ENERGY FLEXIBLE BUILDING CLUSTER

Ilaria Vigna

XXXII Cycle

Supervisor: Roberta Pernetti, Eurac Research
Co-Supervisor: Prof. Gabriele Masera, Politecnico di Milano
Tutor: Prof. Matteo Francesco Ruta, Politecnico di Milano
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 BUILDING 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
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?

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


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

- Climate change
- Macro-economic factors
- Technological improvement
- Building intended use
- Energy production’ cost

- Internal loads
- Solar loads
- User behavior
- Energy prices
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

- Physical connection
- Market aggregation
## 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]

---


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

A **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 CO₂ emissions;

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

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


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.

CO₂ 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**

<table>
<thead>
<tr>
<th>Set-point variation [°C]</th>
<th>Min production</th>
<th>20</th>
<th>20.5</th>
<th>21</th>
<th>21.5</th>
<th>22</th>
<th>22.5</th>
<th>23</th>
<th>23.5</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV production</td>
<td>Max production</td>
<td>20</td>
<td>20.5</td>
<td>21</td>
<td>21.5</td>
<td>22</td>
<td>22.5</td>
<td>23</td>
<td>23.5</td>
<td>24</td>
</tr>
</tbody>
</table>

**CO₂ content in the energy mix forcing factor**

<table>
<thead>
<tr>
<th>Set-point variation [°C]</th>
<th>Min CO₂ content</th>
<th>24</th>
<th>23.5</th>
<th>23</th>
<th>22.5</th>
<th>22</th>
<th>21.5</th>
<th>21</th>
<th>20.5</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ content in the energy mix</td>
<td>Max CO₂ content</td>
<td>24</td>
<td>23.5</td>
<td>23</td>
<td>22.5</td>
<td>22</td>
<td>21.5</td>
<td>21</td>
<td>20.5</td>
<td>20</td>
</tr>
</tbody>
</table>
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.

**CO₂ emissions reduction**

In terms of *carbon efficiency*, the energy flexibility is quantified as the reduction of the CO₂ emissions enabled by the smart control, compared to a reference operation.

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

\[
\text{CO₂ emissions reduction} = \left( \frac{\text{CO₂}_{\text{Emissions}}^{\text{SMART}} - \text{CO₂}_{\text{Emissions}}^{\text{REF}}}{\text{CO₂}_{\text{Emissions}}^{\text{REF}}} \right) \times 100 \%
\]
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

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

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

Building cluster characteristics

New energy efficient buildings

<table>
<thead>
<tr>
<th>Component</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>225.3 m²</td>
</tr>
<tr>
<td>Roof</td>
<td>96.4 m²</td>
</tr>
<tr>
<td>Ground slab</td>
<td>96.4 m²</td>
</tr>
<tr>
<td>Internal walls</td>
<td>225.3 m²</td>
</tr>
<tr>
<td>Floor/ceiling decks</td>
<td>96.4 m²</td>
</tr>
<tr>
<td>Windows</td>
<td>21.7 m²</td>
</tr>
</tbody>
</table>

Geometrical properties: TABULA database.


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

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

Varying parameter
Building thermal mass.

Forcing factors
RES availability
CO₂ content in the energy mix.

Boundary conditions
Bolzano weather data.
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.
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.
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?

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

Large-scale survey

- Questionnaire design
- Survey administration
- Data analysis

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

<table>
<thead>
<tr>
<th>Survey section</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social demographic data</td>
<td>Gender, age, education level, position, office typology</td>
</tr>
<tr>
<td>Perception of renewable energy use</td>
<td>Knowledge of renewable energy sources</td>
</tr>
<tr>
<td></td>
<td>Importance of using renewable energy</td>
</tr>
<tr>
<td>Smart grids, smart appliances and smart meters</td>
<td>Perception and attitude towards smart grid technologies</td>
</tr>
<tr>
<td></td>
<td>Willingness to use smart appliances in the office</td>
</tr>
<tr>
<td></td>
<td>Motivation to accept a flexible energy usage</td>
</tr>
</tbody>
</table>
SURVEY ADMINISTRATION AND DATA ANALYSIS

WHAT
Online questionnaire

WHERE
Offices of the Province of Bolzano

WHO
Office occupants

WHEN
February – June 2017
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);

![](chart1.png)

**Importance of using renewables in office buildings**

- 1. Not at all important
- 2
- 3
- 4
- 5 Very important

![](chart2.png)

**Influence of smart grids on office occupants’ activities**

- 1 In a bad way
- 2
- 3
- 4
- 5 In a good way
DATA ANALYSIS

Knowledge of RES and familiarity with smart grid concept

- Familiarity with smart grid
- Knowledge of renewable energy sources
- High educational level
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

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Ratio of total respondents (N=922)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possibility to override, at any time, that control</td>
<td>78%</td>
</tr>
<tr>
<td>Not compromising privacy</td>
<td>75%</td>
</tr>
<tr>
<td>Environmental advantages</td>
<td>74%</td>
</tr>
<tr>
<td>Effective electricity bill savings</td>
<td>68%</td>
</tr>
<tr>
<td>Not interfering with the work activities</td>
<td>68%</td>
</tr>
<tr>
<td>Be informed of the control actions and savings generated</td>
<td>46%</td>
</tr>
<tr>
<td>Only if needed to ensure electricity supply</td>
<td>17%</td>
</tr>
<tr>
<td>Other</td>
<td>3%</td>
</tr>
</tbody>
</table>

Barriers

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Ratio of total respondents (N=922)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference with privacy</td>
<td>65%</td>
</tr>
<tr>
<td>No override function</td>
<td>65%</td>
</tr>
<tr>
<td>Risk of interference with the work activities</td>
<td>59%</td>
</tr>
<tr>
<td>Unawareness on the control actions</td>
<td>40%</td>
</tr>
<tr>
<td>Risk of damaging equipment</td>
<td>37%</td>
</tr>
<tr>
<td>Unawareness on the motive requiring that action</td>
<td>37%</td>
</tr>
<tr>
<td>Might be too complex to operate</td>
<td>35%</td>
</tr>
<tr>
<td>Mistrust in the electricity utility</td>
<td>32%</td>
</tr>
<tr>
<td>Lack of contractual legitimacy</td>
<td>31%</td>
</tr>
<tr>
<td>Other</td>
<td>3%</td>
</tr>
</tbody>
</table>
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 CO₂-savings and energy matching improvement;
- informing researchers about existing energy flexibility indicators possibly applicable at the building cluster level and scoping their use.
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.
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

ilaria.vigna@eurac.edu
ilaria.vigna@polimi.it
+39 0471 055 648