POLITECNICO DI MILANO
Department of Architecture Built environment and Construction engineering (ABC)

EURAC RESEARCH BOLZANO
Institute for Renewable Energy, Energy Efficient Buildings group (EEB)

ENERGY FLEXIBLE BUILDING CLUSTER

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XXXII Cycle

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INTRODUCTION AND PROBLEM STATEMENT

“It is in everyone’s long-term interest to have a rapid and orderly transition towards a cleaner, more sustainable and less carbon intensive energy future.”

— Miguel Arias Cañete, EU Commissioner for Energy and Climate Action

EUROPEAN ENERGY POLICY FRAMEWORK

TARGETS

2030

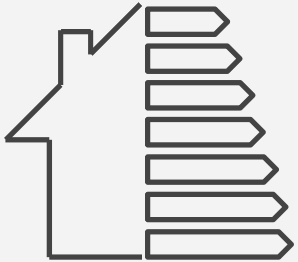
- Greenhouse gas emissions reduction;
- Share for renewable energy increase;
- Energy efficiency improvement.

2050

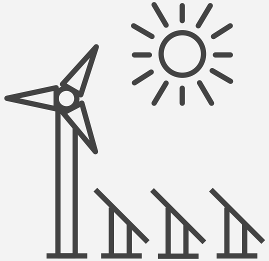
- Climate-neutral EU – net-zero greenhouse gas emissions.

EUROPEAN ENERGY POLICY FRAMEWORK

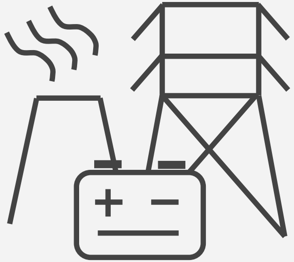
THE CLEAN ENERGY FOR ALL EUROPEANS PACKAGE



Energy efficiency first



Clean energy uptake



New electricity market design

Energy consumer empowerment

PROBLEM STATEMENT

Exponential growth of RES

Extensive electrification of the demand

Energy flexibility to preserve grid stability

- Lacks a uniform understanding;
- Need to consider buildings in a wider energy landscape.

ENERGY FLEXIBLE BUILING CLUSTER

RESEARCH OBJECTIVES

RESEARCH OBJECTIVES

01

Provide a theoretical framework for the definition of energy flexibility of building clusters.

02

Develop and test a methodology to evaluate the energy flexibility performance at building cluster scale.

03

Define first steps towards office end-user’s perspective dealing with energy flexibility in office buildings.

METHODOLOGY AND RESULTS

01 - PROVIDE A THEORETICAL FRAMEWORK FOR THE DEFINITION OF ENERGY FLEXIBILITY OF BUILDING CLUSTERS

What is a building cluster?

How to define the energy flexible building cluster?

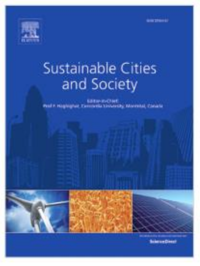
Which are the energy flexibility indicators available in literature possibly applicable at the building cluster level?

METHODOLOGY

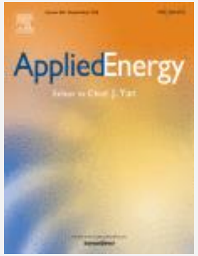
01

Literature review analysis

- Energy flexibility and building cluster concepts;
- Existing indicators for energy flexibility applicable at building cluster scale;
- Current operative approaches for energy flexibility evaluation.



Vigna I., Pernetti R., Pasut W., Lollini R. (2018). New domain for promoting energy efficiency: Energy Flexible Building Cluster, Sustainable Cities and Society 38, 526-533.

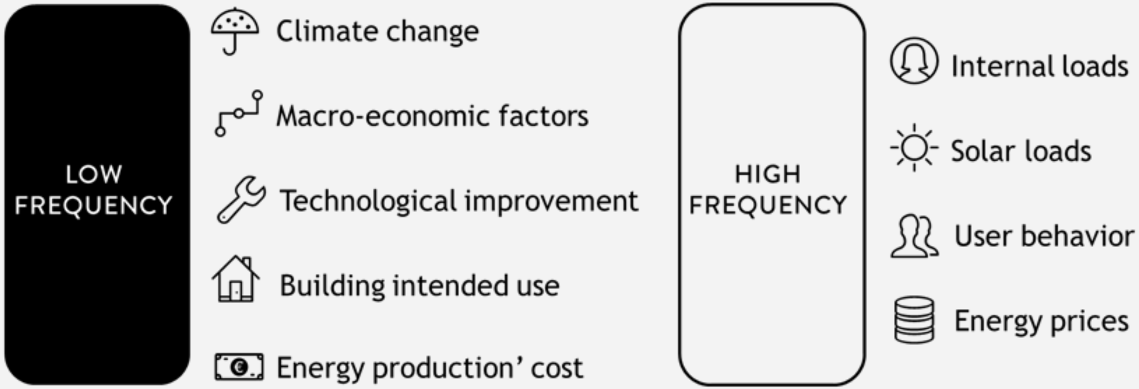


Zhang X., Lovati M., Vigna I., Han M., Gal C., Feng T. (2018). A review of urban energy systems at building cluster level incorporating renewable-energy-sources (RES) envelope solutions. Applied Energy 230, 1034-1056.

DEFINITION OF ENERGY FLEXIBILITY

"Energy flexibility represents the capability of a building to react to one or more forcing factors, in order to minimize CO_2 emissions and maximize the use of renewable energy sources".

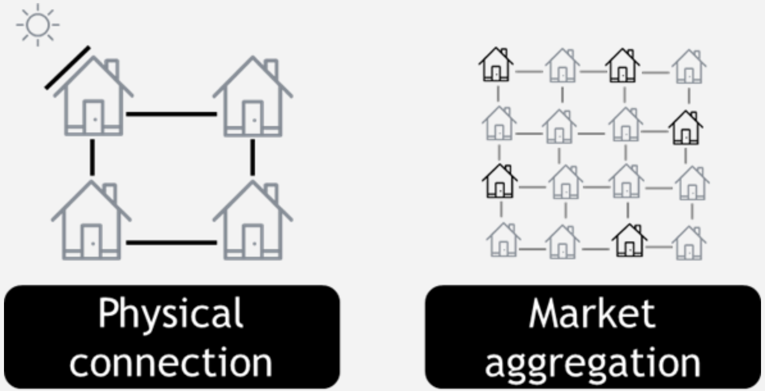
FORCING FACTORS



DEFINITION OF BUILDING CLUSTER

“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”.

BUILDINGS’INTERCONNECTION



REVIEW OF EXISTING ENERGY FLEXIBILITY INDICATORS POSSIBLY APPLICABLE AT THE BUILDING CLUSTER SCALE

INDICATORS OF ENERGY FLEXIBILITY POSSIBLY APPLICABLE AT BUILDING CLUSTER LEVEL
Costs
Specific Cost of Flexibility [1] Spark Spread [2] Total Supply Spread [2] Flexibility factor [3]
Thermal level
Available Storage Capacity [4] Comfort Index [5]
Electric level
Grid Control Level [6] Load Matching Index [7] Grid Interaction Index [7]
Thermal-Electric level
On-site Energy Ratio [8] Annual Mismatch Ratio [8] Maximum hourly surplus [8] Maximum hourly deficit [8] Ratio of peak hourly demand to lowest hourly demand [8]
Other relevant indicators
Homogeneity index [9] Smart-ready Built Environment Indicator [10]

[1] R. De Coninck, L. Helsen, "Bottom-up quantification of the flexibility potential of buildings", Building Simulation Conference, Chambéry, August 2013.

[2] A. Piacentino, C. Barbaro, "A comprehensive tool for efficient design and operation of polygeneration-based energy μgrids serving a cluster of buildings. Part II: Analysis of the applicative potential", Applied Energy 111 (2013), pp. 1222-1238.

[3] J. Le Dreau, P. Heiselberg, "Energy flexibility of residential buildings using short term heat storage in the thermal mass", Energy 111 (2016), pp. 991 -1002.

[4] G. Reynders, "Quantifying the impact of building design on the potential of structural storage for active demand response in residential buildings", PhD thesis, 2015.

[5] L. Shen, Y. Sun, "Performance comparisons of two system sizing approaches for net zero energy building clusters under uncertainties", Energy and Buildings 127 (2016), pp. 10–21.

[6] M. Ahmadi, K. Kulvanitchaiyanunt, "Optimizing Load Control in a Collaborative Residential Microgrid Environment", IEEE Transactions on Smart Grid 6 (3) (2015).

[7] K. Voss, I. Sartori, A. Napolitano, S. Geier, H. Gonzalves, M. Hall, P. Heiselberg, J. Widen, J.A. Candanedo, E. Musall, B. Karlsson, P. Torcellini, "Load Matching and Grid Interaction of Net Zero Energy Buildings", Proceedings of 8th EuroSun Conference, Graz, September 2010.

[8] M. Ala-Juusela, M. Sepponen, C. Tracey, "Defining the concept of an Energy Positive Neighbourhood and related KPIs", 2nd EC DG CONNECT EeB KPIs workshop, Proceedings of the Sustainable Places Conference, Nice, October 2014.

[9] R. Jafari-Marandi, M. Hu, O.A. Omitaomu, "A distributed decision framework for building clusters with different heterogeneity settings", Applied Energy 165 (2016), pp. 393–404.

[10] M. De Groote, J. Volt, F. Bean, "Is Europe ready for the smart buildings revolution? Mapping smart-readiness and innovative case studies", BPIE Report, 2017.

REVIEW OF EXISTING OPERATIVE APPROACHES FOR ENERGY FLEXIBILITY EVALUATION

Directive (EU) 2018/844
Smart Readiness Indicator (SRI)

Qualitative approach
according to the number and type of smart services provided by its components (multi-criteria assessment method).

IEA EBC Annex 67
Energy Flexible Buildings

Quantitative approach
based on simulations and physical indicators, according to the Flexibility Function.

01 – CONCLUDING OBSERVATIONS

- The metrics for the evaluation of building cluster energy flexibility are still fragmented and there are no indicators specifically dealing with the capability of a building to maximize the use of renewables and minimize CO_2 emissions;

- The currently proposed operative approaches to determine energy flexibility in buildings require further development.

02 - DEVELOP AND TEST A METHODOLOGY TO EVALUATE THE ENERGY FLEXIBILITY PERFORMANCE AT BUILDING CLUSTER SCALE

How to implement and practically apply to the building cluster level the IEA EBC Annex 67 approach to quantify the energy flexibility?

How to quantify the energy flexibility performance of building clusters in terms of improvement of renewable energy usage and decrease in energy-related carbon emissions?

How to define a modelling approach to determine demand profiles of building clusters?

METHODOLOGY

02

Energy flexibility quantification methodology for the building cluster scale

- Forcing factors setting
- Control strategies design
- Indicators definition
- Cluster-tailored modelling approach
- Energy and flexibility performance evaluation: case study application

Vigna I., Lovati M., Pernetti R., “Modelling approach for building cluster scale”, 9th SimAUD Conference, 4-7 June 2018, TU Delft.

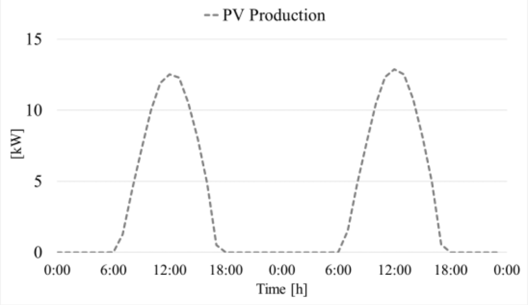
Vigna I., Lovati M., Pernetti R., “A modelling approach for maximizing RES harvesting at building cluster scale”, 4th IBPSA – England Conference BSO18, 11-12 September 2018, University of Cambridge.

Vigna, I., De Jaeger, I., Saelens, D., Lovati, M., Lollini, R., Pernetti, R. “Evaluating energy and flexibility performance of building clusters”, 16th IBPSA Building Simulation 2019, 2-4 September 2019, Rome.

FORCING FACTORS SETTING

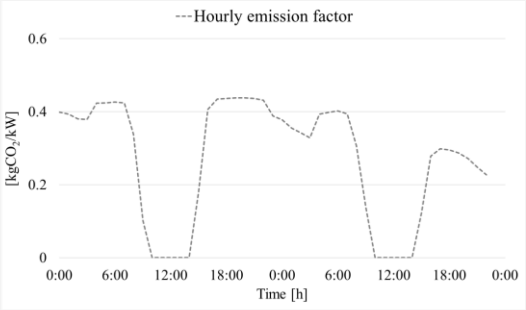
Availability of renewable energy sources

- Defined as the hourly renewable energy production profile of a photovoltaic (PV) system locally installed in the cluster.



CO_2 intensity in the national energy mix

- Defined as the hourly profile of carbon emissions content in the national electricity demand, calculated according to the European emission factors for consumed electricity.



CONTROL STRATEGY DESIGN

A rule-based forcing factor-aware control is defined, acting on the modulation of the indoor temperature set-point for affecting the timing operation and the power requested by the heating system, without compromising thermal comfort (EN16798-1, 2019):

RES availability forcing factor

PV production	Min production	⟷							Max production
Set-point variation [°C]	20	20.5	21	21.5	22	22.5	23	23.5	24

CO_2 content in the energy mix forcing factor

CO_2 content in the energy mix	Min CO_2 content	⟷							Max CO_2 content
Set-point variation [°C]	24	23.5	23	22.5	22	21.5	21	20.5	20

INDICATORS DEFINITION

Flexibility Index

In terms of ***energy efficiency***, the flexibility performance is quantified as the reduction of the energy demand not covered by renewables, i.e. the improvement of energy usage during periods of available renewable production.

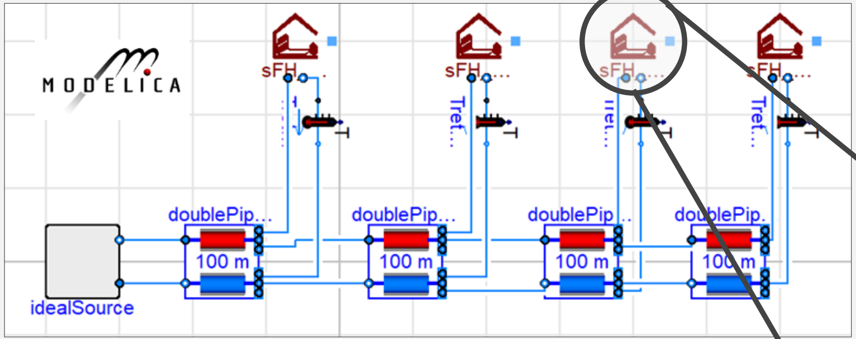
$$FI = \int \left(q_{match}^{REF} - q_{match}^{SMART} \right) dt \; / Q_{consumed}^{REF}$$

CO_2 emissions reduction

In terms of ***carbon efficiency***, the energy flexibility is quantified as the reduction of the CO_2 emissions enabled by the smart control, compared to a reference operation.

$$CO_2 \text{ emissions reduction} = \left(\frac{CO_{2\,Emissions}^{SMART} - CO_{2\,Emissions}^{REF}}{CO_{2\,Emissions}^{REF}} \cdot 100 \right) \%$$

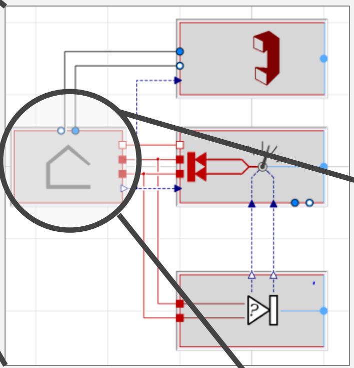
CLUSTER-TAILORED MODELLING APPROACH



Model of the building cluster integrated with the thermal grid in Dymola environment

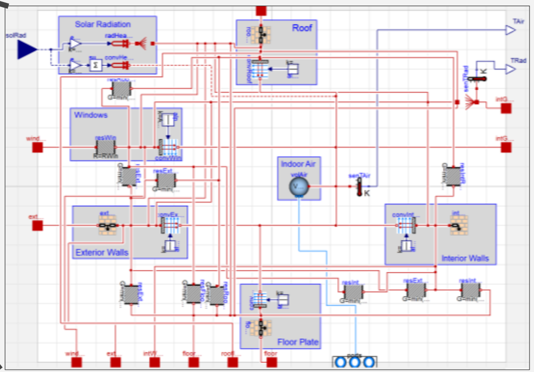
OpenIDEAS framework
Integrated District Energy Assessment by Simulation

KU LEUVEN



General layout of the Modelica building model using the templates of IDEAS-library

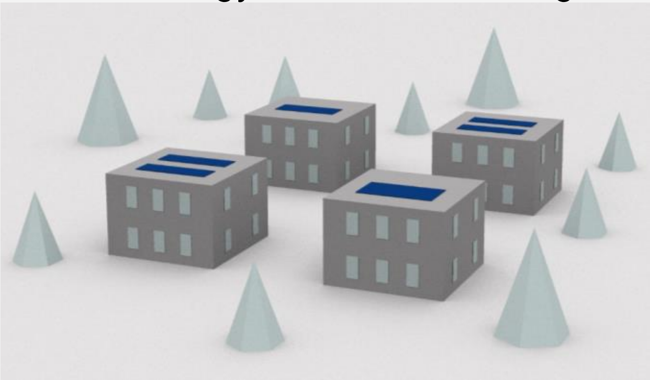
Reduced-order model of the structure of each building forming a cluster



CASE STUDY APPLICATION

Building cluster characteristics

New energy efficient buildings



Single-Family House SFH	
Volume	607 m^3
Gross heated area	174 m^2
Number of floors	2
Component area	
External walls	225.3 m^2
Roof	96.4 m^2
Ground slab	96.4 m^2
Internal walls	225.3 m^2
Floor/ceiling decks	96.4 m^2
Windows	21.7 m^2

Geometrical properties: TABULA database.

Thermal properties: D.M.26.06.2015, 2015 (nearly Zero Energy Buildings).

In each configuration, the cluster is composed of four residential single family houses, connected to a district heating system that allows thermal energy exchange between buildings.

CASE STUDY APPLICATION

Building cluster configurations

	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Building thermal mass level	Heavy (H)	Light (L)	Medium (M)	Very heavy (HH)
Structural core	Concrete	Timber	Hollow bricks	Insulating concrete
Heat capacity [MJ/K]	68	25	41	78

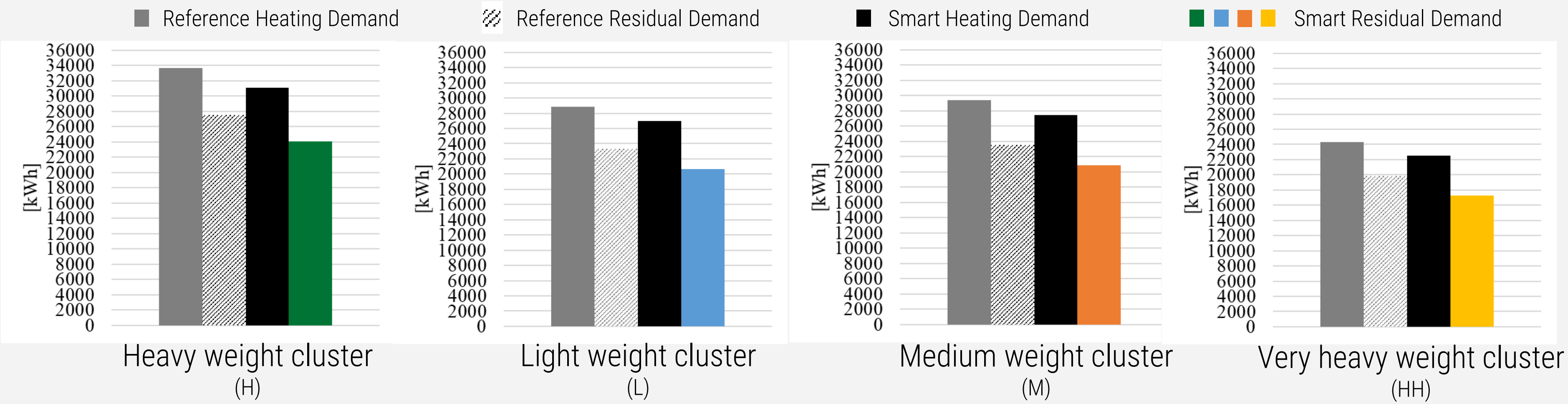
Varying parameter
Building thermal mass.

Forcing factors
RES availability
CO_2 content in the energy mix.

Boundary conditions
Bolzano weather data.

CASE STUDY APPLICATION

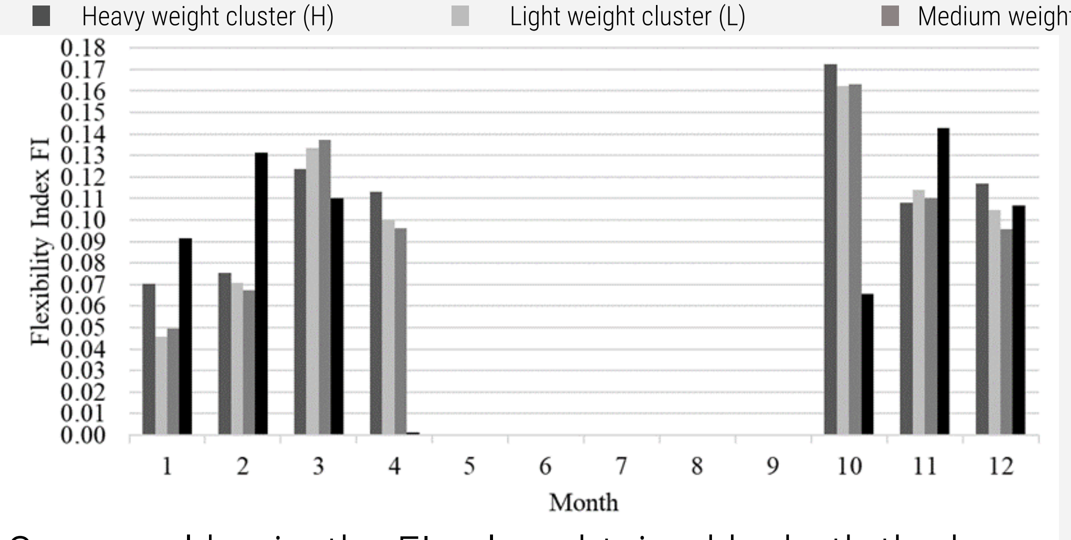
RES availability forcing factor – Energy performance

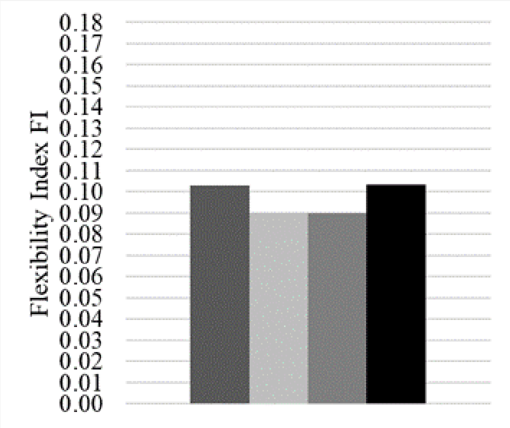


For all configurations, the smart operation improved the energy usage during periods of available renewable production, resulting in a reduction of the residual demand (i.e. the energy demand not covered by renewables) ranging from 11.5% and 12.7% compared to the reference operation.

CASE STUDY APPLICATION

RES availability forcing factor – Flexibility performance

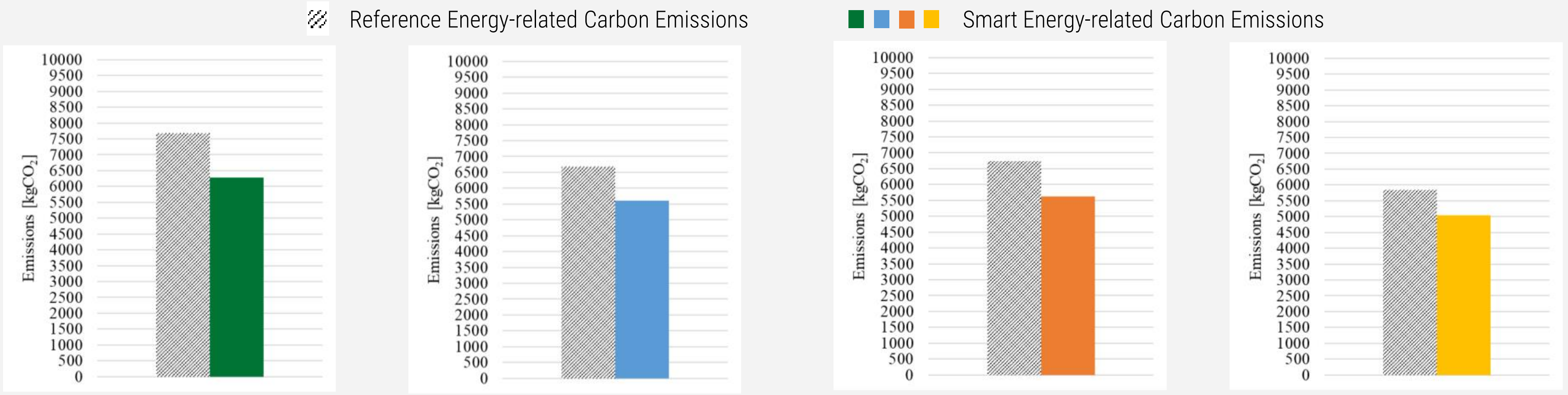




On annual basis, the FI value obtained by both the heavy (H) and very heavy (HH) weight cluster configuration was higher than the FI of the light (L) and medium (M) weight configurations. This means that, in this case, the higher thermal mass increased the flexibility index of the cluster.

CASE STUDY APPLICATION

CO_2 content in the energy mix forcing factor – Emissions reduction



Heavy weight cluster (H) | Light weight cluster (L) | Medium weight cluster (M) | Very heavy weight cluster (HH)

For all configurations, the smart operation enabled an annual carbon emissions decrease between 14% and 18%, against a slight increase (~5-6%) of the heating demand of the cluster compared to the reference operation.

02 – CONCLUDING OBSERVATIONS

- A quantification methodology for energy flexibility of building cluster is developed and two indicators are designed to evaluate energy flexibility as reduction (i) of the energy demand not covered by renewables and (ii) of the energy-related carbon emissions;

- From the preliminary case study application, the results show that:
  - the smart control of all the simulated cluster configurations enables an improvement of RES usage and a decrease in carbon emissions;
  - the possible occurring risks of thermal comfort impairment and increase in energy consumption can affect the implementation of energy flexibility.

03 - DEFINE FIRST STEPS TOWARDS OFFICE END-USER'S PERSPECTIVE DEALING WITH ENERGY FLEXIBILITY IN OFFICE BUILDINGS

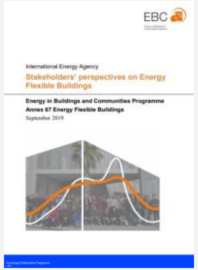
What considerations arise from the office building case study in terms of office occupants' perception of renewable energy usage and perception and attitude towards smart grid, smart appliances and smart meters?

METHODOLOGY

03

Large-scale survey

- Questionnaire design
- Survey administration
- Data analysis



Contribution in project deliverable for the IEA EBC Annex 67 project.
Vigna I., Pernetti R., Pasut W., Lollini R., Li R. (2019). Occupants in Energy Flexible Buildings – Large-scale Italian survey. In Ma, Z. (Ed.), Stakeholders' perspectives on Energy Flexible Buildings.

QUESTIONNAIRE DESIGN

An online questionnaire is prepared in two languages, Italian and German, consisting of 16 multiple-choice questions.

Survey section	Questions
Social demographic data	Gender, age, education level, position, office typology
Perception of renewable energy use	Knowledge of renewable energy sources Importance of using renewable energy
Smart grids, smart appliances and smart meters	Perception and attitude towards smart grid technologies Willingness to use smart appliances in the office Motivation to accept a flexible energy usage

SURVEY ADMINISTRATION AND DATA ANALYSIS

WHAT
Online questionnaire

WHERE
Offices of the Province of Bolzano

WHO
Office occupants

WHEN
February – June 2017

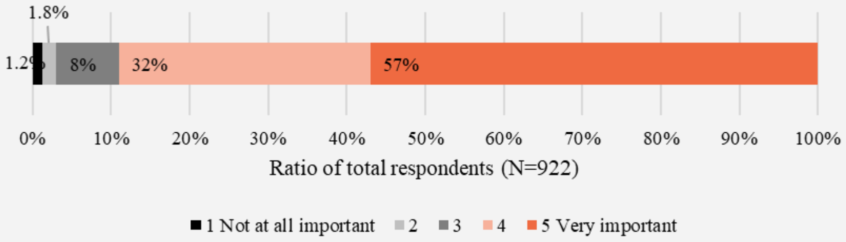
922
Completed questionnaires

Statistical analysis
SPSS software

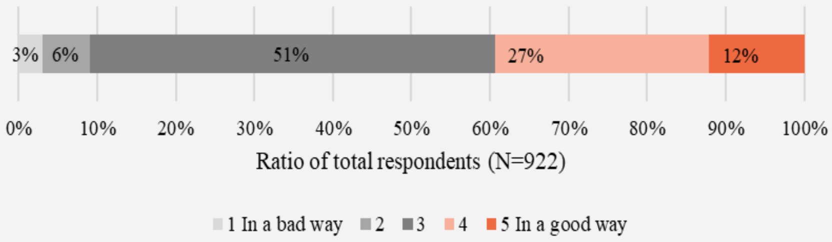
DATA ANALYSIS

Knowledge of RES and familiarity with smart grid concept

- More than 65% of the sample is aware of renewable energy sources, while the smart grid concept is unfamiliar to most of the respondents (45% never heard about it and 2% state that they perfectly understand the concept and its consequences);



Importance of using renewables in office buildings



Influence of smart grids on office occupants' activities

DATA ANALYSIS

Knowledge of RES and familiarity with smart grid concept

Familiarity with smart grid

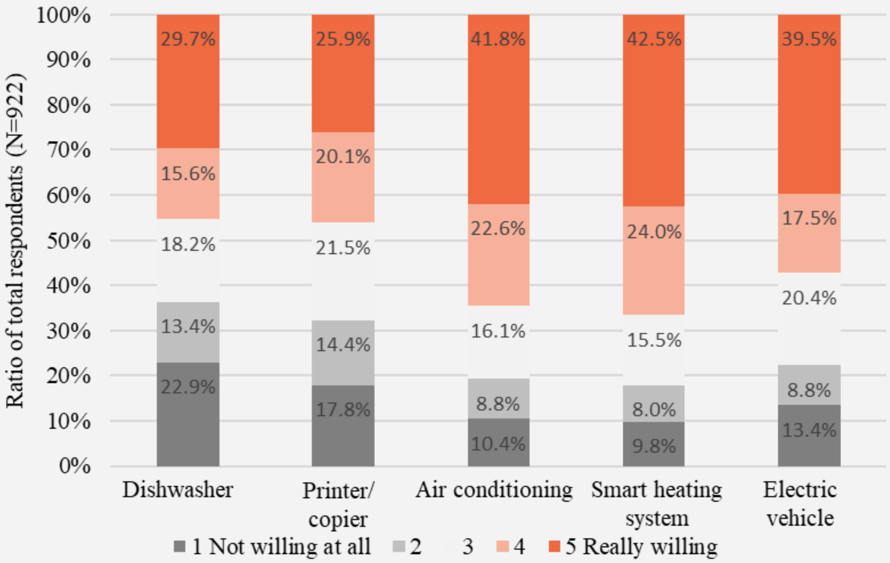
Knowledge of renewable energy sources

High educational level

DATA ANALYSIS

Willingness to use smart appliances in the office

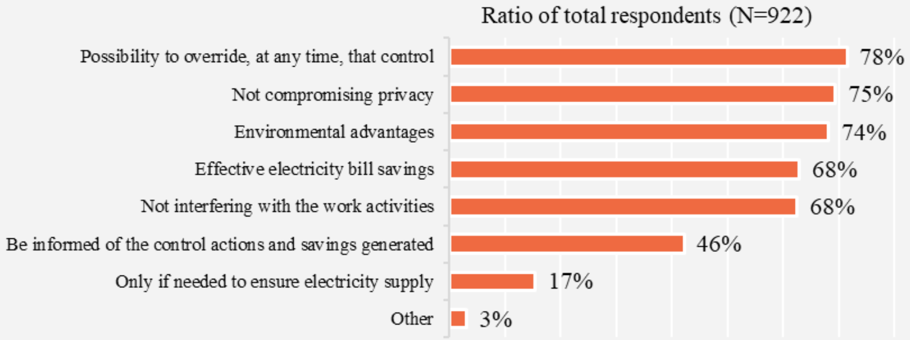
There is a lack of diversity in willingness to use remote or manual control options for smart appliances.



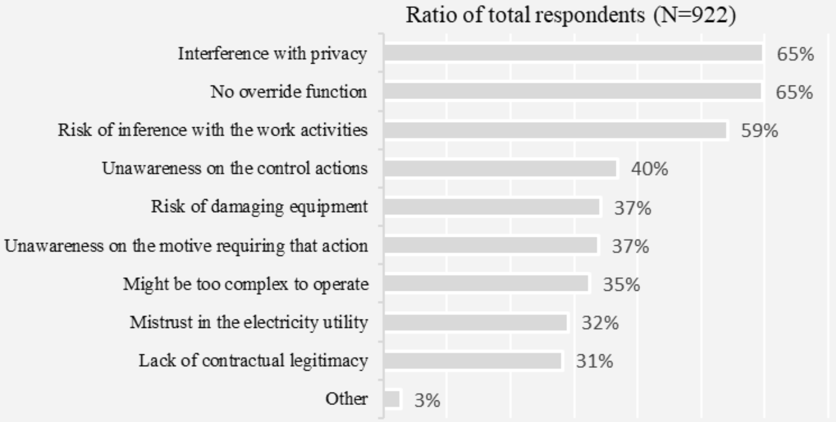
DATA ANALYSIS

Motivation to accept a flexible energy usage

Motivations



Barriers



03 – CONCLUDING OBSERVATIONS

- To investigate the office occupants' perspective dealing with energy flexibility, a large-scale survey is conducted in the office buildings of the Province of Bolzano;

- Given the limited representativeness of the sample, the outcome of this office end users analysis allows to make preliminary considerations:
- high educational level and high knowledge of renewables may positively lead to higher familiarity with smart grids;
- privacy issue can represent an important barrier in the control of smart appliances, while the possibility to override the control, not compromising the privacy and environmental advantages are important motivating factors to adopt smart technologies.

CONCLUSION AND FUTURE RESEARCH

CONCLUSION

- Considering the importance of the knowledge development for future smart energy grids, the thesis contributes to the future role of grouped buildings (cluster) in this framework by:

- drawing up a common formulation of the energy flexible building cluster concept, which emphasizes the capability to react to forcing factors in order to obtain CO_2-savings and energy matching improvement;
- informing researchers about existing energy flexibility indicators possibly applicable at the building cluster level and scoping their use.

CONCLUSION

- A quantification methodology for the practical assessment of the energy flexibility performance of building clusters has been developed:
- two specific indicators are designed to enable the evaluation of an energy flexible building cluster in terms of ***energy efficiency*** and ***emission efficiency***;
- a cluster-tailored modelling approach has been developed in Modelica language to figure out the demand profiles of building clusters interacting with the energy grids and can be applied and replicated by the scientific community.

CONCLUSION

- Building user adoption of energy flexibility solutions can influence the viability of demand response strategies. Focusing on office buildings, a large-scale survey has been conducted in the Province of Bolzano to assess occupants' perception of renewable energy and perception and attitude towards smart grid and smart technologies;

- As preliminary results obtained from the case study, office occupants were largely aware about RES and conversely, poorly familiar with the smart grid concept. Thus, policy should strengthen communicative instruments to boost office end-user's awareness towards smart grid concept, both in terms of benefits and technical aspects.

FUTURE RESEARCH

- The energy flexibility indicators and quantification methodology call for future follow-up and testing on simulated and practical cases;
- The Modelica cluster model should be improved;
- The rule-based control strategy can be enhanced through the design of a model predictive control;
- Further user research is needed in multiple regions and covering multiple types of stakeholder.

THANK YOU FOR YOUR KIND ATTENTION

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