$ as reported in Equation (1). All the terms under the integrals are expressed as power (i.e. in kW).

$$FI= \int \left(q_{match}^{REF} - q_{match}^{SMART}\right) dt \ / Q_{consumed}^{REF} \qquad (1)$$

For the heating period, the residual demand of the clusters Q_{match}^{REF} and Q_{match}^{SMART} are respectively calculated as the maximum value between 0 and the difference between the energy demand of the cluster and the renewable energy produced:

$$Q_{match}^{REF}= \int \max\left(0, q_{consumed}^{REF} - q_{produced}^{REF}\right) dt \qquad (2)$$

$$Q_{match}^{SMART}= \int \max\left(0, q_{consumed}^{SMART} - q_{produced}^{SMART}\right) dt \qquad (3)$$

Thus, the residual demand refers to the energy demand not covered by RES and must therefore be satisfied with non-renewable energy sources.

In the next section, the results obtained from the simulations for the energy and flexibility performance of the clusters are presented and discussed.

5 Results and Discussion

Energy performance

In Figure 5, the monthly heating demand values of the heavy H (top) and light L (bottom) cluster configurations are reported:

- the grey bars show the total heating demand of the cluster during reference operation (R), i.e. the energy performance of the cluster before considering the contribution of the PV production and without the smart control;

- the grey dashed bars show the residual demand of the cluster during reference operation (R), i.e. the energy savings of the cluster considering only the contribution of the PV production (without smart control);

- the black bars show the total heating demand of the cluster during smart operation (S), i.e. the energy performance of the cluster considering only the contribution of the smart control;

- the green bars (for the heavy H cluster configuration) and the blue bars (for the light L cluster configuration) show the residual demand of the cluster during smart operation (S), i.e. the energy savings of the cluster considering both the contributions of the PV production and the smart control affecting the timing operation of the heat pump.

The values of the residual demand of the simulated configurations (Q_{match}^{REF} and Q_{match}^{SMART}) are calculated as shown in Equation 2 and Equation 3. For the whole heating period, it is visible that both the PV system and the smart control contributions result in significant energy savings.

Considering the yearly energy demand shown in Figure 6 and Table 3, for both heavy weight (H) and light weight (L) configurations the smart operation (S) improved the energy usage during periods of available renewable production, resulting in a reduction of 14% of the residual demand (i.e. the energy demand not covered by renewables) compared to the reference (R) operation.

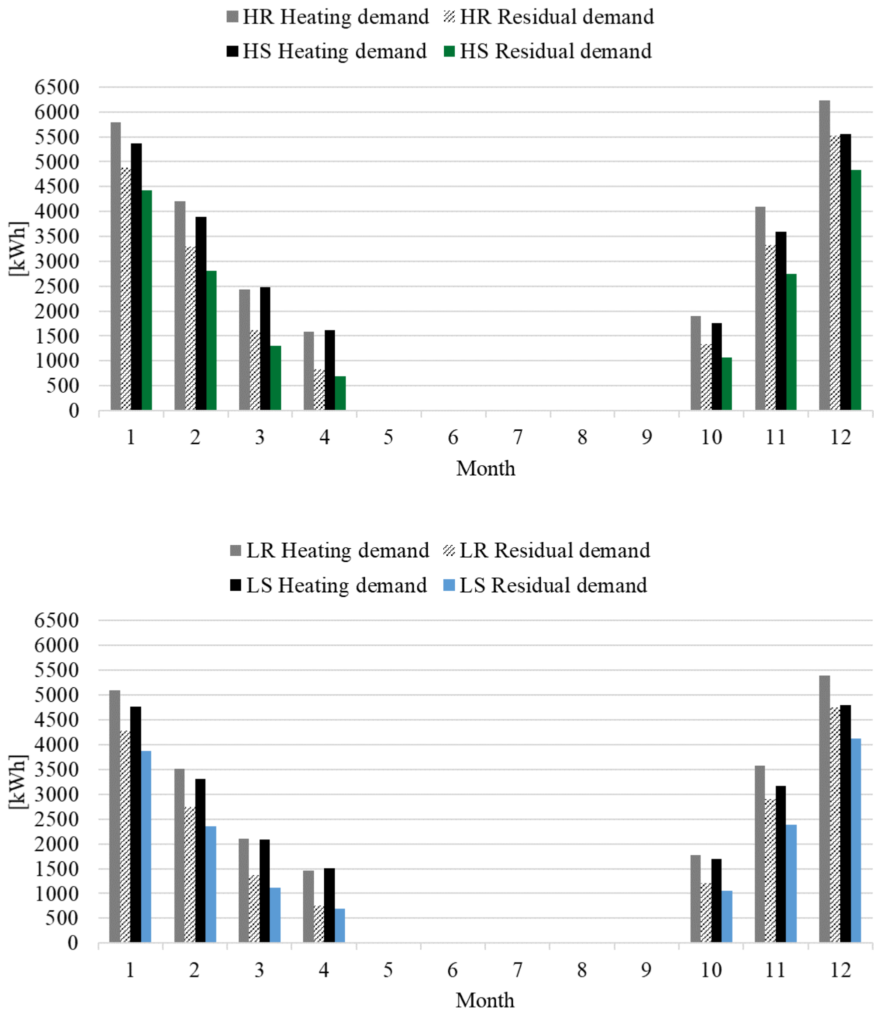

Figure 5. Monthly heating demand of the heavy weight (H) (top) and light weight (L) (bottom) simulated cluster configurations. Reference case (R) versus smart case (S).

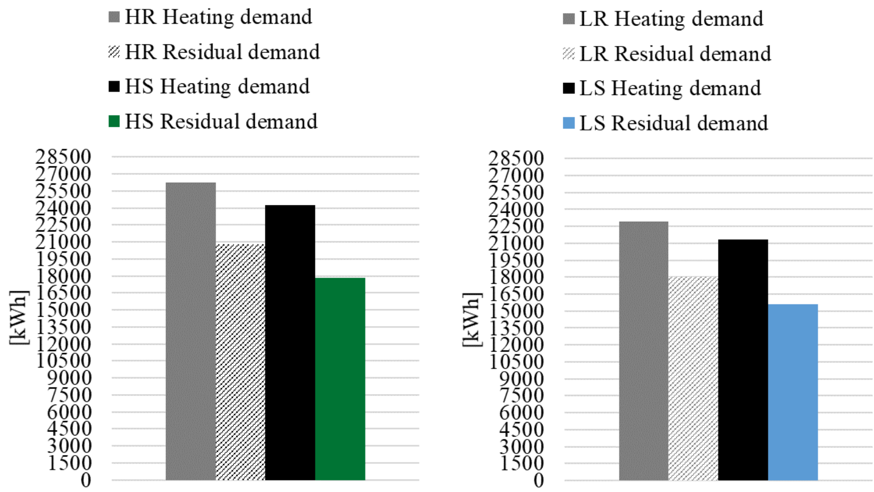

Figure 6. Yearly heating demand of the heavy weight (H) (left) and light weight (L) (right) simulated cluster configurations. Reference case (R) versus smart case (S).

Table 3. Yearly heating demand values for different cluster configurations.

	Heavy configuration (H)		**Light configuration (L)**	
	Reference (R)	Smart (S)	Reference (R)	Smart (S)
Heating demand [kWh]	26262	24263	22900	21338
Residual demand [kWh]	20804	17865	18023	15600

The daily trends for two representative days of January and March are respectively presented in Figure 7 and Figure 8. Figure 7a and Figure 8a report the variation of the smart set-points (red lines) compared to the reference set-points (black dashed). Figure 7b and Figure 8b show in grey bars the forcing factor signal based on available renewable energy produced by the PV system.

Figure 7c and Figure 8c report the indoor temperature trends for one representative building of the cluster for both heavy (H) and light (L) configurations, during reference (R) and smart (S) operation. It is visible that during unoccupied periods in which the heating system is switched off, the heavy weight building cooled down more rapidly than the light weight building, since the control is not able to fully activate the thermal mass.

Figure 7d-e and Figure 8d-e present the heating demand of the reference (black dashed line) and smart configuration (green line for the heavy cluster and blue line for the light cluster) and the trend of the PV production (grey dotted line). What the smart control tries to do is to decrease the heating demand during periods of null PV production and shift/increase it during periods of available renewable energy. During the representative days of January, it is not possible to completely shift the smart heating demand curve in correspondence to the PV production curve because the PV starts to produce at around 9 AM but the heating system has to be turned on at 7 AM to ensure comfort conditions, both in reference and smart operation. Anyway, the smart control positively contributes to decrease the energy demand during periods of absence of renewable production and increase it during periods of available renewable production for both the heavy and the light configurations. During the representative days of March, the PV system starts in advance to produce renewable energy (7 AM) and thus it is visible a better correspondence with the trend of the heating demand. Here again, the smart control lowers the demand during periods without renewable energy production and tries to shift it during periods of available renewable energy for both the heavy and light configurations.

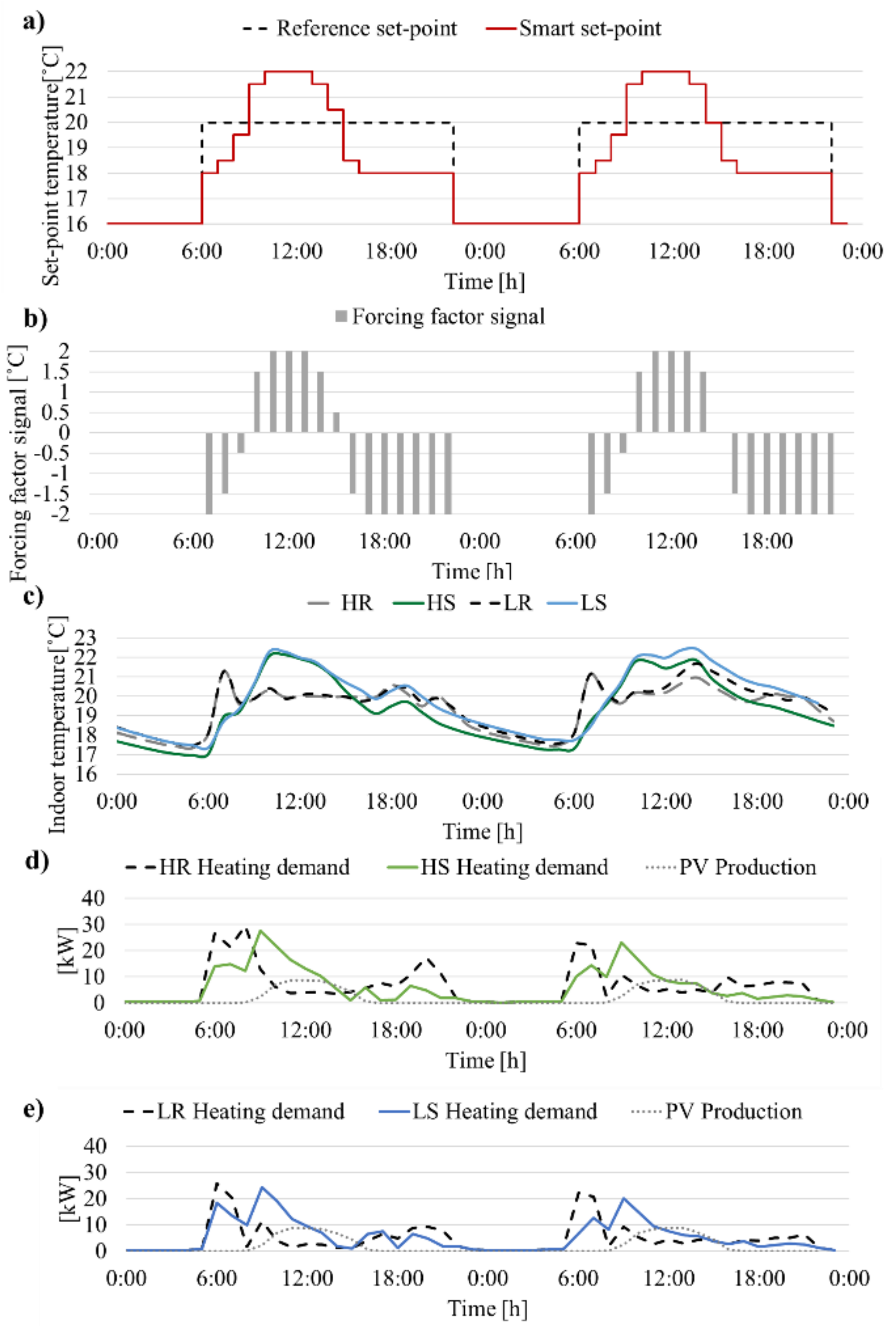

Figure 7. Daily trends for two representative days in January. a) Temperature set-point of reference and smart operation; b) Forcing factor signal; c) Indoor temperature of one representative building of the cluster for both heavy weight (H) and light weight (L) configurations, during reference (R) and smart (S) operation; d) Heating demand of the simulated heavy weight (H) configurations (reference case (R) versus smart case (S)) and PV production profile; e) Heating demand of the simulated light weight (L) configurations (reference case (R) versus smart case (S) and PV production profile.

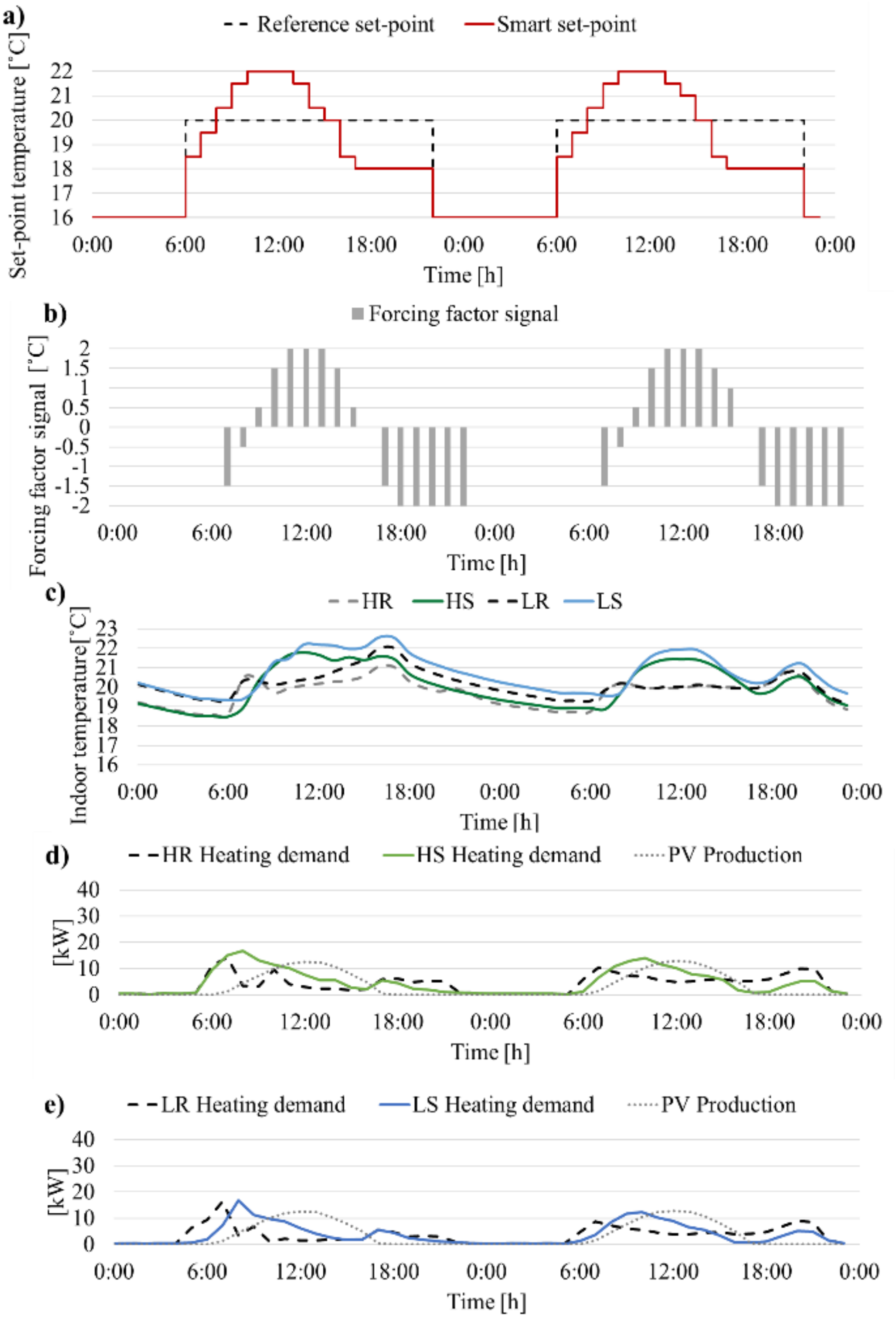

Figure 8. Daily trends for two representative days in March. a) Temperature set-point during reference and smart operation; b) Forcing factor signal; c) Indoor temperature of one representative building of the cluster for both heavy weight (H) and light weight (L) configurations, during reference (R) and smart (S) operation; d) Heating demand of the simulated heavy weight (H) configurations (reference case (R) versus smart case (S) and PV production profile; e) Heating demand of the simulated light weight (L) configurations (reference case (R) versus smart case (S) and PV production profile.

Flexibility performance

The values of the Flexibility Index FI of the two configurations, calculated as reported in Equation 1, are shown in Figure 9 and Figure 10. From the monthly results, it is visible that in the cold months of January, November and December, the light cluster is more flexible than the heavy cluster. On the contrary, during the warmer months of April and October the FI for the heavy cluster is much higher than for the light cluster; however, the residual demand is quite low in these months, so the energy saving is limited.

Therefore, on annual basis, the FI value obtained by both cluster is the same (0.11). This means that in this case, the higher thermal mass does not increase the flexibility index of the building, because as stated above, the heavy building cools down more during unoccupied hours and the smart control cannot charge the thermal mass to obtain a heat exchange with the indoor. On the contrary, in a warm climate, a high thermal mass is expected to be advantageous, that is to increase the flexibility index.

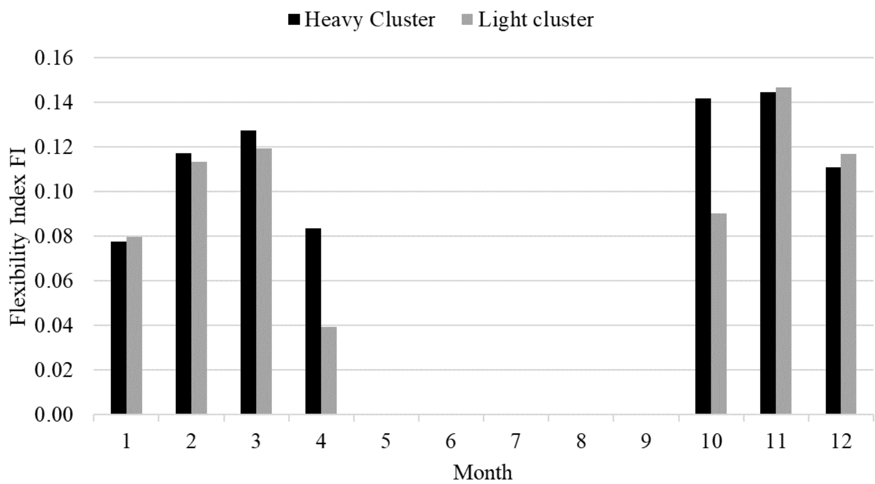

Figure 9. Monthly values of the Flexibility Index FI for the simulated cluster configurations.

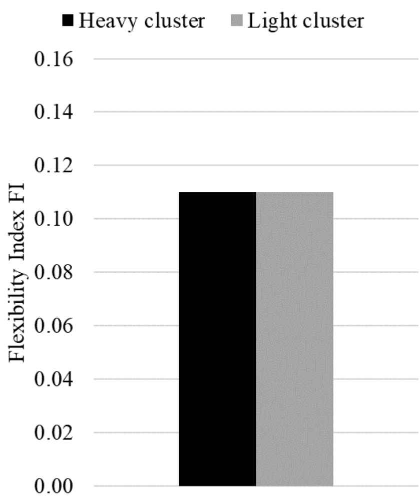

Figure 10. Yearly values of the Flexibility Index FI for the simulated cluster configurations.

Conclusion

This report presented a methodology to define building cluster models connected to a thermal network in Modelica language. Two building cluster configurations were modelled using the IDEAS library and a variation of the thermal mass level (Heavy and Light) of the opaque building components was performed. The energy and flexibility performance were evaluated for the heating period. The availability of local RES production from a PV system was settled as forcing factor and flexibility was defined as the ability of the building to minimize the heating energy usage during the absence of RES production and maximize it during periods of available renewable production, in order to reduce the use of non-renewable energy sources. Based on the methodology defined in IEA EBC Annex67 project, the energy flexibility potential of the different scenarios was assessed.

A scenario for reference operation of the buildings with constant heating temperature set-point at 20 ˚C during the day (7AM-11PM) and 16 ˚C during the night (11PM-7AM) was initially simulated. According to the availability of local renewable energy, a smart set-point was provided based on a forcing factor signal (temperature modulation of 20 ˚C ± 2 ˚C with variation intervals of 0.5 ˚C), with the aim of decreasing the heating demand during periods of null PV production and shift/increase it during periods of available renewable energy.

For the whole heating period, the smart operation of both the heavy and the light smart cluster configurations enables an improvement of RES usage, with a consequent reduction of the residual demand (i.e. non-renewable energy demand) of 14% compared to the reference residual demand.

For both cluster configurations, the flexibility performance is evaluated defining a Flexibility Index (FI) to quantify the amount of energy that can be shifted towards RES-availability through the smart control operation in comparison to the reference case. In this first application, the FI obtained for both configurations is the same, so in this case the higher thermal mass of the building does not increase the flexibility index, because the heavy building cools down more during unoccupied hours and the control cannot fully charge the thermal mass.

To conclude, this work introduces a preliminary approach for modelling a building cluster in Modelica language and a methodology to evaluate the cluster flexibility performance. There are some issues that will be fine-tuned in the next developments of the model, e.g. the ventilation rate defined according to the forcing factor, an improved storage capacity model of the envelope and the analysis of the cooling demand. In addition, the methodology for the flexibility assessment will be applied considering different forcing factors (e.g. energy price or CO_2 intensity of the energy used) and further variations in the cluster features (e.g. insulation level, building use, building typology). Moreover, the control strategies will be improved to enhance the flexible behaviour of the whole building cluster and more detailed comfort evaluations will be performed.

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