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Master of Science course in Energy and Nuclear Engineering

Master of Science Thesis

A preliminary study of Demand-side Management techniques in an office building

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Abstract

The expected growth of energy demand together with the increasing awareness about climate change issues has considerably increased the international community attention towards Renewable Energy Sources (RES). Nevertheless, high penetration of intermittent RES may significantly affect electricity security. Demand-side Management (DSM) is a set of technologies and programs whose purpose is to modify the user consumption pattern. It represents a cost-effective way that can support the pursuit of a more sustainable energy sector in all its aspects: equity, security and environmental sustainability. As a matter of fact, DSM contribution may help in ensuring the electricity balance when system reliability is jeopardized, so it increases security and consequently allow a higher penetration of RES. Moreover, considering the direct involvement of demand-side, it allows the consumer to participate in the energy market, improving energy equity.

This thesis work represents a preliminary approach in investigating opportunities related to Demand-side Management practices in an office building, the Energy Center of the Polytechnic University of Turin. Firstly, it has been proposed a systematic procedure to approach to Demand-side Management in buildings, especially offices, covering from the gathering of information to strategy implementation and verification. Then, the preparation phases have been performed to the case-study analysed. An energy monitoring phase has been carried out, which for electricity consumption has been based on the evaluation of building typical consumption profiles through a clustering technique. Finally, through direct observation of energy consumption and internal temperature profiles, it has been proposed some DSM strategies which have been discussed in terms of controllability and observability of the variable interested, in order to have a qualitative measure of the flexibility potential of the building. For some cases, related benefits in terms of energy savings and consequent effects on thermal comfort have been estimated.

In general, thanks to the high sophistication of the Building Management System, the Energy Center presents good flexibility potential. Results show that two load curtailing strategies analysed for cooling and heating season, presents respectively a potential energy saving of 10% and 6% on daily consumption, without compromising the users comfort. The mild climate of Turin and a consequent considerable difference between external and internal temperature observed during night ours in summer period, suggests the implementation of a free-cooling strategy. A reduction of daily cooling load it is expected, with an anticipated turning on time for the ventilation system estimated to 2 hours. Moreover, this work has even highlighted the critical issues related to the building monitoring system which require an improvement to both allow more detailed evaluations and future implementation of DSM strategies.

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I would dedicate this work to my fantastic parents, my inestimable source of inspiration.

My Dad, Antonio, who has always been my big hero. I hope to become half the man that you are, it would be a triumph for me.

My lovely Mom, Pinuccia. I wish you could be here and looking at our promise becoming reality. It has been my greatest motivation during these years, I always feel you so close. Anyway, this is just the first goal. I promise that this is just the begin.

Turin, 18/03/2019

Vitangelo Vitulli

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Acronyms

ACER	Agency for the Cooperation of Energy Regulators
AHU	Air Handling Unit
APE	Attestato di Prestazione Energetica
ARERA	Autorità di regolazione per Energia Reti e Ambiente (Italian NRA)
BACS	Energy Management and Control System
BACS	Building Automation and Control System
BEM	Building Energy Modelling
COP	Coefficient of Performance
DER	Distributed Energy Resources (or Distributed Generation, DG)
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand-side Management
DSO	Distribution System Operator
DSP	Duct static pressure
EER	Energy Efficiency Ratio
ESCO	Energy Service Company
GTA	Global Temperature Adjustment
IAQ	Indoor Air Quality
IGV	Inlet Guide Vain
JRC	Joint Research Center
NOCT	Normal Operating Cell Temperature
NRA	National Regulatory Authorities
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RES	Renewable Energy Sources

RSE	Ricerca sul Sistema Energetico
STC	Standard Test Conditions
TER	Total Efficiency Ratio
TES	Thermal Energy Storage
TSO	Transmission System Operator

1. Introduction

"Demand-side management" (DSM), also known as "Demand-side flexibility" or "Load Management", can be defined as:

"technologies, actions and programmes on the demand-side of energy meters that seek to manage or decrease energy consumption, in order to reduce total energy system expenditures or contribute to the achievement of policy objectives such as emissions reduction or balancing supply and demand." (Warren. P. [1]).

Analysing the results obtained in two of the main macroscale energy models available, the "World Energy Model" developed by the International Energy Agency (IEA) and the "Global Multi-regional Markal" model of the World Energy Council (WEC), it is possible to observe that in forecasted scenarios, the energy consumption, and so demand, is expected to grow in the following 30-40 years, in particular in emerging economies [2, 3]. Moreover, increasingly aware of the risks related to the climate change issues, the international community goal is to satisfy the actual and future energy demand addressing sustainability. Following the definition provided by the WEC, sustainability includes the three competing aspects of the energy trilemma [3]:

- Energy equity (considers the accessibility and affordability of the service);
- Energy security (reliability of energy infrastructure and ability to balance supply and demand);
- Environmental sustainability (includes energy efficiency of both supply and demand and development of energy supply from renewable and other low-carbon sources).

Concerning the latter element, the future long-term plan of most nations is the decarbonization of the whole energy sector, including [4]:

- Decarbonization of the electricity supply;
- Electrification of heating sector;
- Increasing the deployment of electric vehicles;

On the supply side, a higher penetration of inflexible renewable energy sources (RES) can lead to difficulties in balancing supply and demand, while the decarbonization of transport and space conditioning may induce to both increasing the electricity load and the electricity peak demand, affecting the electricity security [5]. Therefore, the implementation of these measures must be conducted carefully because it could severely affect the grid security.

To date, these issues have conventionally been solved building new generation capacity and dedicated spinning reserve, usually made up of fossil fuel power plants characterized by a higher flexibility and quick response, together with the reinforcement of the grid at transmission and distribution level [4, 6].

Other proposed solutions are represented by energy storage technologies, network interconnections and demand-side management that, in an efficient combination also with the construction of new generation capacity, will be all necessary in the future to address a sustainable energy system.

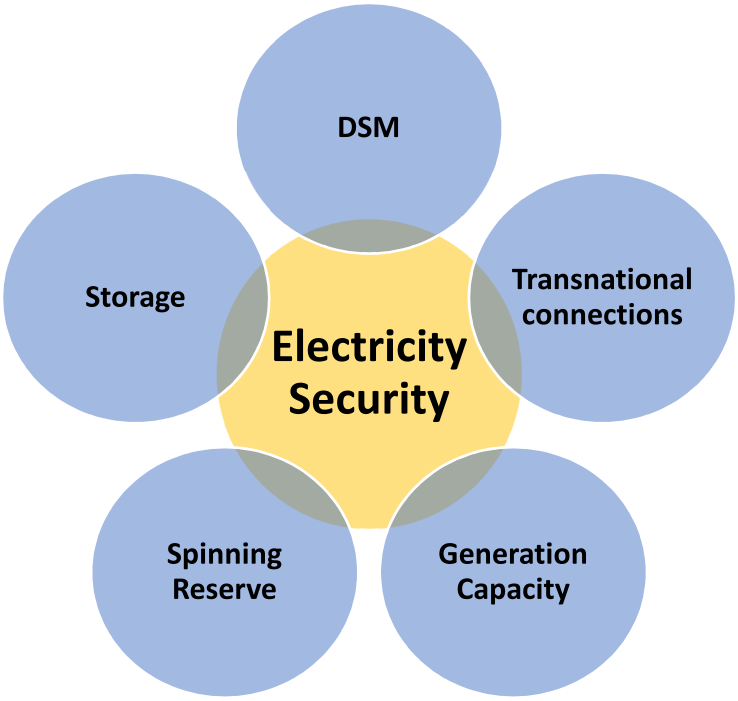

Figure 1. Electricity security resources.

Up to now, technological development of most of energy storage technologies is not enough to allow a massive storage of energy, as for flywheels, electric batteries, large thermal thanks and others. Even if pumped hydro and compressed air energy storage are commercially developed and allow the accumulation of consistent quantity of energy, they are limited by geographical constraints. Interconnections represent electricity transmission networks between different countries and are acquiring a considerable importance and attention in last years. Anyway, it must be considered that their potential is really exploited when the connected countries experience different weather, allowing to reduce renewable sources curtailment. In this context, Demand-side Management (DSM) principles reverse the way to look at the balancing issue, acting no more on the supply side but on the utility one, opening the energy market even to consumers [1], and so completely changing the energy paradigm.

Therefore, as will be further discussed in this thesis work, DSM represents a cost-effective action which could reduce the energy consumption, the peak demand, and can provide stability to the grid leading to several benefits, as [6, 7, 8]:

- Reduction of investments needed for new generation capacity;
- Avoiding the necessity of stand-by power plants for peak loads (usually coal or gas fired), which are costly and operates only in peak times.
- Decreases the need of improvement of the electricity system infrastructure which is highly capital intensive;
- Support a higher penetration of variable renewable energy sources, which affect the system balance due to their high variability;
- Reduction of greenhouse gases emission related to the electricity generation.

Moreover, DSM presents also other direct and economic benefits to the consumer as:

- A direct payment for the value of the demand-side flexibility offered by the consumer.
- Encourages market competition between different flexibility resources (both supply and demand-side) and market players. [9]

Despite Demand-side management have seen a net interest and development in last decade, its concept is not new, as a matter of fact the exploitation of demand side flexibility and its basic applications dates many years ago. Back in the ’60 and ’70 it is possible to find the first implementations of the idea under the general name of utility load management or applications of hot water tanks and off-peak storage heaters in dwellings [1]. Anyway, the first official act in which the Demand-side management has been considered a solution for the energy security has been in the National energy act 1978 in the USA, in particular in the Public Utility Regulatory Policy Act (PURPA) and the National Energy Conservation Policy Act. DSM was part of the Integrated Resource Planning (IRP) introduced in the PURPA, as tools to meet the future energy demand and provide the energy services at minimal cost to customers. These acts and the measures proposed were stipulated to face the energy crisis of those years. While, during ’90s Demand-side management have lost gradually importance, from 2000 the concept has earned an increased interest as a consequence of the low-carbon energy agenda [1, 10].

Globally, a central role is covered by the International Energy Agency (IEA) and its DSM programme. It is organized in 24 different tasks that since 1993 study and analyse different aspects of the Demand-side management with the aim to be a guideline for all the stakeholders, as governments and institutions. Italy participates to the project, represented by the Ricerca sul sistema energetico (RSE) public research institute, since its constitution [11].

Literature and regulators are focusing their attention on the figure of consumers, trying to find different opportunities to let them actively participate to the electricity system providing flexibility services through different DSM strategies and programmes. In particular, high level of consideration is devoted to flexibility resources represented by buildings. Their high contribution to the total energy consumption of about 40% has led lots of organization initiatives and literature study to investigate about their capability in providing flexibility services. One of the most important action, furtherly discussed in this work, is represented by the IEA project *Annex 67,* which is dedicated to the concept of *Energy Flexible Buildings* [12].

The goal of the presented study has been to investigate about the potential of Demand-side Management practices in an office building and the critical aspects that may be encountered in its evaluation. As a matter of fact, following the prescriptions of the literature reviewed and the experience maturated during the thesis work, the author will provide a general suggested framework to approach to Demand-side Management in office buildings. Anyway, with some consideration about the differences related to the intended use, the methodology may be also applied to other kind of buildings. Then, the presented framework has been applied to the case-study, the Energy Center (EC) of Polytechnic University of Turin. Following the mission of the Energy Center, it represents a building conceived as a common environment for public and private institutions with the aim of being a reference at national level for innovative programmes and plants related to the energy sector. In this context, Demand-side Management, which is not a greatly diffused practice in Italy, could represent an opportunity for the Energy Center Initiative in pursuing its mission. Therefore, this thesis work represents a first approach to Demand-side Management, towards the future implementation of the practices that will be analysed. As a matter of fact, in the case-study analysis, after a necessary energy monitoring phase it has been investigated about the flexibility potential of some DSM strategies that could be implemented in the future.

Therefore, this thesis work has been developed in different phases. In Chapter 2 it is discussed the first research part which aimed at overview the European policies related to Demand-side Management practices and the state of diffusion of the main programmes. The attention has then been focused on Italian context. Then, in Chapter 3 the author provides a general overview of all the theoretical aspects involved in studying Demand-side Management in buildings context. In Chapter 4 it is discussed the suggested framework to approach in buildings, with a focusing to the critical aspects that may encountered in medium-large commercial buildings. Then, in Chapter 5 it is analysed the Energy Center Case-study and in Chapter 6 the conclusion of the work is given. Finally, a compendium of some theoretical backgrounds, data sources and assumptions used in Chapter 5, are reported in Chapter 8, as an Appendix.

2. Context of Demand-side Management

2.1 Policies

The European Union is working from decades, as showed in Figure 2, in planning programmes and policies towards a sustainable energy sector, pushing toward affordability, energy security and decarbonization. The imminent goals of its energy agenda, known as 20/20/20, include the reduction of greenhouse gas emissions by at least 20%, an increase of share of renewable energy to at least 20% of consumption, and the assessment of attainment of at least 20% in energy savings with respect to the 1990 levels, by 2020. While, looking at 2030, those targets are increased to 40% reduction of GHG emissions and 27% or renewable share and energy savings [13]. Recently the target proposed has been revised and enhanced to 32% of renewable share and 32,5% of energy efficiency by 2030. [14]

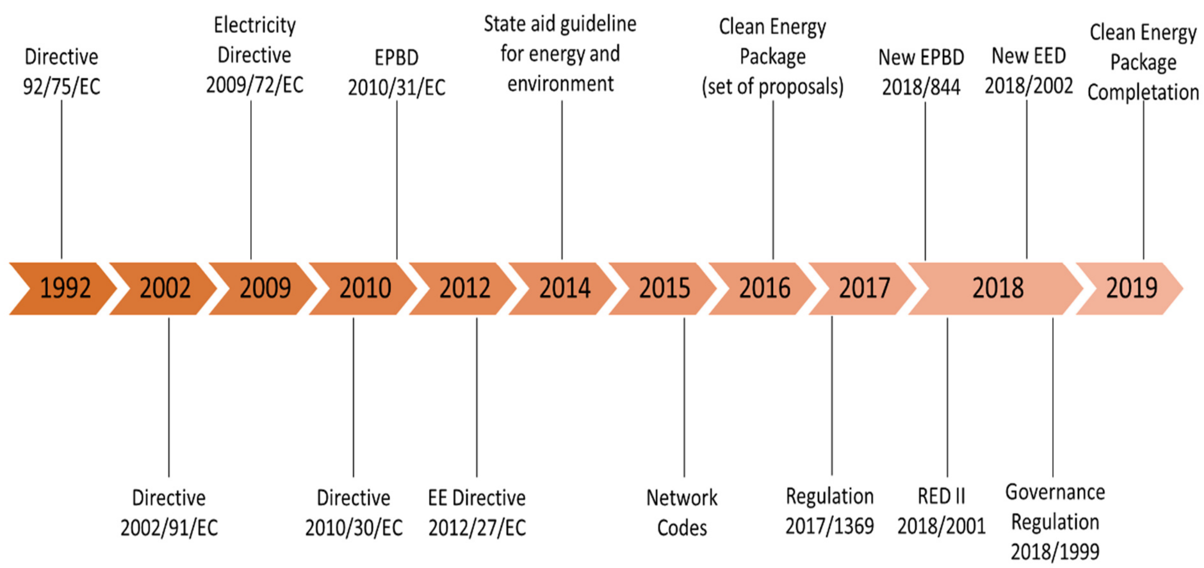

Figure 2. Timeline of main European Policies related to DSM.

In this context, demand-side management programmes can be useful in pursuing energy savings targets and in helping the increase of renewable share providing at the same time a positive contribution to the adequacy of the electricity system. European Union recognised those important roles of DSM and is strongly pushing in investigating and developing demand-side resources in several policy acts, going from energy efficiency measures to demand-response programs.

The first important regulation step towards the improvement of energy efficiency has been represented by the **Directive**[1] **92/75/EC** (then repealed by the **Directive 2010/30/EU** [15] and then by the **Regulation**[2] **2017/1369** [16]) which introduced the energy labelling for the energy related product, that are the ones that directly affect the energy consumption. All the appliances that are sold in Europe are categorized following a scale (to date, from A+++ to D) that reflect their energy consumption, while minimum energy efficiency standards and labelling are indicated for different products. Those labelling must be communicated to the consumer that so is helped doing the best choice in the purchasing phase, pushing toward an improvement of the efficiency of the appliances stock in Europe. Following the development of the energy efficiency of all the utilities, the recent regulation provides the update of the labelling to new standards [16].

In the same way, with a first version of the **Energy Performance of building Directive (EPBD)** represented by the **Directive 2002/91/EC** (replaced by the **Directive 2010/31/EU** [17], recast proposed in 2016), the Energy Performance Certificates (EPCs) for buildings were introduced. As for the labelling for energy related products, the EPCs classify the buildings with respect their energy performances in a scale that each country must establish.

The EPBD introduced the requirement of implementing energy efficiency measures in connection to major renovations to encourage more ambitious renovation activities. It asks to Member states to introduce a cost-optimal system for energy performance requirements for new buildings, as well as for the development of economical support instruments to enhance the renovation of the building stock. In the context of the EPBD it is also include the concept of new (nearly Zero Energy Building), which are buildings with a very small energy consumption, and all the new buildings must belong to this category by the 31 December 2020. Besides, the EPBD pushed member states to encourage the diffusion of smart meters in buildings inviting Member States to produce and submit national plans for their diffusion [13] [17].

The first act of the EU that introduced properly the concept of DSM is the **Electricity Directive (2009/72/EC)** [18] which belongs to the **Third Energy Package** of the European Union and provides a definition for the demand-side management/energy efficiency stating that:

"*energy efficiency/demand-side management' means a global or integrated approach aimed at influencing the amount and timing of electricity consumption in order to reduce primary energy consumption and peak loads by giving precedence to investments in energy efficiency measures, or other measures, such as interruptible supply contracts, over investments to increase*

[1] The Directive is a legislative act of the European Union which sets targets and achievements that Member States should pursuit but left to them the individuation of proper modalities.

[2] The Regulation is a legislative act of the European Union that Member State must receipt and apply as it has been drafted.

generation capacity, if the former are the most effective and economical option, taking into account the positive environmental impact of reduced energy consumption and the security of supply and distribution cost aspects related to it;" (Art. 2.29)

The EU recognised the impact of DSM on security of supply, considering it as an alternative to new generation capacity, its contribution for the fulfilment of environmental goals and its positive effect related to the reduction of both energy consumption and peak load (Art. 3.2, 8, 25.7). It is even recognised the relevant role of start meters. As a matter of fact, the directive states that Member States shall incentivise the diffusion of smart meter setting the target to 80% by 2020. [18].

Another important European directive that encompassed all DSM aspects is the **Energy Efficiency Directive (2012/27/EU)** [19] which establishes a common framework for the Member States in pursuing the 20% target of 2020 and to go further beyond that date.
Considering the energy efficiency aspects, the directive complements the EPBD requires to encourage major renovation and to establish strategies for the renovation of national building stocks (Art.4), considering that public buildings should cover an exemplary role (Art.5).
Moreover, each member should establish an energy efficiency obligation schemes in order to ensure that suppliers and distributors improve their energy efficiency of 1,5% per year until 2020. Often, those targets are achieved by suppliers and distributors through interventions to their customers (Art. 7). The amendment of 2016, as will be further discussed, proposes to extend the target beyond that date, including also other measures in additions to those obligation schemes.
In Art. 9, the commission highlight the importance of providing customers with individual meters that reflect their consumption, when the intervention is technically, and financially possible and long-term potential savings are estimated. While, in Art. 14 which is referred to the supply-side, EU promotes the use of cogeneration as an effective way to improve the energy efficiency and as a good contribution to reach the energy saving targets.
Concerning the aspects related to energy efficiency measures, as will be further discuss in the next paragraph, this directive provides the definition of Energy Performance Contracts (EPC) and energy service providers, mainly represented by Energy Service Companies (ESCOs),
In addition to energy services, the directive states that it is possible to use also alternative measure to achieve the established targets. Those measures are represented by the Demand Response that is framed in the new concept that do not see any more the consumer as passive actor of the energy market. The directive stresses even more the importance of implementing those measures that can provide a reduction or shift in load with a consequent saving in final energy consumption, generation, transmission and distribution. Moreover, because DR could be also related to the response to price signal, Member States should control that "*national energy regulatory authorities are able to ensure that network tariffs and regulations incentivise improvements in energy efficiency and support dynamic pricing for demand response*

measures" (Art. 1.45). The most important part of this directive is the Art. 15.8 that states that Member States shall promote the participation of consumers to the whole energy market, either individually or through the figure of an aggregator. Besides, it is also stressed the importance for the TSO and DSO to threat both supply and demand resources in an equal way in meeting the requirements for balancing and ancillary services.
Finally, in ANNEX XI it also summarizes criteria for energy network regulation and for electricity network tariffs that must reflect the cost-savings derived from demand-side and demand response measure. Moreover, regulation and tariffs should not prevent services for demand-side management measures, including generation sources close to the consumption location and energy storage and should support dynamic pricing for demand response by final customer. [19]

Other legislative texts that support DSM programs are represented by **The Network Codes** (in particular the Balancing guideline [20], the System Operations guideline [21] and the Demand connection code [22]), a series of rules and guidelines delineated by the European Network of Transmission System Operator (ENTSO-E) in collaboration with the Agency for the Cooperation of Energy Regulators, whose aim is to support the European electricity market integration and development. Those rules are essential for the DSM because establish terms and condition for the participation of DSM providers to the market.

Then it is important to consider the **State aid guideline for Energy and Environment (2014-2020)** which represent a communication of the European Commission, with which the Member States can introduce the capacity mechanism. The relevant aspects regard the fact that the Commission invite to consider also alternative ways of achieving the generation adequacy, among which DSM, and so to design the measure in order to allow any capacity that can effectively contribute, to participate to the measure. This guideline has been essential for all the Member states that have revised or planned their capacity mechanism, because ensure that demand-side resources are not excluded.

Finally, it is essential to discuss about the most recent initiative, the so-called **Clean Energy Package.** It has been conceived in 2016 with a set of legislative proposals that regarded different aspect of the energy sector among which energy efficiency, renewable energy, design of electricity market, security of supply and governance rules. The current situation of the proposals has been summarized in Table 1, where it is possible to observe that all of them have reached the conclusion of the negotiation phase, while not all have reached the final publication that is planned for the first half of 2019. This set of rules has been conceived by European Union with the aim of pursuing the creation of an Energy Union and the assessment of the Paris Agreement's target, therefore accelerating the transition to a clean energy innovation.
The main innovative aspect that is important to discuss, even because strictly related to DSM activities, is the willing of EU to providing the consumer a central role empowering them to be

enabled to directly control their choices, because of their consideration of consumers as "*drivers of the energy transition*". Concerning this, it is relevant to start this consumer empowering providing them better information about energy consumption and consequent cost.
Then, new proposals and approved regulation follows four main objectives related to the consumer as:

- Facilitate production of their own energy and managing of it in the best way;
- Active participation even through demand-response services directly or through aggregation;
- Be more involved in the system and be able to respond to price signals;
- Adoption of smart technologies, improving energy consumption and comfort.

Considering the new drafting of the **Energy Performance of Building Directive (EPBD)**, its purpose is to enhance the investment in building renovation in order to accelerate the actual renovation rate towards the decarbonization of the building sector.
An important aspect of this Directive is related to the introduction of the so-called "*smart readiness indicator"*, which indicates the capability of a building unit to modify its operation following the occupants or grid necessity and to improve its efficiency and performance.

Moreover, the Annex IA establish even that the methodology to evaluate such indicators must take into account:

- The ability to maintain energy performance and operation of the building;
- the ability to adapt its operation mode in response to the needs of the occupants;
- the flexibility of a building's overall electricity demand, including its ability in participating in implicit or explicit Demand Response programs;
- the presence of smart systems such as smart meters, building automation and control systems and their interoperability.

In general, the directive strongly pushes to digitalization, through the concepts of smart buildings and smart meters. ICT and IOT technologies will became soon central players of the building sector. Moreover, considering one of the principal objectives of this policy package, represented by moving of the consumer to a central role in the energy market, the data collected thanks to the digitalization should be useful in make him more aware about the energy consumption and the related impact. The behavioural aspect of the consumer is considered as one of the principal factors that affects the energy consumption.

About the new **Renewable Energy Directive (RED II)**, the most important modification regards the revision of the gross renewable share to 2030 that has been increased to 32%, with a possible revision in 2023. Together with the updated target, there are indication about the improvement of the design a stability of the support schemes for the renewable sources and the establishment of a clear and stable framework for the self-consumption.

	European Commission Proposal	**EU Negotiations**	**European Parliament Adoption**	**Council Adoption**	**Official Journal Publication**
Energy Performance in Buildings	30/11/2016	Political Agreement	17/04/2018	14/05/2018	**Directive (EU) 2018/844** (19/06/2018) [23]
Renewable Energy	30/11/2016	Political Agreement	13/11/2018	4/12/2018	**Directive (EU) 2018/2001** (21/12/2018) [24]
Energy Efficiency	30/11/2016	Political Agreement	13/11/2018	4/12/2018	**Directive (EU) 2018/2002** (21/12/2018) [25]
Governance	30/11/2016	Political Agreement	13/11/2018	4/12/2018	**Regulation (EU) 2018/1999** (21/12/2018) [26]
Electricity Regulation	30/11/2016 [27]	Political Agreement	-	-	-
Electricity Directive	30/11/2016 [28]	Political Agreement	-	-	-
Risk Preparedness	30/11/2016 [29]	Political Agreement	-	-	-
ACER	30/11/2016 [30]	Political Agreement	-	-	-

Table 1. State of play of Clean Energy Package set of proposals.

The new **Energy Efficiency Directive** present the revision of the target to 32,5% in 2030, with a possible modification in 2023. Concerning buildings, it presents a particular attention on monitoring systems in particular for heating, cooling and domestic hot water.

The most important contribution of the **Governance Regulation** is about the so-called *"integrated national energy and climate plans"* which Member states shall notify to the

Commission every 10 years starting from 2019. Those reports shall include the planned national objectives, targets and contributions for the five dimensions of the Energy Union, which are represented by Decarbonization, energy efficiency, energy security, internal energy market and finally research, innovation and competitiveness. About the internal energy market, member states have to report the objects related to the increase of the system flexibility, through instruments that can include aggregation and Demand Response services.

Finally, great attention has to be focused to the two interventions on the Internal Electricity Market: the regulation and the directive. The intention is to re-design both wholesale and retail market with the final aim of empowering and putting the consumer in a central role. The main objective in letting the consumer participating in the market is to increase its flexibility and so increasing the security of supply, letting renewable share growing with reduced consequent burdens. About the wholesale market, the main interventions regard the removal of maximum prices of electricity, in order to make prices more reflective of the real value of electricity and so enhance investments in flexibility, as Demand Response. The latter is confirmed as a resource for all electricity market together with storage and generation.

Consumers and the so called *"energy communities"* will be able to actively participate to the market and every consumer will be able to offer demand response services, receiving remuneration, independently or through the figure of an aggregator. In this context, the intervention includes the obligation for all the Member States to introduce a clear legal framework for the participation to the market of the aggregator figure, defining their roles and responsibilities and facilitating their operation framework.

The interventions highlight even more to provide consumers of dynamic pricing contracts which allow them to respond to price signals and actively managing their energy consumption. Moreover, the proposals provide a clear definition of Smart Meter whose principal characteristic is the two-way communication ability, therefore it has to be able to transmit but even receive data for information, monitoring and control purposes.

Concerning the Electricity Directive, the most recent update is represented by the **Document 5076/2019** [31] drafted by the Council of the European Union which discuss about the final compromise text resulted from the agreement, which represent the most similar to the future definitive edition. In a general view, the main improvements with respect to the proposal regard the extension and better clarification of great part of the concepts presented. For example, it has been provided a clear and extended definition of Active Consumer which provide an idea of all the roles that citizen would cover in the near future:

"Active Consumers are single or jointly acting final customers that consume, store, with respect to permissions and boundaries, or self-generate electricity and participate in flexibility or energy efficiency schemes."

Therefore, this document stress even more the importance of the new role of consumers, clarifying which are their rights but even duties and responsibilities in their participation. The new form of the market may ensure the absence of discriminatory procedures for consumer active participation, which must always be voluntary. Concerning Dynamic Tariffs, consumers should be enabled to choose these kinds of contracts being properly informed about costs and event risks. Among the different arguments treated, as already done in the proposals, great importance is given to Demand Response services, about which several briefs are given to Member States. They have to develop a solid national regulatory framework for all the possible participants, in particular for the figure of Aggregators. Following the statements of the Directive, coordinating the action of all the actors, Member States should incentivise the exploiting of flexibility even at distribution level.

In this work the author has just presented an overall idea of the European Policy path until now, focusing the attention on aspects related to DSM. Therefore, readers are invited to consult the original references for deepening understanding.

2.2 Development status

In order to have an idea about the state of art of Demand-side Management in Europe, it is necessary to distinguish at least the principal categories that will be defined and explained in detail in Chapter 3.1.

Starting from **Energy Efficiency (EE)**, a way to assess the status and so the diffusion of practices related to it is to consider the development and spread of Energy Performance Contracts (EPCs) and Energy Service Companies (ESCOs). These two concepts are strictly linked and have been defined in the Energy Efficiency Directive of 2012 [19].

EPCs regard contracts which are stipulated between the end-user and an energy service provider, usually an ESCO, for the implementation of EE improvement projects. Generally, the EPC are formulated in such a way that divide the gained value between the ESCO and the customers.

Depending on the financier of the interventions it is possible to distinguish two main typology of EPC contracts:

- Guaranteed savings model, in which the customer finances the investments, but the ESCO guarantee the savings.
- Shared savings model, in which the ESCO finances and guarantee the savings, but take great part of the interventions profit.

To date, great part of the investments in energy-efficient measures have been involved for three main categories of HVAC, lighting and appliances, because of their shorter payback period with respect to other renovation interventions. [13]

The Joint Research Center (JRC) have analysed the European ESCO market, collecting all the information gathered in a report that provide an overall picture of its status. As it is possible to see in Figure 3, European ESCO market present a large diversity with lots of countries that presents less than 20 ESCOs in their market. Anyway, through the analysis of the NEEAPs, JRC found that there is an increase in the development of ESCO market to 2016 which is mainly driven by regulatory frameworks, financial incentives and increasing awareness. [32]

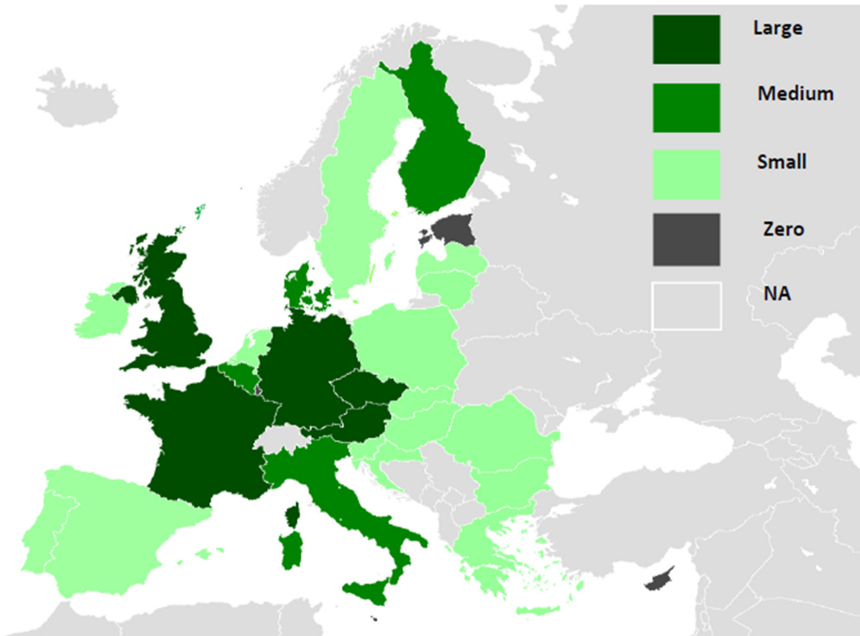

Figure 3. ESCO market status in EU. [32]

While, concerning **Explicit Demand Response**, its development status in Europe is very different from country to country. Two study, conducted by the JRC in 2016 [8] and the Smart Energy Demand Coalition (SEDC) in 2017 [9], analyse the diffusion of the Explicit DR providing approximately the same results that show some virtuous application cases but even barriers that have to be overcame. Anyway, considering the reports published in the previous years by the same institutions, it has been observing an overall increase of interest in enabling DR in most of the countries.

Looking at the JRC work, the authors have divided the EU countries into three groups with respect to the status of their regulation concerning Demand Response [8]:

- First group: includes those countries which have not properly engage with Demand Response reforms. They have received and transposed obligations of European

Directive but not in fact. This means that, in those countries DR is allowed but there are no regulatory frameworks that enable demand side resources to participate in the market. In particular, there are no rules that define the role of the independent aggregators and DR service providers. Therefore, it is possible to practice the DR, but it is still necessary to define the means with which aggregators can offer demand side resources, the way to measure the payment and the markets in which consumers or aggregator can participate with DR resources. In this group there are Portugal, Spain, Italy, Croatia, the Czech Republic, Bulgaria, Slovakia, Hungary, the Baltics, Cyprus and Malta.

- Second group: includes those countries whose have limited the aggregators to service provider to the retailers instead of independent players that propose offers to the consumer. This is an important factor, because the programs implemented will be the one positive for the retailers which could not be the same of those positive for the consumer. Moreover, consumer could not be offered a clear value for their flexibility, but it will be included in the electricity bill, aspect that lead them to accept the entire package or to reject. In this group there are Germany, the Nordics, the Netherlands and Austria.
- Third group: includes those Member States which enable both DR and independent aggregation. These markets represent the most developed in Europe, even if they still present some barriers and technical modalities that have to be improved. In this group there are Belgium, France, Ireland and the UK.

On the other hand, in the SEDC report, although there are some differences related to some differences in the countries analysed and the fact that it has been drafted the following year, the main results are mainly the same, individuating four main groups as showed in Figure 4. Anyway, it is important to note that the classification provided by this institution has a relative base, because compare the countries and their DR reforms development in relation to each other, therefore even “commercially developed” classified Member States still presents negative aspects that must be improved. Therefore, it is possible to distinguish:

- A first group of countries which presents the most developed status, providing the best conditions for the inclusion of DR in the markets, includes Switzerland, France, Belgium, Finland, Great Britain and Ireland. The main similar aspects similar in these countries are represented by the enabling of DR participation in a number of markets and the institution of independent aggregation. Anyway, these countries still present problems and barriers that must be overcame, in particular related to measurement and verification procedures.

- A second group that includes Austria, Denmark, Germany, Netherland, Norway, and Sweden. These countries still present some regulatory barriers that impede the participation of DR in the market. Even though several energy markets are already opened to demand-side resources, its participation is made difficult due to technical requirements, lack or clear roles and responsibilities and unequal competition with traditional supply sources. Anyway, all these countries are working to find solutions to these problems.
- A third group of countries which have performed a preliminary exploration of Demand Response measures as Poland and Slovenia. With respect to the previous report no changes have been made to their regulatory framework, impeding a further participation of DR to the electricity market.
- A forth group includes Spain, Portugal, Estonia and Italy. These countries have not yet allowed to demand-side resources to participate to their energy market. [9]

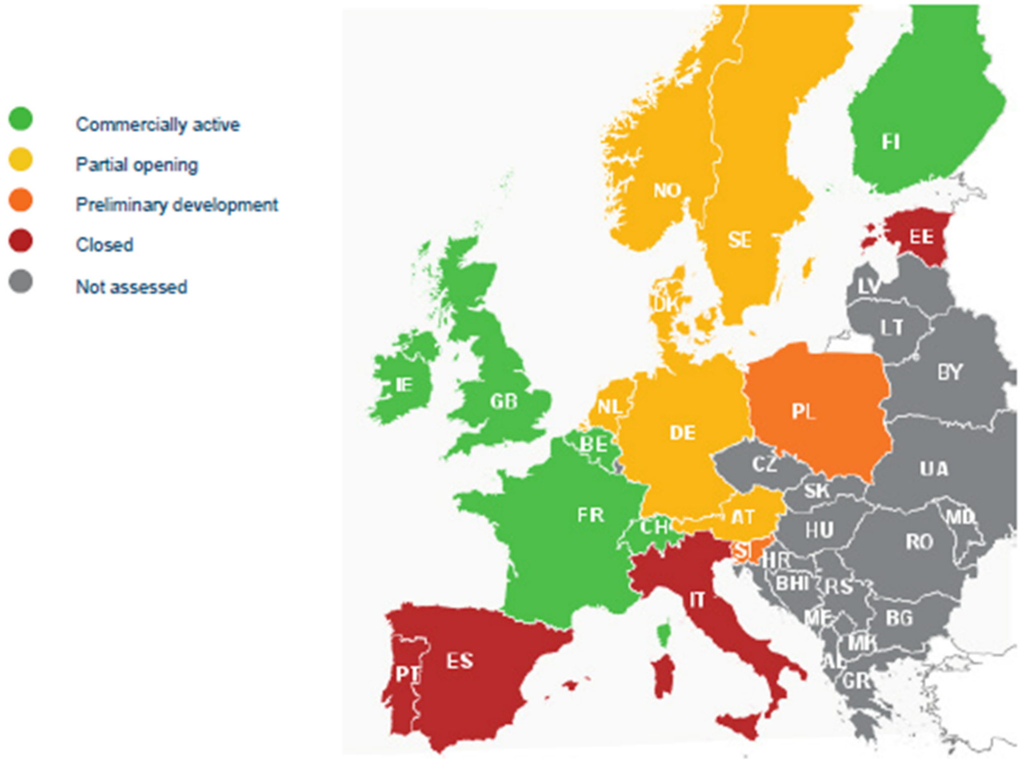

Figure 4: SEDC, Map of Explicit Demand Response in Europe in 2017. [9]

Anyway, it is important to note that the Italian situation is already evolving. As a matter of fact, Italy has started to take measures for enabling DR, exploring its potential and application in the market also through pilot projects. The Italian situation will be analysed with more details in the following section.

The other typology of Demand Response is the Implicit Demand Response, also known as price-based DR. It involves the participation of the consumer through the use of dynamic tariffs, a concept that will be discussed in the following chapters.

As already exposed for the Explicit Demand Response, even for dynamic tariffs the development status in Europe is not homogeneous. The Agency for the Cooperation of Energy Regulators (ACER) has conducted a survey which shows that approximately 80% of the reviewed Member States adopt time-based tariffs in electricity supply. Anyway, as it is possible to observe in Figure 5, those kinds of tariffs are in general available to all categories of consumers but adopted less frequently by residential ones.

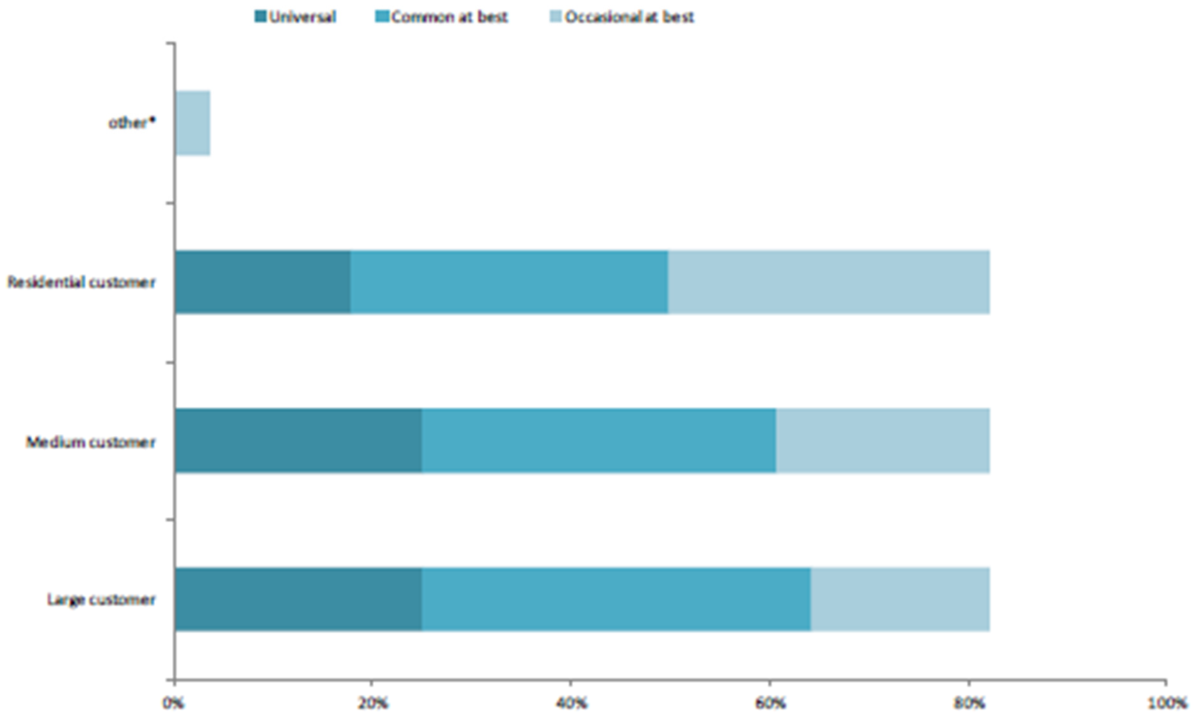

Figure 5. Use of time-based tariffs in electricity supply in % of Member States. [5]

Moreover, as it is possible to observe in Table 2, there is not homogeneity even for the typology of tariffs applied with most popular time-based pricing programs diffused in Europe are represented by on- and off-peak tariffs. Among all the Member states there are some virtuous countries which have adopted different forms of time-based tariffs since different years.

Type of dynamic tariffs	Member States
Seasonal	FR, HU, PT, RO, UK
On-peak	BE, HR, CZ, DK, FI, FR, DE, HU, IE, IT, LV, LT, NL, PT, RO, ES, SK, UK
Off-peak	AT, BE, HR, CZ, DK, EE, FI, FR, DE, EL, HU, IE, IT, LV, LT, NL, PT, RO, ES, SK, UK
Other time of use	CZ, DK, FI, IE, IT, LU, NL, ES, SE, UK
Critical Peak	FR
Real time	AT, BE, EE, FI, DE, NL

Table 2. Type of time-used tariffs adopted in European Member States.

Finland, in addition to flat tariffs, allow consumers to choose among:

- Two different TOU tariffs adopted by approximately the 80% of consumers;
    - Seasonal
    - Day/night tariff
- Real Time Pricing: based on the results of the wholesale market and adopted by approximately the 10% of the consumers. The application requires the installation of a smart meter to allow the consumer paying according to his hourly consumption and the price for that hour.

Another virtuous example is represented by the **France** that adopted the so-called Tempo-tariffs since 1995. This kind of tariff combines the structures of the Time-of-use (TOU) and Critical peak pricing (CPP). Moreover, it considers three types of days during the year, dividing each day in two periods obtaining 6 price levels. For each day of the year it is assigned a colour whose quantity of days pre-planned while the kind of day is assigned the day before. Therefore, it is possible to distinguish:

- Red days: less frequent with a high price.
- White days: characterized by medium price level.
- Blu days: which represent more frequent and cheaper days.

This represent a very effective program which have presented a maximum saving in energy consumption of 45% with a bill saving for the consumer of about 7% [33] [34].

2.3 Enabling Technologies

Together with this increasing interest related to its multiple benefits, mainly push to the actual worry concerning the energy security, DSM development has been surely strongly pushed by the spreading of ICT technologies. In particular, Smart Meters and Building Automation and Control Systems (BACS), are generally considered as “enabling technologies” [35] [36] [37] [38] for the development and implementation of DSM strategies.

Concerning the first, as shown in Figure 6 that collect all the minimum requirements that a Smart Meter must present, it is possible to individuate the main characteristic related to DSM, the two-way communication ability. It is necessary in order to let consumers receiving system operator or third-party signals for a certain contracted service or to receive price signals related to dynamic schemes. As already mentioned in previous paragraphs, European Union has set a target of 80% for Smart Meter roll-out and new proposal for electricity directive states that all consumers should be allowed to require its installation. Concerning its deployment in EU Member States, as shown in Figure 7 there are some virtuous countries, among which Italy, that have already reached the target years ago. Their strong deployment was mainly driven by the intention to reduce high labour cost related to monthly manual electricity consumption accounting. As a matter of fact, up to now the great part of countries that have deployed Smart Meters use them for remote reading but not for DSM purposes.

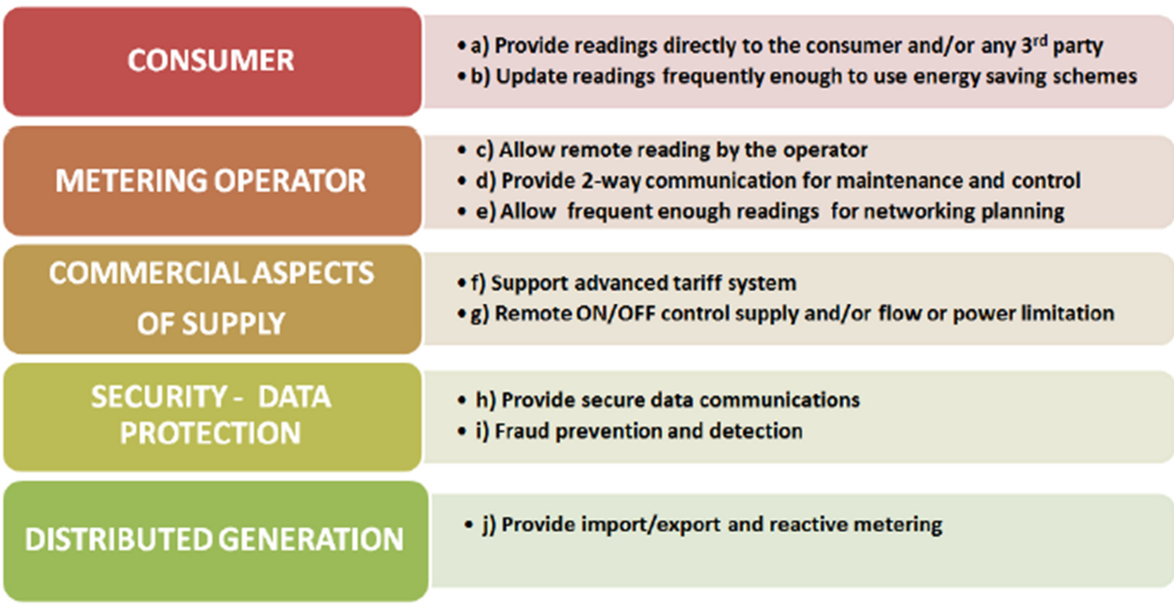

Figure 6. Smart Meter minimum functional requirements [39].

On the other hand, BACS are particularly useful for the implementation of Flexibility Strategies at the utility level. For example, it can be programmed to curtail or reduce the energy consumption of some of the equipment installed as response to the request of the System

Operator or the aggregator. Its deployment has been particularly useful for the equipment management of medium-large buildings and even more, clusters of buildings.

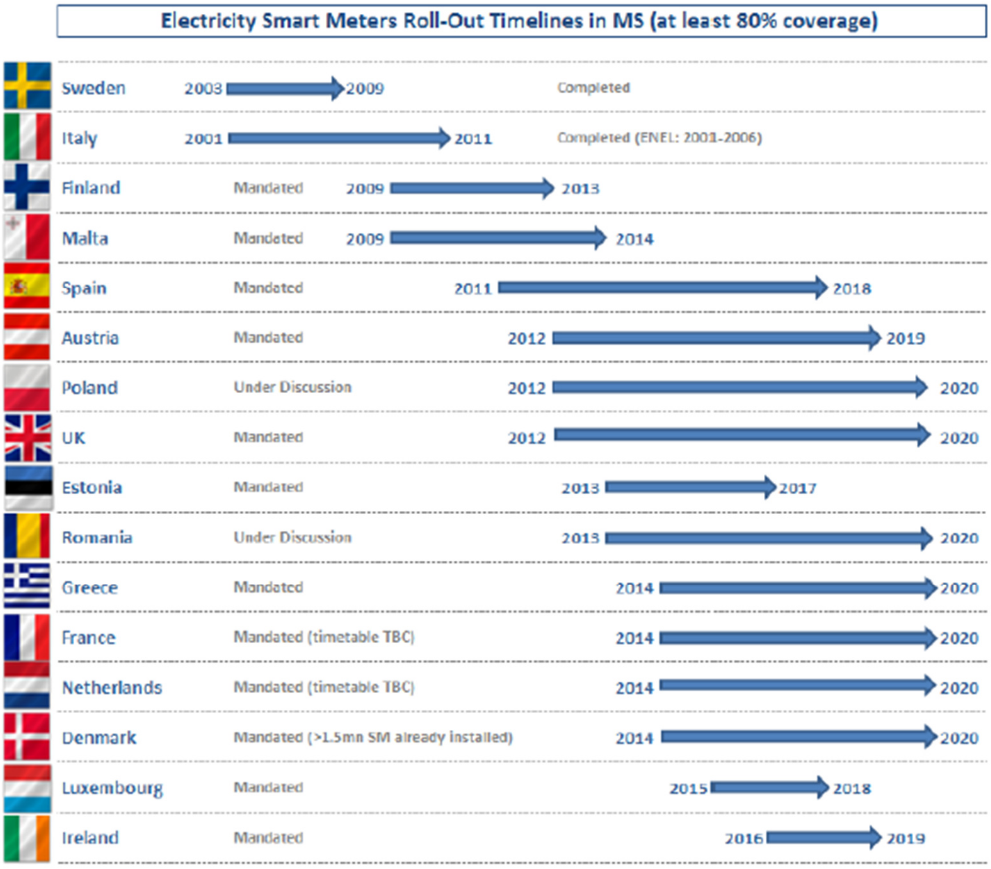

Figure 7. Status and forecasting of Smart Meter deployment in some EU countries [39].

Finally, considering a more practical aspect, ICT technologies have a relevant role in simplifying the involvement of consumers. As a matter of fact, as stated in [38], the automation of flexibility strategies is fundamental considering the possible reluctancy of final users to directly responses day by day to system operator requests or tariffs signals.

2.4 Italian focusing

As for other industrialized countries, the concept of "management of the load" has seen its diffusion in Italy since '70. Firstly, interruptible load programs were adopted as solution for critical events related to insufficient generation capacity. While during 90's those programs lost gradually their importance, the attention re-growth in the new millennia. Starting from '80s, in Italy were introduced the first Time-of-Use tariff, a service that was initially dedicated to high tension customers and then even for medium tension ones. [40]

Concerning **Energy efficiency**, focusing the attention on buildings, its proceedings started several years ago with the **Law n. 373/76** [41] that regarded the containment of the consumption for heating purposes in buildings, introduced after the petroleum crises of '70s.

After that, in order to highlight the most important legislative acts, it is necessary to include the **Law n. 10/91** [42] (and subsequent modification) which established, following the criteria indicated by the policy on energy saving drafted by the European Economic Community, the rules for the actuation of the national plan for the rational use of energy and the development of renewable energy sources. This represent the first law the regulated the project modalities and management of the building/plant system, with the aim of ensuring energy savings, environmental sustainability and comfort of building occupants. Moreover, this law obliges the building owner to present to the Municipality the technical relation drafted by the responsible engineer to attest that the prescriptions have been followed. Finally, another important aspect introduced by the law 10/91 was the figure of the "responsible for the conservation and the rational use of energy" which represented the actual figure of the Energy Manager.

The path through energy efficient buildings has seen different subsequent legislative acts drafted by the Italian Government that have introduced new prescriptions or modified the one already present. The most important legislative act of the last years is represented by the **Law 90/2013** [43] with which Italy transposed the EU directive 2010/31/EU about the energy performance of buildings. It included the definition of the concept of nearly zero energy buildings (NZEB) and substituted the old certificates with the new one Attestato di Prestazione Energetica (APE). The legislative act has been then actuated with the **Ministerial Decree of 26/06/2015** [44] which is composed of three distinct decree:

- The first, concerning the calculation methodologies for building energy performance and the establishment of the minimum requirements.
- The second, which defined the prescriptions that must be followed for the drafting of the technical relation for the different cases about new construction and renovation of the building or the technical systems.

- The third, which defined the national prescriptions for the Italian energy certificate, the APE.

The calculation method indicated by the prescriptions of the decree, used to evaluate the energy performance of buildings is mainly represented by the UNI 11300 series. It is important to observe that those series of regulations are based on the international and European standard EN ISO 13790 which present a calculation method that has been recently substituted by the normative EN ISO 52016 [45]. The latter has been approved by the Italian standard authority UNI, therefore the prescriptions for the calculation of energy performance of buildings could change in the future.

Another important legislative act related to Energy efficiency is the **Legislative Decree 102/2014** [46] which transposed the European directive 2012/27/EU, whose prescriptions can be summarized in:

- It established the national target for the energy saving;
- Established the mechanism of the White Certificates, which had to provide an important contribution in pursuing the energy saving target;
- Imposed the mandatory execution of the energy audit for big industrial buildings;
- Imposed the introduction of effective metering systems and thermostatic valves in buildings;
- Introduced the concept of Energy Performance Certificate (EPC) and predisposed the certification for the Energy Service Companies (ESCOs), following the standard UNI CEI 11352;
- Introduced disposition for the enhancement of energy efficiency, renewable energy sources, distributed generation and the active participation of the demand to the energy system. As a matter of fact, the Ministry charged the authority to develop, in cooperation with the TSO, the modalities to let the consumers participate in the grid services, even in aggregated forms.

As mentioned in the previous paragraph Italy is not among the virtuous countries about the development of **Demand Response** solutions. Anyway, Italian governments are starting to evaluate Demand Response potential charging the Italian NRA to program and develop the necessary study and evaluations. Moreover, the X Commission “Attività produttive” has approved on 2/8/2017 the series of proposals collected in the so-called Clean Energy Package, previously presented.

In general, looking at the European and national institutions reports it is possible to observe an increasing interest in Italy for these themes while there is still working to do to make the source developed as for other European countries. In this section the author aims at providing an overall idea of the development status of DSM in Italy and the possible future evolutions. The major intervention in the Italian context regard the dispatching services that can be summarized as illustrated in the scheme of Figure 8.

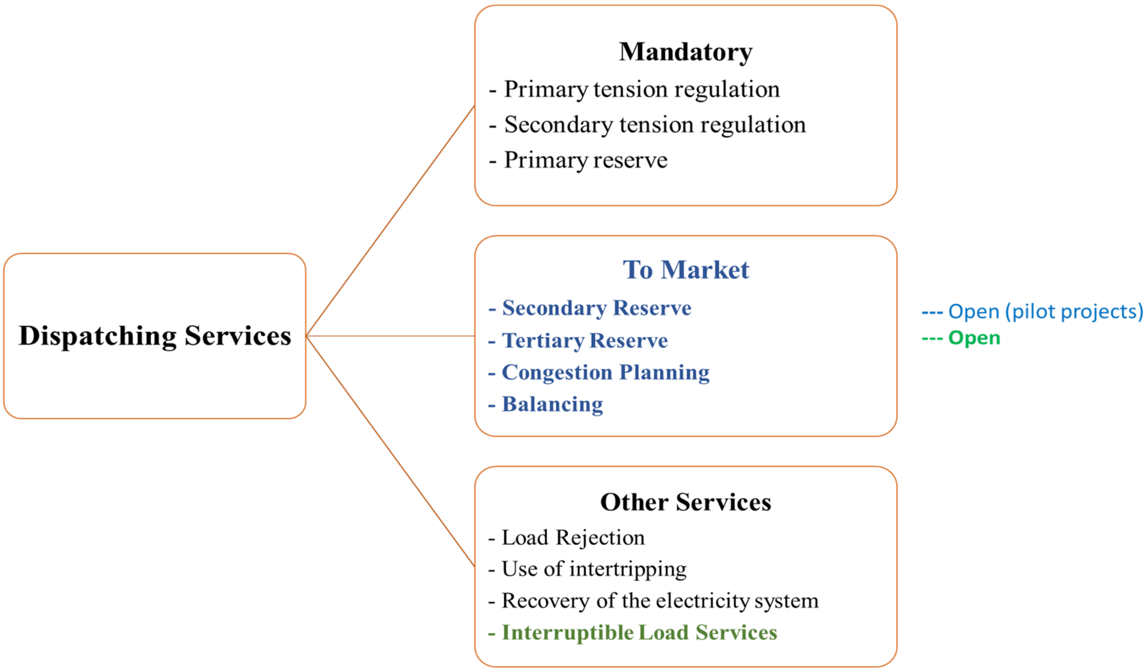

Figure 8. Typologies of dispatching services present in Italian System.

2.4.1 Interruptible Loads

As already mentioned, before 2017 the Interruptible Loads [47] were the only one service present in Italian system that can be related to DSM.

Observing the planned period 2018-2020 the amount of interruptible load available is of 3.900 MW. This service has remained independent with respect to the Balancing Market, as a matter of fact it is used only when resources supplied on the MSD are insufficient to maintain the operational security of the system.

In order to participate to this kind of programs users must presents two main requirements:

- Minimum capacity of 1 MW
- Guarantee user disconnection in two available modalities:
    - In real time, with an activation time of less than 200msec following a remote signal sent by the TSO;
    - In deferred time, in emergency condition with an activation time of less than 5 sec. following a remote signal of the TSO.

Therefore, the service has remained dedicated to large customers without considering smaller ones with the eventual possibility of aggregation.

2.4.2 Ancillary Services Market

An important intervention that started focusing the attention in DSM field, in particular in Demand Response is represented by the starting procedure for the opening of the Mercato dei servizi di dispacciamento (MSD) electricity market to DSM technologies, in particular demand and storage resources. As already mentioned, this market includes part of the ancillary services that have been previously presented.

The procedure began with the **Document for Consultation 298/2016/R/eel** [48] drafted by the Italian National Regulation Authority (NRA) ARERA which defined the authority's orientations for the first phase of the Market Reform which included the evaluation of the opening of the MSD to the demand, non-programmable renewable sources and distributed generation with the main aim of creating a technology neutrality for the dispatching resources. Through this document, the authority exposed the main limits and all the features, starting the discussions and consultations of the project with the interested parties. Moreover, the authority discussed even the different aspects that should be treated in the successive phases among which the most important one regards the introduction of the figure of the aggregator.

Then, with the **Resolution 300/2017/R/eel** [49] the authority has defined the criteria to allow the participation of the demand, storage systems, non-programmable renewable sources and distribution generation to the MSD charging the TSO Terna to individuate and perform initial pilot projects. It stated that this initial phase was necessary to acquire useful elements for the reform and to make available, as soon as possible, new dispatching resources.

An important aspect of this resolution regarded the concept of aggregation through the definition of virtual entities called Unità virtuali abilitate (UVA) which have been differentiated with respect to the unity that they include. Therefore, the resolution defines:

- UVAP (Unità virtuali abilitate di produzione), characterized by the presence of not significant production units, including storage systems.
- UVAC (Unità virtuali abilitate di consumo), characterized by the presence of consumption units;
- UVAM (Unità virtuali abilitate miste), characterized by the presence of consumption units;
- UVAN (Unità virtuali abilitate nodali), characterized by the presence of significant production unit, non-significant production unit and consumption unit that belong to the same transmission point of the electricity network.

In addition, the resolution the new figure of the aggregator, identified in the Balance Service Provider (BSP) who represent the responsible actor for the participation of the UVA to the MSD.

Moreover, the resolution:

- Highlight the minimum criteria that must be respected to be admitted to the pilot project;
- Defined for the different cases, which is the counterpart for the dispatching services (which is coincident or not with the aggregator, so the Balance Service Provider – BSP);
- Expose the basic procedure necessary for the enabling of the UVA;
- Explicit the modes to valorise the effective unbalances.

Finally, the resolution established that the TSO Terna had to individuate the pilot projects that could come even from the interested operators of the sector, starting as first phase to propose a pilot project regarding the UVAC and one concerning the UVAP.

Then, the regulation proposed by Terna for the pilot project regarding the participation of the demand to the MSD has been approved with the **Resolution 372/2017/R/eel** [50] in the end of May 2017. The regulation established the minimum requirement of the UVAC to participate to the pilot project as:

- A minimum introducing of 10 MW within 15 minutes from the received order from the TSO;
- A minimum time of 4 hour that the regulation has to be kept.

Moreover, the regulation established that the UVAC were enabled for the tertiary power reserve and balancing services of the MSD and for this first experimental phase, only the UVAC located in NORD and CNORD market zone could participate.

Another important criterion that should be respect by the UVAC was that each withdrawal point had to present an instrument able to do real time measurement sent to Terna with the modalities established in the Grid Code.

While, in August 2017 the Italian authority approved with the **Resolution 583/2017/R/eel** [51] the pilot project regulation proposed by Terna regarding the participation to the MSD of the distributed generation, so the UVAP. The regulation established the minimum requirements for the UVAP to participate as:

- A minimum modulating capacity of 5 MW (increasing or decreasing) within 15 minutes from the received order.
- The regulation has to be kept for at least the 3 consecutive hours.

Moreover, for the pilot project the UVAP are enabled for the services of congestions during the planning phase, tertiary power reserve and balancing.

Then, the authority charged Terna to present at least other two pilot projects related to the participation of UPR[3](Unità di produzione rilevanti), constituted by all significant production units, including the ones which were not already enabled to the dispatching services, and UVAM. In particular, the authority suggested Terna to program the pilot project of the UVAM exploiting the results obtained from the two previous pilot projects.

Therefore, after a Terna proposal, ARERA approved the proposed regulation for the participation to the MSD of the UPR with the **Resolution 383/2018/R/eel** [52] dated July 2018. The significant production unit, not mandatory enabled, have been enabled for the services of congestion during the planning phase, rotating and/or substitution tertiary power reserve and balancing. The criteria to be enabled are differentiated for each service that the UPR should provide and summarized in Table 3.

In addition, it specifies the criteria for hydroelectric generation sources which, in order to be enabled, must present a ratio between the deliverable energy and the maximum power at least equal to 2 hours, while non-programmable renewable energy sources have to be connected electrically to storage systems (enabled for resources for congestions and rotating/substitution tertiary power reserve).

	Min. Power variation (increasing or decreasing)	Response time	Duration of the regulation
Congestion during planning phase	5 MW	15 min	/
Rotating tertiary power reserve	5 MW	15 min	120 min
Substitution tertiary power reserve	5 MW	120 min	8 hours
Balancing	2 MW	15 min	/

Table 3. UPR enabled dispatching services for the pilot project.

[3] The relevant production units are defined as the units for which the total power of its associated generation groups is not less than 10 MVA.

Finally, with the **Resolution 422/2018/R/eel** [53] the authority has approved the regulation proposed by Terna for the participation of the UVAM to the MSD, modifying some specification of the resolution 300/2017/R/eel. Therefore, in general a UVAM can be defined as an aggregated of consumption, production and storage units connected to the grid at all tension level. For the first time, this pilot project enables even the participation of the *vehicle to grid* technologies, considering the storage systems used for the e-mobility at the same level of the others.

The regulation identifies two kind of UVAM distinguishing:

- UVAM "A": made up of non-significant production units, consumption units, storage units and significant production units not already mandatory enabled which share the connection point to the grid with one or more consumption unit and with a maximum injection in the grid of 10 MVA;
- UVAM "B": made up of significant consumption unit which share the connection point to the grid with one or more consumption unit and with a minimum injection into the grid of 10 MVA.

For the pilot project these virtual units have been enabled for dispatching services of congestions during the planning phase, rotating and/or substitution tertiary power reserve and balancing. The criteria to be enabled depends on the service that the UVAM have to provide and have been summarized in Table 4.

	Min. Power variation (increasing or decreasing)	Response time	Duration of the regulation
Congestion during planning phase	1 MW	15 min	120 min
Rotating tertiary power reserve	1 MW	15 min	120 min
Substitution tertiary power reserve	1 MW	120 min	480 min
Balancing	1 MW	15 min	120 min

Table 4. UVAM enabled dispatching service for the pilot project.

2.4.3 Capacity Market

As already mentioned, the capacity market has been conceived as a mechanism that provide the disposal of generation capacity needed to ensure the desired level of production capacity and so, security of supply.

The Italian Capacity mechanism, following the dispositions of the Ministerial decree n. 379/03, has been introduced by the Italian authority ARERA with the **Resolutions 98/11** [54] and **Resolution 375/2013** [55] then approved with **Ministerial decree of 30/06/2014** [56]**.** The first phase of the mechanism provides the procurement 4 year before from the enabled production units that make available their capacity. Because of the negative opinions of several interested parties intervened in the consultation, this first phase did not involve the demand but only significant production units. Anyway, even though already approved by the Ministerial decree, in order to follow the prescription contained in the European State aid guideline for Energy and Environment (2014-2020) and the indications of the Ministry itself, the mechanism have been subject to other several consultations, whose final have been approved by the authority with the **Resolution 261/2018** [57]**.** The main reason that lead to a revision of the capacity mechanism is represented by the previous and actual aim. While the initial scope of the implementation of a capacity mechanism was related to the assessment of the generation capacity, problem emerged with the blackout in Italy in 2003, now it is even driven by the necessity to make the system flexible due to the substantial increase of non-programmable renewable generation. An important improvement lead with the different consultations and indications of the authority, is represented by the introduction of demand participation to the Capacity Mechanism. The actual reform has not been yet approved by the Italian Ministry of economic development, but the actual final project drafted by Terna present the participation of the so-called "Unità di consumo per il mercato della capacità" (UCMC) with the mandatory criteria to be enabled to the MSD market. The reduction in withdrawal of consumption units is intended physically as increase in injection, therefore as established in the regulation drafted by Terna, can participate to the capacity market all the point of withdrawal (single or in aggregated form) that present the following summarized main criteria:

- Minimum modulating power of 1 MW;
- Response time of 15 minutes from the TSO request;
- Keep the regulation for 2 consecutive hours;
- Cannot includes production units;
- All the aggregated points must be equipped of remote controlling systems the communicate with the TSO.

2.4.4 Retail Market and Tariff Schemes

As already showed in the European status of the time-based electricity tariffs, Italy is not one of the most virtuous countries about the implementation of those practices. To date, the Italian retail market can be mainly subdivided into three main typologies of service that the consumer can chose [58]:

- **"Maggior tutela" service**, which includes to clients, domestic or small enterprises in low-voltage, that do not participate in the free market and are subjected to fixed prices established by the authority ARERA;
- **"Free market" service**, which provide more variable prices that are established directly by retailers following the energy market;
- **"Salvaguardia" service**, that represent a "pillow service" for the clients that have not a contract in the free market and cannot access to the Maggior tutela service, therefore user in medium-voltage or medium-big enterprises in low-voltage.

In general, considering the two services it is possible to individuate three different typologies of tariffs that the consumer can chose:

- Flat Tariff: with a price of electricity fixed during the day, independent with respect the time the energy is consumed. This tariff can be adopted both in maggior tutela or free market.
- Two-time tariff: a peak/off peak tariff that differentiate two different prices depending the moment in which the energy is consumed. This kind of tariff can be adopted by both maggior tutela and free market and distinguishes:
    - High price level: F1 price range. (Mon – Fri, 8:00 to 19:00);
    - Low price level: F2 (Mon – Fri, 19:00 to 8:00) and F3 (weekend and holidays) prices ranges, often indicated in the bill as F23.
- Multi-time tariff: that provide three different prices ranges which depends both on the time of the day and the day of the week. It can be adopted only by non-domestic users for the maggior tutela service or by all clients in free market and distinguishes the following prices ranges:
    - Peak time range (F1): with high price level (Mon – Fri, 8:00 to 19:00);
    - Intermediate time range (F2): with medium price level (Mon – Fri, 7:00 to 8:00 and 19:00 to 23:00 or Sat, 7 to 23);

- Off-Peak time range (F3): with lower price level (Mon – Sat, 23:00 to 7:00, Sunday and holidays).

Therefore, Italian development status is not one of the most advanced of the European framework, anyway growing attention of Government, authority and market players push to a deepening investigation of the subject. Considering the actual situation and the indications included in new regulations and directives of the European Union it is possible to suppose a future and not so far strong growing of the sector both on market and technical sides.

3. Theoretical aspects in Buildings

3.1 Definition and classification

In this Paragraph will be provided a general overview of the concept related to the DSM, looking at the different nomenclature adopted in literature and giving an overall idea of the definitions and classifications from the principal technologies and strategies to the implementation programs that can be adopted for the single buildings.

The application of concept that are very similar to the Demand-side Management can be found even in the '60, as already explained in the previous chapter, under different terminologies. As a matter of fact, historically demand-side management has been called with several names, in particular "load management". It has been the engineer Clark W. Gellings who coined the actual name, giving the following definition:

"DSM activities are those which involve actions on the demand (i.e. customer) side of the electric metre, either directly or indirectly stimulated by the utility. These activities include those commonly called load management, strategic conservation, electrification, strategic growth or deliberately increased market share." [59]

The concept has gained a particular interest in the last decade and the original idea has seen some changes related to the development of technologies involved, maturated knowledge and evolution in energy targets that have brought researchers and experts to extend it. As a matter of fact, this development led to several definitions of Demand side management in literature that differs for the aspects included, the drivers or the way to look at the purposes.

For example, it is possible to find definitions that consider also distributed energy resources (as [6] [60] [37]) or not (as [61]), others that exclude energy efficiency (as [60]). Besides, considering the main reason that lead to the diffusion of DSM during '80s, the energy crisis, it was mainly driven by saving in energy and monetary cost related to energy security issues. While, it is now proven that it can also provide an important contribution in reaching carbon free targets, allowing a higher penetration of renewable energy sources or reducing energy demand and so CO2 emissions [1]. The definition elaborated by Gellings looked only at interventions in the electricity sector, while it is also possible to find in literature studies which make use of that nomenclature for other energy applications related to gas [5] or district heating networks [62].

Moreover, in literature there is a lack of studies that assess for the theoretical framework of DSM [37] [63] and great part of the research focus the attention only on the application of some sub-systems of DSM without considering an overall definition of it, concentrating for example on Demand Response [9] [10] [35].

Therefore, after a literature review, this work has adopted the definition provided by Peter Warren, because it represents a more general but at the same time complete view, trying to capture all features and typology of interventions that have been implemented and actors that DSM can involve. It defines the DSM as:

"Demand-side management (DSM) refers to technologies, actions and programmes on the demand-side of energy meters, as implemented by governments, utilities, third parties or consumers, to manage or decrease energy consumption through energy efficiency, energy conservation, demand response or on-site generation and storage, in order to reduce total energy system expenditures or to contribute to the achievement of policy objectives such as emissions reduction, balancing supply and demand or reducing consumer energy bills." [37]

Comparing it with the first definition provided by Gellings, it is possible to see that the main concept is still the same: the change in paradigm switching the attention from the supply to the demand-side, therefore matching the available supply through interventions on the demand.

The three terms "technologies, actions and programmes" aims at highlighting the dual nature of DSM interventions that can be both through technologies or change in consumer behaviour. The definition adopted considers the applications of DSM to different kind of energies, as a matter of fact has changed the term "electric" into "energy". Moreover, it includes all the load shaping effect of those programs, which can be both to manage or decrease the energy consumption and in addition to the classical drivers represented by the assessment of energy security, it considers also the achievement of the main actual energy policy objectives, as emissions reduction and higher penetration of RES, and savings on consumer bill.

Finally, it introduces all the actors that can be involved, including in addition to utilities even government, third parties and consumers. Anyway, it is important to notice that the interested parties, excluding the consumer, may change with respect to the different DSM activity considered, as for example Energy Service Companies (ESCOs) for energy efficiency or Systems Operators and Aggregators for Demand Response.

3.1.1 DSM Technologies

The classification represented in the scheme of Figure 9, following the definition adopted, distinguish three main categories that can be individuated among all the programs related to the Demand-side management. The distinction is mainly based on the approach used, the technology implemented, and the characterization in time of the application.

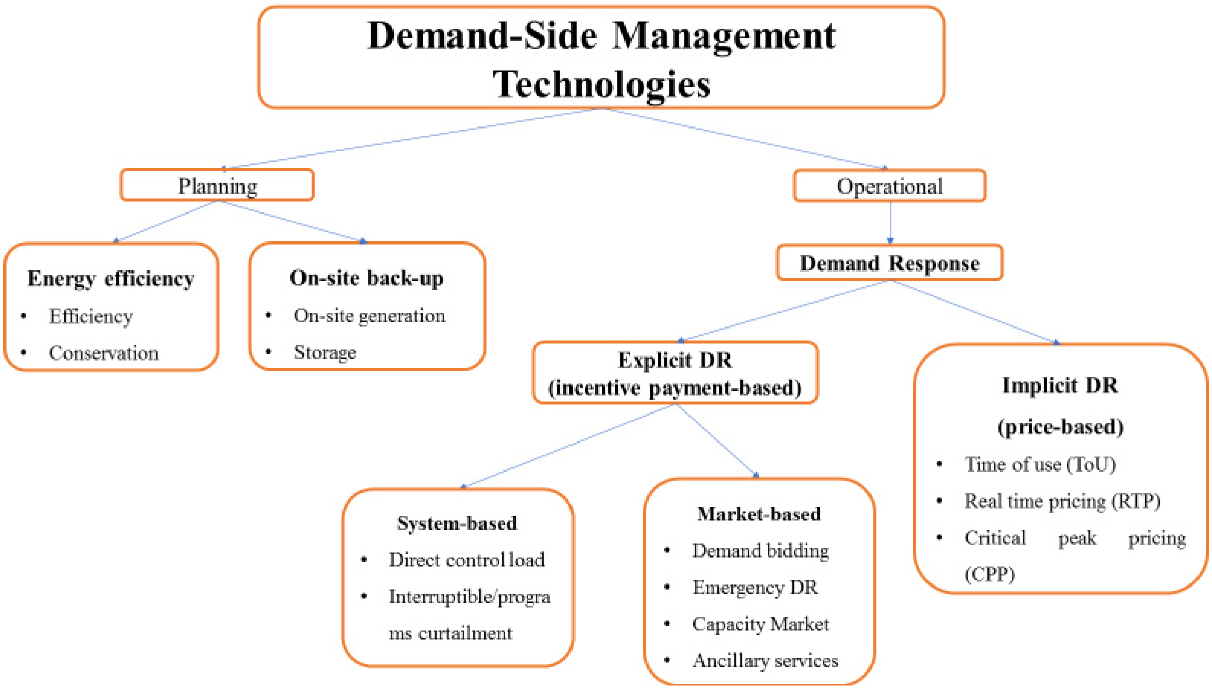

Figure 9. Demand-side management technologies.

The first distinction that is possible to individuate, separate DSM technologies into two main branches considering the time-scale of the intervention considered. Therefore, it is possible to differentiate:

- **Planning,** which includes almost "permanent" intervention that see for example the installation of an additional generation source or storage, the substitution of an old and less efficient equipment or the permanent change in operation set-up of a system.
- **Operational,** which includes temporary interventions that can be considered as event-based as for example network needs or change in prices. Among operational interventions it is possible to distinguish different time-scale, but the common characteristic is that the implementation is not systematic and permanent as for Energy efficiency, but it is event-driven.

Anyway, this can't be considered as a net subdivision. As a matter of fact, even though storage solution can be seen as permanent interventions, they could be also exploited for Demand Response programs and so temporary ones.

3.1.1.1 Energy Efficiency

The notion energy efficiency, in general, is defined as the ratio of output of performance, service, goods or energy, to input of energy [19]. Anyway, in this context it is important to make a distinction between Energy efficiency and Energy conservation, that sometimes are used as synonyms [60].

Energy efficiency measure are generally considered the ones that reduce the energy consumption while providing the same service or performing the same function. Anyway, it not always provides a reduction in energy because it is also to apply energy efficiency interventions to produce more of a service without consuming more energy ("rebound effect").

Energy conservation refers to all actions that aims at reducing the overall energy consumption through a reduction in the energy service. For example, an increase (reduction) of the temperature set-point during the cooling (heating) season for energy savings perspectives or behavioural interventions that help in reducing wasted energy as turning off the lights when leaving a room.

The main characteristic of this interventions is the consequent long-term effect that can be considered as "permanent" until a new action is performed. For example, the substitution of a water boiler in a dwelling with a new and more efficient one will provide a "permanent" energy saving, considering the same use of the equipment by the consumer. Moreover, in case of behavioural programs, it is necessary the continuity of the consumer in following the new path without switching back to the traditional habits, except for behavioural actions imposed by governments.

In the literature it is possible to find a lot of measures that can be reconducted to energy efficiency. In this context, can be very useful the classification provided by Xia et. Al. [64] which summarize all the possible energy efficiency measure in four categories. They are the so-called POET (Performance, Operation, Equipment and Technology efficiency) components of the energy efficiency and includes:

- Technology efficiency: efficiency measures associated with energy conversion, processing, transmission, distribution and usage.
- Equipment efficiency: efficiency of isolated individual energy equipment with respect to given specifications. It is mainly related to capacity, specifications, standards, constraints and maintenance. The classic example is the substitution of the incandescent lights with more efficiency compact fluorescent lights.

- Operation efficiency: efficiency measures related with the proper coordination among all the different components of the system. It includes physical, such as sizing and matching, time, as time control mechanism, and human coordination.
- Performance efficiency: determined by external but deterministic indicators such as production, cost, energy sources, environmental impact and technical indicators. Often those indicators are in conflict and require a trade-off research, as a matter of fact an energy system is usually designed to maximize the production and at the same time minimize cost and emission.

These categories may represent a good guideline through energy efficiency measures related to DSM, but it is important to notice that the categories presented do not always have a net boundary.

3.1.1.2 Distributed Generation

The concept of Distributed Generation (DG) includes all small on-site generation and storage facilities which are characterized by decentralization in technology, space and time with respect to the conventional high capacity power plants that fed the national grid.

Even though the concept of distributed generation may be also found separately with respect to DSM, it is importance to notice that on-site back-up generation facilities and storage solutions can be used to provide Demand-side management services.

On-site generation includes all small-medium generation solutions which are installed close to the end-user and directly connected to the Distribution Network. In order to assess their use in DSM activities it is necessary to divide this category into two additional sub-classes: firm and intermittent power. Firm power technologies include those that can be controlled as a function of the demand. They are represented by microturbines, Stirling engines, small hydro and medium-scale gas and diesel generators for industrial customers and can be used for peak shaving applications or as back-up solutions in situations of grid unavailability or during high energy cost periods [1] [65].

Intermittent technologies are characterized by a random generation and their production cannot be controlled. They are generally represented by solar panels or wind turbine whose uncontrollability is related to the energy source availability which is not predictable. [65]

Storage solutions represent a set of technologies which can temporary retain energy, making it available also in time of scarce availability. Towards a more sustainable energy system, their main function is to make intermittent energy sources more competitive both in energy and economic terms. The classical example is represented by solar technology whose energy source is not available during the whole day, allowing the consumer to use energy even during the night.

Storage technologies may also be used to perform DSM activities. The older application of DSM through the use of storage technology, as already discussed, has been represented by the use of water thermal storage charged in off-peak periods, during which the energy is cheaper.

A growing and interesting application of storage utilities for Demand-side management purposes is represented by plug-in electric vehicles, though their batteries, in particular for residential applications [66] [60].

The development status and commercial availability of these technologies change a lot from application to application and it is possible to classify energy storage systems with respect to the energy form stored as:

- Mechanical storage systems: pumped hydro power plants, compressed air storage, flywheels;
- Thermal Energy storage (TES): sensible heat storages, latent heat storages;
- Chemical energy storage: electrochemical batteries, Organic molecular storage;
- Biological storage;
- Magnetic storage;
- Hydrogen storage.

Generation and Storage solutions are studied and used also on the supply-side. Therefore, in this category are considered only the applications used to provide DSM services. Moreover, distributed generation is not completely independent with respect to Demand Response because usually it is used as demand side resources to provide DR services, or DR programs may represent the input for their scheduling and application. For example, considering the classical use of storage solutions to save money charging energy during off-peak when electricity is cheaper to use it during more expensive peak period, require a Time-of-Use tariff scheme that provide on-peak/off-peak electricity price. Anyway, these solutions are considered as DSM technologies because even independently with respect to DR programs they can contribute to the energy security issue acting on the demand-side, introducing additional power capacity to help release the increasing burden of power demand [6].

3.1.1.3 Demand Response

Demand response is represented by a set of programs which aims at modifying the consumption patterns by end-use customers through incentives or changes in the price of electricity over time in order to reduce the electricity consumption at times of high market price (when electricity demand is high) or when grid reliability is jeopardized [8]. It represents the form of DSM that make consumers active participants of the grid operation through programs that aims at exploiting their flexibility. Their participation to DR programs is always voluntary, but there are some activities among incentive-based programs which may include penalties if the pre-contracted reduction is not satisfied [36].

Differently from Energy efficiency programs, DR strategies achieve the temporary reduction of the demand by temporary reducing the service targeted. Obviously, these interventions must minimize any possible negative impact on the occupants of the building, therefore the reduction in service must be accurately evaluated with respect to certain constraints. Moreover, in studying the application of DR control strategies it could be possible to achieve the reduction in demand without any reduction in service, mainly due to non-optimum operation. In this case, the application of the DR intervention must be evaluated as permanent energy efficiency implementation related to the operation. [67]

The main objective of DR activities is to reduce consumption at critical times, and it is possible to assess that aim through different programs which are mainly divided into two categories.

Explicit Demand Response (also known as incentive-based) programs, which include all the programs with which end-user flexibility, directly competing with supply sources, is sold in the electricity market or provided as a network service to system operators, directly in case of large consumers, or indirectly through a demand response service provider, that may be a third party (aggregator) or coincide with the supplier. It is also called incentive-based DR because it is mainly represented by explicit bill credits or payments provided to customers for pre-contracted or measured load reductions. [36]

A very important actor in the markets of Explicit Demand Response is represented by the figure of the Aggregator. It represents a new and additional figure in the electricity market whose aim is to aggregate more non-significant utilities creating sort of big virtual loads that can sell their flexibility in the wholesale market. In general, depending on the program to which the consumers participate and so the service provided, the consumer may lead the system operator to directly act on its load, may respond to system operator's requests which occur in case of necessity or may directly sell its flexibility on the wholesale market. In the case of smaller and non-significant utilities, the consumer subscribes flexibility contracts with the Aggregator, which then operates in the market and communicate with the system operator.

A very general overview about the Explicit Demand Response framework has tried to be provided in Figure 10. It shows the possible interactions among the different actors that may be involved, but the modalities and the specific actors involved depends on the market structure at national level.

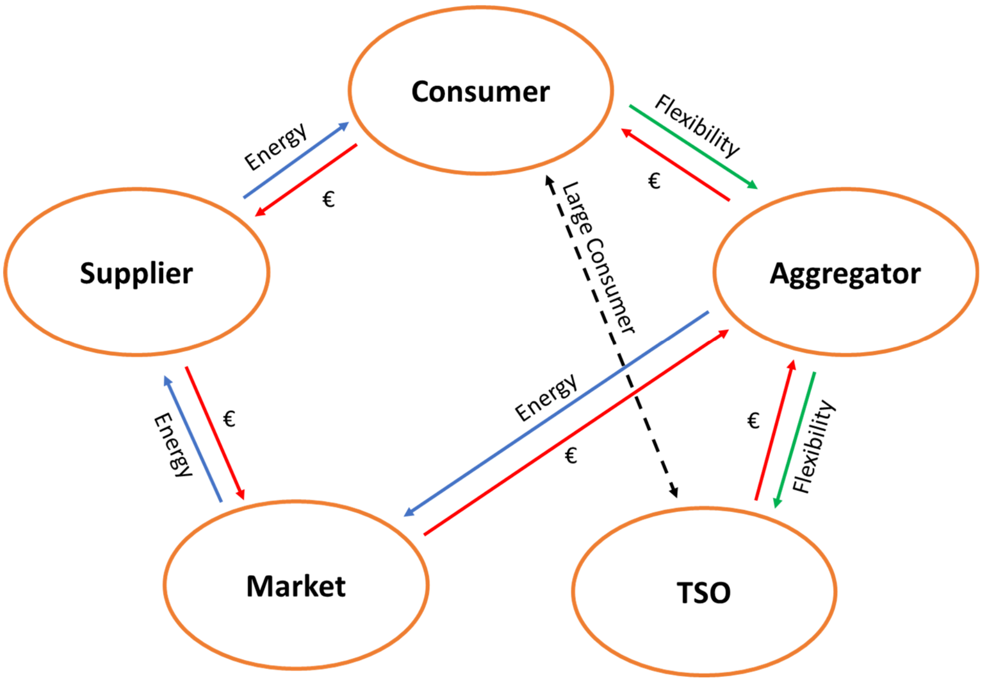

Figure 10. General framework of Explicit Demand Response.

Among Explicit DR programs is possible to distinguish [10] [35] [36] [68]:

- Classical programs.
  - Direct Control Load (DCL): programs with which utilities or System operators can remotely shut down participant equipment on a short notice, usually to face reliability contingencies.
  - Interruptible/Curtailable Programs: customers receive upfront incentive payments or rate discounts to reduce their load to predefined values during system contingencies. Customers may be charged of penalties for failure to curtail.
- Market Based DR.
  - Emergency DR Programs: participating customers are paid incentives for measured load reductions during emergency conditions. Generally, are mandatory commitment to reduce load, with penalties if not supplied;
  - Demand Bidding: programs with which customers can directly (or through aggregators for medium-small users) offer their reduction in energy demand into the wholesale electricity market.
  - Capacity Market: A program offered to customers who can commit to providing pre-specified load reductions when system contingencies arise. Usually, participants receive a day-ahead notice of events and are penalized if they do not respond to calls for load reduction;
  - Balancing and ancillary services market: they refer to the participation of demand-side to balancing reserves, used to ensure real time balance of demand

and supply, and to ancillary services, with which TSO guarantee the security of supply

Implicit Demand Response (also known as price-based) programs, which include those programs mainly represented by tariffs schemes with which the consumer can choose to be exposed to time-varying electricity prices, which aim at reflecting the value and cost of the electricity in different periods. These programs are mainly used to incentivize the consumption of energy during off-peak periods, to which correspond low-prices, to reduce energy demand during peaks, characterized by higher prices of electricity.

In this case, the consumer is not directly remunerated for its flexibility, but the advantage is represented by savings in the electricity bills.

The main categories in which time-variant electricity price are distinguished are represented by [10] [33] [69]:

- Time-of-use (ToU): a tariff scheme with different unit prices for different time blocks, which may vary during the day, the month, the season or the year. Usually the prices are set in advance with respect to the period of application. A classic example of Time-of-use tariff is the day/night price scheme.
- Critical Peak Pricing (CPP): represent a program in which the utility set higher prices during critical peak periods to disincentivize the consumption. Usually customers are notified the day before. Are more effective than ToU and are used mainly for energy security problems.
- Real-time pricing (RTP): the price of electricity generally fluctuates hourly, reflecting the dynamic changes in the wholesale market price. Generally, the electricity prices are set one hour ahead or sometimes the day before.
- Peak-Time Rebates (PTR): which are tariffs that remunerate the users in order to reduce the consumption, with respect a calculated baseline, during critical events. Usually, if the consumer doesn't want to participate, he has to pay the normal tariff.

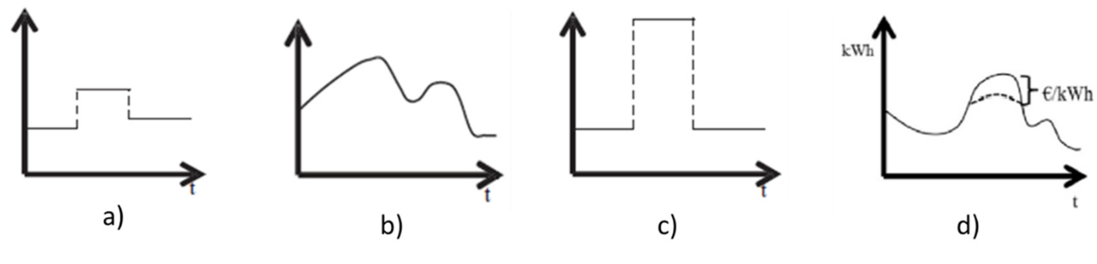

Figure 11. Price-based DR programs. a) ToU. b) RTP. c) CPP. d) PTR.

In general, this kind of tariffs are usually known under the name of "Dynamic Pricing". It is possible to characterize them by different grades of dynamism which can be characterized by two main criteria: the way of setting prices and the way of setting the time intervals in which it may change [33].

3.1.2 DSM Strategies

The following classification presented is the oldest one, formulated and adopted by Gellings [59], which reflects the effect on the load shape that DSM technologies may provide. It can represent even the scope of the application of Demand-side activities whose aim, as previously exposed, is to modify the consumption pattern.

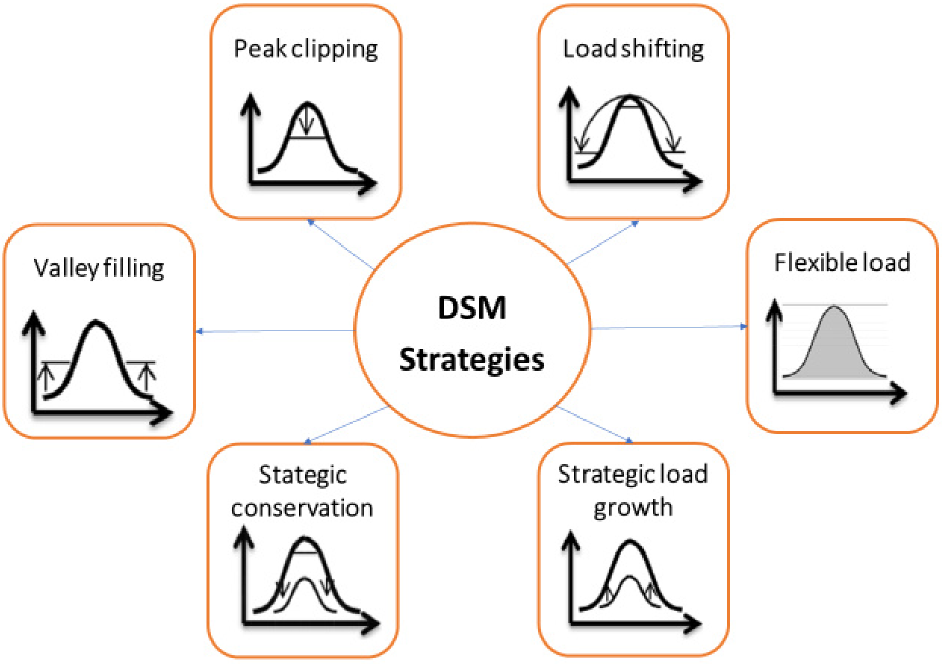

Figure 12. Demand-side management strategies. (adapted from [59])

Therefore, it is possible to distinguish several interventions on the load shape as illustrated in Figure 12:

- Peak clipping: It represents a reduction of the peak demand, which is represented by the highest request in terms of power.
- Valley filling: It focus the attention on off-peak loads. For example, it can reveal useful when there is a high production of renewable energy sources during off-peak periods.
- Load shifting: It aims to move the load from on-peak to off-peak periods. Together with peak clipping, this kind of interventions may lead to a decrease in necessity of spinning record power plants, because lead to a flattening of the load pattern.
- Strategic Conservation: as already said, it aims at an overall reduction in energy consumption. This strategy is related even with Energy Efficiency in the case in which it provides a reduction in energy expenditures.
- Strategic Load Growth: On the contrary with respect to Strategic Conservation, it provides an overall increase of the energy load and so, consumption. It can be caused

by an increase in loads related to electrification measures, as well as by economic development. For example, a widely diffusion of electric vehicles and electric kitchens in Italy, would lead to a considerable increase in the overall load pattern.

- Flexible Load Shape: it is a concept that initially was related with the supply-side, concerning the reliability. As a matter of fact, it has been always related to the capability to continuously balance supply and demand. In this case, the change is represented by the point of view. A flexible load can be obtained through several interventions: acceptance by customer of variation in quality of a certain service in change of incentives, interruptible or curtailable loads and individual customer load control devices with operates services with constraints.

As already specified for some of them, it is possible to link the strategies, and so the desired modification of the load pattern, to the technology that have to be adopted in order to obtain it (Figure 13).

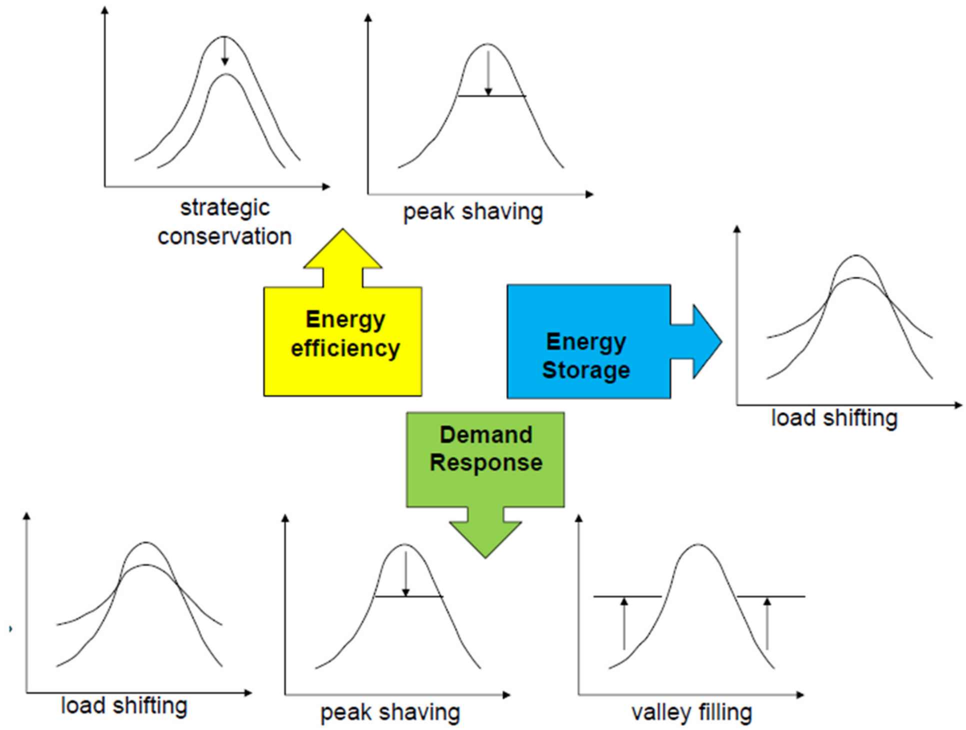

Figure 13. DSM technologies and strategies association. (adapted from [70])

For example, Arteconi et Al. [70] put in relationship the technologies investigated to the consequent change in load shape. Energy Efficiency DSM technologies are related to strategic conservation strategies and consequently even to peak shaving. While, Thermal Energy Storages may be exploited to implement load shifting strategies, whose potential is directly correlated to the capacity of the storage (association that is valid even for other storage technologies). On the other hand, Demand Response could be used for peak shaving, or valley filling purposes.

Here, the author considers relevant to add a link between DR and load shifting. An explication example could be represented by the application of a pre-cooling strategies to response to a DR request event, which lead to a shift in load.

3.1.3 Demand-side Flexibility in Buildings

Following the presentation of the principal technologies, programmes and strategies related to Demand-side Management, it is important to focus the attention on a concept related to a terminology frequently used in the previous paragraphs: Flexibility. Up to date, the term has been usually associated to the supply side, considering it as the capability to continuously balance supply and demand [71]. Anyway, with the introduction of DSM practices, it has been extended even to demand-side. As a matter of fact, it is important to introduce the concept of Energy Flexible Buildings, largely treated by the IEA, in the program IEA EBC Annex 67, who defines energy flexibility of buildings as:

"…the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements."

The interest in building energy consumption is greatly increased during last years, due to the forecasted increasing of energy demand together with their dominant contribution of buildings to the total energy consumption, which stands for approximately the 40% [12].

Therefore, in order to participate to flexibility programs previously presented, it is necessary to evaluate on the building system-side how to provide such services and therefore through which energy system gathered the flexibility.

Considering the main concepts treated in the literature reviewed, the author proposes in this work a conceptual scheme, showed in Figure 14, which can be useful to be followed in order to understand which aspects are involved in Demand Flexibility.

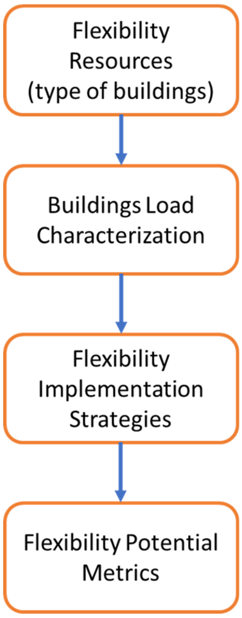

Figure 14. Conceptual scheme for the assessment of Building Energy Flexibility.

Therefore, following the proposed conceptual scheme it is possible to observe that at the top of the scale the main flexibility resource is represented by buildings which are mainly subdivided in: Industrial, Residential and Commercial buildings.

Concerning Industrial buildings, as stated by Lindberg et al., they present a relatively small potential that is even difficult to be exploited due to the numerous constraints that have to be respected in relation to the production activity of the specific Industry sector. As a matter of fact, the major limitation is represented by the fact that the industries reviewed presented a production equal to 100% of their capacity, therefore no flexibility is showed in the productivity process [72]. While, as stated by Aduda [73], Residential buildings have good potential while still need for large deployment of ICT technologies. In particular, residential application requires the aggregation of several small distributed loads and so for an elaborate communication infrastructure. Finally, Commercial Buildings show a high potential thanks to the fact that they are usually already equipped with BACS systems, allowing an easier implementation of DSM algorithms.

Therefore, following the individuation of the different kind of buildings the next step regards the categorization of the different energy services that could be installed in a building. The first subdivision can be based on the interaction of the different utilities with the power grid. Therefore, it is possible to distinguish:

- Self-generation utilities: which includes all the energy production plants that could be installed in the building, as for example PV panels, small CHPs, small Wind Turbine, etc. It is necessary to make the distinction between controllable generation, whose flexibility can be exploited when necessary and desired, with respect to un-controllable generation sources, typically renewable, which cannot be scheduled. Moreover, as states by Chen et Al. [71], RES usually provide power during grid power peak time, providing in this sense a positive effect reducing the peak power demand and so representing flexibility.
- Storage utilities: that could be represented by both Thermal (TES), exploited to store heat, cool or DHW, or Electrical (EES) Storage technologies.
- Loads: which includes all the services installed in the buildings that require power to work, mainly represented by HVAC, lighting, Plug-in, etc.

Considering the case-study that will be analysed in this thesis work, the attention for the building characterization will be focused on Commercial Buildings, particularly on Office buildings. Moreover, considering the innovative aspect in the load flexibility, the attention will be focused on characterizing loads.

3.1.3.1 Loads Characterization

Considering the mostly end-use loads systems installed in buildings, it is possible to categorise them following their features and the way through which their control could provide energy flexible services. First of all, it is necessary to make a distinction between the loads that won't surely have any flexibility potential because related to the conduction of the building system and productivity and safety of the occupants. While on the other hand it is possible to identify such systems that may have a potential related to flexibility. Anyway, that potential is strictly related to the characteristic of the specific system installed, but event to the service to which it is designed for. In general, following the different categorization proposed in literature [60] [71] [74] [38] it is possible to distinguish:

- **Thermostatically controlled loads**: whose operation follows a temperature set-point. This category includes the load that represent the higher energy consumption in buildings, heating and cooling (HVAC), in addition to DHW boilers.
- **Shiftable Loads**: whose operation can be shifted in time without affecting the service that they provide. This kind of loads are mainly present in a domestic context, as for example washing machines.
- **Curtailable Loads**: which includes services whose operation can be switched off or reduced when necessary. The most important service in this group is represented by lighting which could present dimmable characteristics.
- **Non-Curtailable Loads**: which includes loads whose operation cannot be interrupted. It includes Safety systems, BACS and all the loads necessary for the primary scope of the building. For example, in office buildings where productivity is essential, plug-in loads, so PCs, and some lights cannot be curtailed.

3.1.3.2 Flexibility implementation strategies

Energy Flexibility is often treated in literature as the deviation that a utility may offer with respect the optimal or normal operation, usually called baseline, that is exploited as a reference to evaluate flexibility [71]. In order to provide this deviation, it is possible to exploit on-site generation utilities, storage buffers or modify the load pattern of the different energy services and appliances installed in the building. Therefore, following the characterization of the loads, this paragraph will focus the attention on the way through which gather flexibility of that equipment, and so the flexibility implementation strategies.

Following the literature reviewed, as summarized in Table 5, the author will provide a general overview of the most diffused and discussed possible implementation strategies. The most targeted loads are represented by HVAC and lighting systems [67], because usually represents the buildings energy service with the highest contribution to the energy consumption.

Obviously, the applicability of the presented strategies depends on different parameters, among which even the specific characteristics of the system installed, as for example all air or air-water HVAC systems, CAV or VAV. For a deep understanding of the different strategies, the system involved and the possible consequences, the author strongly recommend the reading of the exhaustive guide written by Motegi et Al. [67].

Another important concept that have to be considered in assessing demand flexibility is **granularity**, an important feature related to the BACS system and so the control capabilities of the automation system. Smaller is the portion of the building that can be controlled independently, higher is the control granularity. This characteristic greatly enhances the flexibility potential, allowing the operator, for example, to apply a strategy just to such zones which present a lower consequent burden for the occupants. Therefore, this characteristic influences an essential feature that all the variable involved in the flexibility strategy must presents: **Controllability**, or rather that the possibility to modify its value by the user. Strictly related to the concept of the controllability, is the one of **Observability,** so the availability of the variable measure to observe its evolution as a consequence of the implementation of the flexibility strategy and in particular to monitor the change in comfort parameter, as will be discussed in the next paragraph.

3.1.3.2.1 HVAC Strategies

Global Temperature Adjustment: which regard the increase (reduction) of the Temperature Setpoint of the entire facility during the cooling (heating) season. Concerning the strategies that involve the HVAC system, it represents the most effective because reduce the loads of all the systems related to the service, as for example Air Handling Units (AHU), fluid distribution equipment, and heating/cooling systems. This strategy requires the presence of ambient temperature control devices which are able to adjust the load of the different utilities involved, which obviously depends on the kind of system installed in the building. For example, for all air system, the control device is represented by Variable Air Volume (VAV) dampers, while for primary air systems, the heating/cooling control system is represented by the valves of the water circuit. This kind of strategy may even present energy efficiency potential in the case in which there are some occupants that are more comfortable during the flexibility event, suggesting a permanent change of such zones.

Passive thermal mass storage. This strategy provides the reduction (increase) of zone temperature setpoints during off-peak hours in order to store cool (heat) in the building thermal mass, to then re-increasing the setpoint and unloading the cooling (heating) system. Obviously, in order to apply such strategy, it is necessary for the building analysed to present good thermal mass performances. Mild climates, with a high variability of the external temperature during the days, may present a good potential for pre-cooling strategies operated without cooling systems but just with mechanical or natural ventilation. Anyway, as stated by Motegi et Al., those kinds of strategies are very difficult to be evaluated and must be always properly tested.

Fan Power Reduction. It provides the reduction of the load consumed for ventilation purposes. Depending on the characteristic of the HVAC system, there are different possible actions presented to adjust the fan loads. For example, Christantoni et Al. [75] [76] evaluated an on/off curtailment strategy and a supply air flowrate adjustment. While, Hao et Al. [77] evaluated a fan power regulation acting on the drive speed and Motegi et Al. [67] discussed the reduction of the duct static pressure setpoint.

Supply air temperature adjustment. The scope of this strategy is to increase (reduce) the supply air temperature (SAT) setpoint to reduce cooling (heating) load. As stated by Motegi et Al., it could have different effects and implication depending on the kind of system installed (CAV or VAV), but the main common advantage is represented by a considerable energy savings of reheating.

Fan quantity reduction. It operates shutting off some of the fans or package units. This could be a very disruptive strategy whose application have to be evaluated with careful considerations. As a matter of fact, its applicability mainly depends on two factors: the number of fans or packages installed in the buildings and the level of occupancy during the period of application. Anyway, in order to evaluate the applicability of this strategy it is necessary to take care of the comfort conditions related to the Indoor Air Quality (IAQ); the remaining fans have to guarantee the minimum ventilation requirements.

Fan fixed duty cycle. It regards the operations of the AHU fans at specific level in specific period of the day. This strategy requires an appropriate test in order to evaluate the eventual consequent discomfort to the occupants.

Distribution Valve Limiting. Provide the limiting or reduction of the distribution valve position in order to reduce the heating or cooling load. Depending on the typology of HVAC system installed, the distribution valve interested by the strategies can be different, including valves of AHU heat exchangers or fluid distribution valves in air-water HVAC systems. For the applicability and the consequences related to this kind of strategy, it is necessary to take into account the possible effect of its implementation on the control of the system.

Supply water temperature adjustment. This strategy provides the increase (reduction) of the supply water temperature in order to reduce the chiller (heater) demand. For example, Christantoni et Al. [76] evaluated the potential of flexibility coming from the increase of the chiller supply water temperature from 6°C to 12°C.

Heater/Chiller Demand Limiting. Provide the setup of an upper bound limit for the operation of the central plant chiller or heater. For example, Aduda et Al. [7] evaluated the flexibility potential of a chiller cyclical operation, acting on a zonal temperature setpoint reset.

Chiller/Heater Quantity Reduction. The effect of this strategy is similar to the one previously discussed, but it addresses buildings with central plants which presents multiple utilities installed. Therefore, for example, as discussed by Motegi et. Al [67], it may provide the shutting-off of some of the chiller units.

3.1.3.2.2 Lighting Strategies

As already discussed previously, even for lighting system the applicability of the strategies that will be discussed strongly depends on the kind of system installed and, in particular, on the control possibilities and its granularity.

Light Switching. It regards the switch-off of entire zone illumination systems or a fraction of lamps, particularly when daylight is available. It has to be applied after solid evaluations considering the purposes on the areas on which act. For example, office spaces must be excluded because of the consequent possible disrupt of occupants productivity. This strategy could have a good impact when applied to common area during periods in which they are not used, but present not so high potential for buildings whose lighting system is regulated with presence sensors.

Stepped dimming. It is applied to stepped-dimming ballasts which are typically characterized by a single enclosure with multiple lamps that may be switched off gradually.

Continuous dimming. Which represent the best lighting system flexibility strategy, but require specific properties of the system, dimmable ballast control. Thanks to this feature, lighting level can be reduced gradually, therefore without disturbing occupants. In this context it is particularly interesting the large diffusion of the Dali protocol system that strongly increase the granularity of light control and allow for continuous dimming [78].

<table>
<tr><th>Building Service</th><th>Target Load</th><th>Flexibility Implementation Strategy</th><th>Literature Reference</th></tr>
<tr><td rowspan="11">HVAC</td><td rowspan="3">Whole Heating/Cooling System</td><td>Global Temperature Adjustment</td><td>[7] [67] [79] [80]</td></tr>
<tr><td>Passive Thermal Mass Storage</td><td>[67] [81] [82]</td></tr>
<tr><td>Supply air Temperature adjustment (SAT)</td><td>[67] [76]</td></tr>
<tr><td rowspan="3">Air/fluid Distribution</td><td>Fan Power Reduction</td><td>[67] [79] [82] [83] [77] [76]</td></tr>
<tr><td>Fan Fixed Duty Cycling</td><td>[7]</td></tr>
<tr><td>Distribution Valve Limiting</td><td>[67]</td></tr>
<tr><td>Humidifier</td><td>Fixed/modulated operation</td><td>[83]</td></tr>
<tr><td rowspan="3">Central Plant</td><td>Supply water temperature adjustment</td><td>[67] [80] [76]</td></tr>
<tr><td>Chiller/Heater demand limit</td><td>[67]</td></tr>
<tr><td>Chiller/Heater quantity reduction</td><td>[67]</td></tr>
<tr><td colspan="2" rowspan="3">Lighting</td><td>Light Switching</td><td>[67]</td></tr>
<tr><td>Stepped dimming</td><td>[67]</td></tr>
<tr><td>Continuous dimming</td><td>[67]</td></tr>
</table>

Table 5. Summary of main Flexibility Implementation Strategies.

3.1.3.3 Energy Flexibility Metrics

The final step for the assessment of energy flexibility of a building is its “quantification”, which may involve different parameters that can describe its characterization. Following the literature reviewed and the study conducted on flexibility evaluation and implementation of Demand Response strategy [70] [73] [76] [83] , the author has summarized in Table 6 the main parameters used to evaluate their applicability and potential benefits, while Figure 15 shows an example of daily load profile with the main characteristics in terms of energy, power and time.

	Metrics	**Definition**	**Unit**
Energy and Power	Potential Flexibility	The flexibility that the generic utility observed could provide, but its specific applicability is constrained by controllability and observability.	[%], [W]
	Actual Flexibility	The net flexibility that a resource may offer considering controllability and observability features.	[%], [W]
	Power	Power increase or reduction during the flexibility event.	[W]
	Energy	Total energy surplus or deficit during the flexibility event.	[Wh]
Time Characteristics	Response time	Time taken for the Flexibility Resource to respond to the event request.	[seconds], [minutes]
	Availability Period	Duration of the flexibility event during which building installation are available to provide the service.	[minutes], [hours]
	Recovery period	Time necessary to restore normal operation.	[minutes], [hours]
Rebound Effect	Rebound power	A peak in power subsequent to the flexibility event associated to the restore of normal operation.	[W]
	Rebound energy	Energy consumed to restore normal operation conditions.	[Wh]
	Rebound duration	Time period taken to return to normal operation conditions.	[minutes], [hours]
Comfort Assessment	Thermal comfort	Occupants comfort in terms of ambient temperature. Usually assessed through PVM indicator.	[PVM], [°C]
	Indoor Air Quality	Occupants comfort in terms of quality of the internal environment. Usually evaluated through the CO_2 concentration.	[ppm]
	Visual comfort	Assessment of the necessary level of illumination.	[lux]
	Occupants dissatisfaction	Quantify the percentage of occupants dissatisfied with respect internal comfort conditions.	[%]
Monetary Assessment	Monetary Savings/Incomes	Quantify the monetary benefits.	[€], [€/kWh], [€/kW]

Table 6. Summary of main Energy Flexibility evaluation metrics.

Obviously, in order to evaluate the reduction in energy consumed and in power absorbed from the grid, it is necessary to have a reference "ordinary pattern" that have to be compared to the one obtained applying a flexibility strategy.

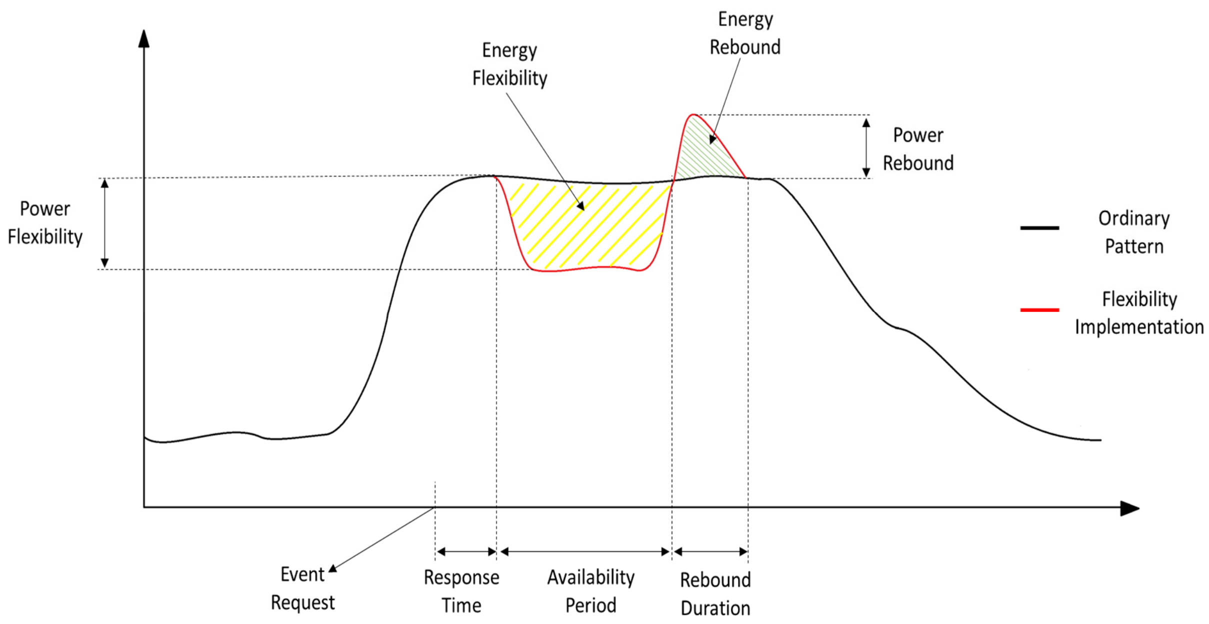

Figure 15. Representation of the main parameters that characterize energy flexible for a sample load profile.

An important effect that must be taken into account assessing Demand Flexibility potential, particularly of HVAC implementation strategies, is represented by **Rebound**. Successively to a flexibility request event, for example during a Demand Response program, the restoration to the normal operation setup of the parameters adjusted to gather flexibility could lead to a consumption peak, as showed in Figure 15. The targeted load may require an extra energy quantity to bring the system back to the pre-event operation mode. The possibility of rebound effect must be carefully evaluated and avoided, as suggested by Motegi et Al. [67], who presented in his guide some *Rebound avoidance strategies* as:

- Slow Recovery Strategy: which provide the gradual setpoint restoration of the variable targeted by the flexibility strategy implemented;
- Sequential equipment recovery: which can be applied when there is several equipment targeted by the flexibility strategy. It provides the gradual re-activation of the single pieces of the equipment;
- Extended control period: it may be usually applied when the previous two are difficult to be implemented. It provides the extension of the flexibility event to the end of the occupancy period (and so the shutting-off of the plants).

Finally, particular attention must be paid to the concept of **Reduction in Service**. Since their conception, buildings purpose is pursuing the best comfort conditions for its occupants, while target loads that may be involved in flexibility strategies implementation, represent building services designed to satisfy that comfort. As already previously, flexibility strategies that interest load utilities may affect their normal operation, causing possible discomfort effects. Therefore, in applying those strategies for some programs, as for example Demand Response, it has to be guaranteed a certain minimum level of comfort for the occupants. As a matter of fact, as said by Motegi et Al. [67], the scope of the presented strategies must be to meet the demand savings target without compromising the occupants conform and the activity that they are performing. In particular for Commercial Buildings, as suggested by Aduda et. Al [73], labour cost accounts for a consistently higher part with respect to energy cost, therefore ensuring workers comfort is a key requirement. Considering the principal load buildings targeted by the strategies discussed in the previous paragraph, main indoor conditions that have to be monitored are represented by thermal comfort, Indoor air Quality (IAQ) and visual comfort.

Thermal comfort is defined by ASHRAE 55 standards as: *"Condition of mind that express satisfaction with the thermal environment"* [84]. This definition makes understandable the subjective nature of the thermal comfort, that may be perceived differently by each occupant. Moreover, it is influenced by different factors that have to be taken into account for its assessment, which are Metabolic rate, Clothing insulation, Air temperature, Radiant temperature, Air speed and Humidity. Most diffused thermal comfort model that includes all these parameters is represented by Predicted Mean Vote (PMV) model, introduced by Fanger et. Al. in 1970 and successively adopted by ASHRAE [84] and ISO [85] standards.

Category	PMV	PPD [%]	Operative Temperature* [°C] (Winter)	Operative Temperature* [°C] (Summer)
I	-0.2<PMV<+0.2	<6	22 ± 1	24,5 ± 1
II	-0.5<PMV<+0.5	<10	22 ± 2	24,5 ± 1,5
III	-0.7<PMV<+0.7	<15	22 ± 3	24,5 ± 2,5

* Considering a clothing factor (clo) of 0.5 (summer) and 1.0 (winter), an activity level of 1.2 met, an ideal relative humidity of 50% and maximum air speed of 0.15 m/s during winter and 0.25 m/s during summer.

Table 7. Thermal comfort Standards recommendation for office buildings [84] [85].

The PMV is usually coupled with the Percentage People Dissatisfied (PPD), which is useful to understand and predict the percentage of occupants that will be dissatisfied with the indoor climate. In other cases, fixing the activity level, humidity, clothing and air speed it is possible to represent the thermal comfort through the Operative temperature, considered as the mean value between air temperature and mean radiant temperature.

Indoor air quality (IAQ) indicates the quality of the internal air of a building both in terms of health and comfort conditions. It is usually indicated as required levels of ventilation or CO_2 concentration. Differently from thermal comfort, its assessment does not vary with respect to the seasons but is affected by occupancy, kind of activity processes performed inside the building and eventual presence of emissions from equipment or furniture [86]. Usually for IAQ monitoring subsequent to the implementation of flexibility strategies, the parameter observed is the CO_2 concentration, as performed by Christantoni et Al. [76] and Aduda et Al. [87]. Table 8 summarizes main IAQ Standards recommendation.

Category	Minimum Ventilation Rate [l/s per person]		Minimum Ventilation Rate [l/s per m^2]		CO_2 levels (above external) [ppm]
	EN 15251 [86]	ASHRAE 62.1 [88]	EN 15251 [86]	ASHRAE 62.1 [88]	EN 15251 [86]
I	10		1		350
II	7	2.5	0,7	0.3	500
III	4		0,4		800

Table 8. Indoor Air Quality Standards recommendation for office buildings.

Finally, considering visual comfort, it could be related both to a safety matter than to the productivity of the occupants of an office building. As already said, labour cost has a higher impact for offices, therefore the possible discomfort must be accurately taken into account to keep as higher as possible workers productivity. European Standard EN 15251 suggest a minimum light level for office buildings of 500 lux.

Strictly correlated to the concept of reduction in service there is the one of **Acceptability.** As already discussed, for example, thermal comfort is a subjective concept that may change from user to user. Therefore, as performed by Aduda et Al. [73], it is suggestable to include in the implementation tests occupants interview in order to evaluate the grade of acceptability of the strategy tested. It can be quantified through an index as percentage of occupants dissatisfied in terms of consequent internal comfort.

3.2 Building Energy Modelling

This chapter provide a general assessment regarding building energy simulation methodology exploited in order to assess its performances and responses under different conditions. Even though it represents a very powerful tool for energy assessment, it is not so easy to obtain high-fidelity energy forecasting models for building system due to the high variability of certain boundary conditions as weather, occupancy and certain operation schedule and due to a usual lack of detail monitoring, in particular of the sub-system, related to constraints in costs.

In order to evaluate Flexibility potential and quantify the benefits obtainable with the implementation of DSM practices, it is possible to adopt two different alternatives:

- Direct approach: which provide the direct implementation of different building strategies and the observation of measurement related both to energy savings and comfort standards as performed, for example, by Aduda et Al. [7].
- Indirect approach: through simulation models to predict which could be the effects of different strategies applied as performed, for example, by Christantoni et Al. [76].

Will be seen that these two approaches are not completely independent. As a matter of fact, in the commissioning framework of DSM they belong to two different phases, the simulation for a first assessment of DSM potential and the implementation with monitoring, to control the effective working.

Since their conception hundreds and hundreds of years ago, buildings have presented as main function the separation of the human habitat inside with respect to the external condition, trying to guarantee to the occupants an ambient as much comfortable as possible. Obviously, during the years the way to assess this comfort evolved, becoming more and more accurate, effective and efficient. The great part of the systems used to provide comfort to the occupants requires energy and all of them concur to the overall energy consumption of the building system. Today, the Building is a very complex system in which different sub-systems interact pursuing the original aim of comfortability.

Building Energy Modelling (BEM) can be a useful tool in assessing the performance of buildings, both in terms of energy consumed and comfort provided depending on the model adopted. In these terms, it can be exploited for different purposes:

- Design evaluations: as for example the sizing of systems and plants installed, or the prediction of building performances in the design phases.
- Energy auditing: for the evaluation of building system performances ex-post construction.

- Simulation of interventions and control strategies: as for example Flexibility implementation strategies.

The level of detail of the model implemented is directly related to the purpose of the user. More accuracy is required, less are the physical processes that can be neglected.

As already said, even though BEM is usually exploited to perform energy analysis, buildings major scope is to ensure comfort to their occupants. Therefore, usually the results associated to the BEM can be distinguished in:

- Energy assessment: as Heat balance, Load profiles and Energy Consumption
- Comfort assessment: Temperature trends, Comfort Indicators and Daylight availability.

It is important, when evaluating the implementation of DSM strategies to continuously control the values of the major Comfort indicators, as for example the thermal ones Predicted Mean Vote (PVM) and the Predicted Percentage Dissatisfied (PPD), in order to ensure that the internal comfort of the building remains in an acceptable range.

Considering the different technologies and strategies involved in DSM and analysed in the previous chapter, excluding the planning categories, it is possible to individuate one of the main characteristics of DSM: dynamicity. Therefore, in order to assess potential, benefits and consequences related to the application and implementation of DSM it is necessary to perform dynamic building simulations that may help in predicting building behaviour under several aspects.

In this chapter will be discussed the main aspects that may differentiate a building energy model related to DSM interventions: factors considered that affect energy consumption, the simulation time-step chosen, and the modelling approach followed. Then, the attention will be focused on the RC models that will be adopted in this work for the considered case-study.

3.2.1 Factors that affect Energy consumption

The first phase that have to be accomplished is the individuation of all the factors and system characteristics that may affect the energy load and the overall consumption. Considering literature studies [82] [79] [89] and the indications presented in the international standards as EN ISO 52016 [45] [90] (accepted even by European Union and Italy) or ASHRAE [91] the author has individuated five main branches that includes the different parameters that affect building energy consumptions, as reported in Figure 16**.** Anyway, not all those parameters are always present in the model, because it depends on the decision of the user to include or neglect all the phenomenon that they represent.

External conditions probably represent the factors that major affects the energy consumption of a building. As indicated in the scheme, this branch includes climate conditions and site parameters. The first regards parameters as external environment temperature, relative humidity, solar radiation and wind conditions (speed and direction). While, the site characteristics refer to location of the building, orientation, possible shading by topography or surroundings buildings and ground properties.

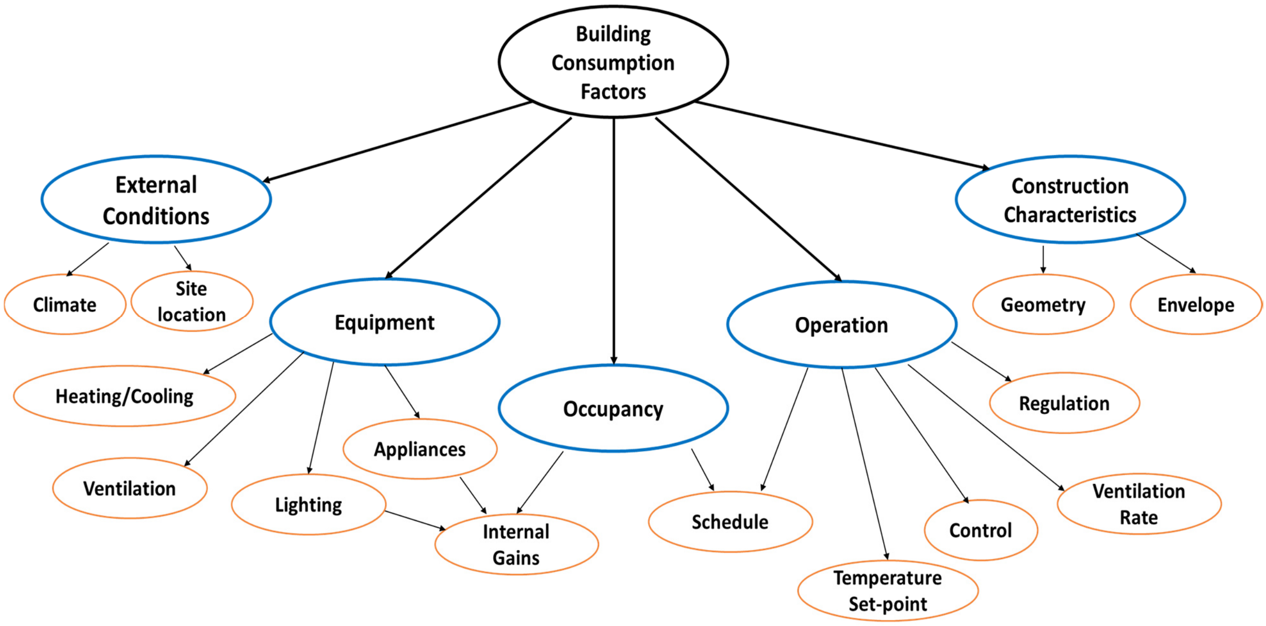

Figure 16. Factors that affect building energy consumption.

Construction characteristics includes the two major aspects related to the structure of the fabric: Geometry and Envelope. The geometry mainly refers to the shape and to the zones' geometry of the fabric, while the Envelope includes all the parameters linked to the thermophysics characteristics of the building as construction materials, windows, thermal bridges and openings for infiltrations. The Envelope characteristics are very important for DSM activities because reflects the thermal mass properties of the buildings, which represent the thermal inertia of the building to the changing of the external conditions.

The two aspects presented previously, are the characteristics that mainly concern to the structure of the fabric. In addition, it is important for building energy simulation models to consider even the so-called "building-system" interaction. In order to capture even this aspect, it has to be added to the model the equipment installed and the logic that constitute the operation and regulation conduced.

The **Equipment** refers to the typology and installation characteristics of all the systems present in the building to satisfy the main services required from the occupants, identified in: Heating, Cooling, Domestic Hot Water (DHW), Ventilation, and Lighting. It includes the central unit plants, which generate and/or transform the energy, eventually store it, the distribution system, to the diffusion equipment of the service in the different rooms of the building. Obviously, the kind of equipment installed may change a lot depending on the destination of use of the fabric.

In addition to the major systems, it is important to consider even other appliances, because even though their energy consumption is relatively small with respect for example HVAC demand, their operation contributes, together with lighting and occupancy, to the internal gains, which represent both a positive contribute during the heating season, while an additional load during the cooling season.

Occupancy refers to the presence rate of people in the building during the analysed period and it is a very important aspects for building energy modelling, whose modelling and prediction is largely studied because represents one of the most stochastic elements in BEM [92] [93]. The first contribution of the occupancy is related to the internal gains, because it is necessary to consider an additional contribution to them that becomes from the metabolic rate of the people present in the building. In addition to the internal gains, the occupancy may be also related to a behavioural factor, another stochastic source that can strongly influence the energy consumption. Occupancy may even be related to the schedule of the equipment installed. As a matter of fact, instead of the on/off-time control of the services, an efficient way to regulate their operation is to relate it to the occupancy pattern [93].

Finally, **Operation** refers to the regulation of the technical systems, the control strategies implemented, the set-point values of the different systems in terms of temperature, ventilation rate or CO_2 concentration, etc. It refers both to the control of the central units for the generation and/or transformation of the energy but even to the control of the single zones or single rooms ambient conditions. Besides the regulation and control, there is the schedule of all the systems, which may be characterized by a fixed on-off at specific times, roughly related to the occupancy, or can be direct correlated to a predicted occupancy pattern previously elaborated.

3.2.2 Calculation method

The calculation method is mainly related to the time-step chosen for the building performance simulation which constitute the resolution of the output provided. As a direct consequence, it has to be considered that even the time-variant input data, as for example weather conditions, must reflect the time-step chosen for the simulation. In relation to DSM purposes, it must be chosen in relation to the implementation strategies that the user wants to analyse.

Through the study of the literature analysed [94] and the indications of the ISO standards previously indicated, it is possible to individuate three main categories of calculation methods:

- Steady-state models
- Quasi steady-state models: which are based on steady-state calculations but introduce dynamic effects through correlation factors related to standards empirical utilization factors. These kinds of models are often applied with monthly time-steps and so uses aggregated input data represented by average monthly values, to provide outputs that

are mostly related to the overall energy consumption. Generally, these methods are used for the fulfilment of the EPCs (in Italy the Attestato di Prestazione Energetica, APE), that gives as results energy performance indicators that categorize the building under investigation with respect to a reference one. They are more indicated for Energy Efficiency interventions and more qualitative evaluations, because of their reduced resolution that would not allow to capture programs of smaller time-scale.

- Dynamic models: present an improvement that is not related with the accuracy of the result. Dynamic models are chosen to capture the effect correlated to the influence of dynamic parameters that can have both an external nature related to the weather, as for the daily variation of the external temperature, or an operational one, related for example to the daily occupancy of a building. Obviously, this kind of models, in relation to the time-step chosen, require input data with a higher frequency. With respect to monthly methods models it is possible to observe and so to account for more variable conditions. Regarding the time-step used in dynamic simulations, in relation to DSM strategies evaluation, it is possible to individuate two main choses:
  - Hourly models: a good starting point to estimate energy and cost savings related to different implementation strategies and technologies, from Energy Efficiency to Demand Response.
  - Sub-hourly models: mostly used for evaluations of changing in the load pattern in a time frame smaller than the our or necessary to the assessment of the technical feasibility of certain DSM programs. For example, 15 minutes time-step models are generally sufficient to observe interesting load variabilities due to certain factors, while for programs whose request event belongs to ancillary services, minutes or sometimes seconds time-step are necessary because of the required very short time response.

Generally, the choosing among the different time-steps, and so the calculation methodologies, must be conducted considering different criteria, among which the purpose of the analysis, the effect that would be observed and the technical system on which the user wants to operate. In term of flexibility of the model developed the best choice to do is to take the time-step as small as possible. This because, aggregating the outputs, it is possible to do the same evaluations and considerations of larger time-step models. On the other hand, smaller time-step require input data which are more difficult to be gathered and a computational time that for large buildings and so complex models could not be negligible.

3.2.3 Modelling Approach

Then, after the evaluation of the input parameters that constitute the factors that affect the building energy consumption and the time-step simulation which characterize the quality of the result obtained, it is important to considerate the approach that the user adopt. It is possible to distinguish three main kind of modelling typology with respect their physical or numerical characteristic, as show in Figure 17 and well described by Li et Al. [95].

White-box models, also known as forward modelling approach, are mainly based on a very detailed physical description of the building system under investigation, including all the sub-systems. They are characterized by a very good capability in capture all the building dynamics but requires lots of time bot for their development and solution.

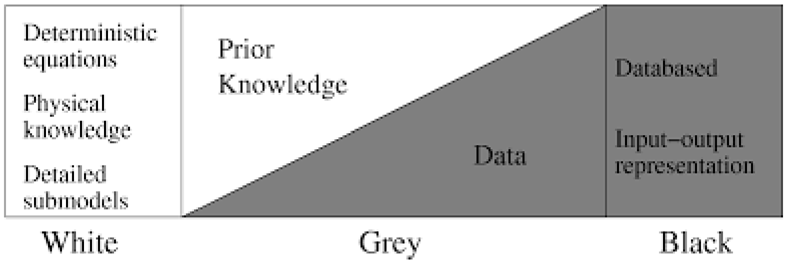

Figure 17. White, Grey and Black-box energy models' relation. (Henrik Madsen)

All the physical characteristics required, including building structure, building systems and equipment may be obtained from design plan, manufacture information or direct on-site measurement. Then, the core of the model, represented by a simulation engine based on mathematical equations, simulate the building operation and evaluate all the output requested by the user in terms of energy, comfort or even economic evaluations.

They require a lot of time and accuracy to be set up in the proper way, because every detail of the building structure and the system installed is required. Anyway, high attention and effort in the development of the model is reflected in a very good accuracy in capture the system dynamics and in a high flexibility in simulating the system behaviour under different conditions. The time-consuming development and the high computational time required make White-box models not so indicated for real-time energy consumption modelling applications.

In the context of white-box based energy models, software tools as EnergyPlus, developed by the US Department of Energy, and TRNSYS are widely use, even for DSM strategies evaluations [4] [76]. EnergyPlus, in particular, is a text-based software that is usually coupled with user interface systems as for example OpenStudio which slightly simplify the labour of the user, allow having even a view of the building system analysed. The main advantage of softwares based on the EnergyPlus simulation engine, is the presence of several tools that, after the development of the model, allow the user making lots of kind of analysis. For example, concerning DSM strategies analysis, a very useful instrument is the Energy Management System (EMS) section, which allow the user to simulate the behaviour of a virtual building EMS and to program it in order to studies different kind of strategies and programs [96].

Obviously, they represent the only one chose in case of any evaluation during the design phase, because there is no availability of measured data.

On the other hand, it is possible to individuate **Black-box** models, which are completely data-driven models that exploit statistical instruments in order to match the model's parameters to the building energy consumption. Usually, the are also known as "inverse models", because the starting point is represented by energy measurements, which have to cover a sufficient period and are used to train the parameters of the model to be able to forecast the energy consumption in different situations. Most diffuse methods for the parameters tuning are regression techniques or Artificial neural networks (ANNs). Comparing these kinds of models to White-box ones, the main characteristics that emerge are an easier development, a strongly higher computational efficiency, but longer training periods. Moreover, in substitution of the huge amount of model's parameter required for white-box typology, black-box contains fewer aggregated terms that often lose any physical meaning. A critical aspect that have to be taken into account is represented by the fact that black-box models are less flexible than white-box ones because strongly dependent on boundary conditions to which they have been trained for, therefore forecasting errors may occur when the training period and data do not cover all the possible operation conditions. [91] [95]

Finally, it is possible to individuate **Grey-box** models even indicated as hybrid models. They try to include the advantages of both the previous presented models using a simplified physical description to simulate the behaviour of building energy systems together with the identification of model coefficients through statistics or parameter identification methods. Therefore, with respect to White-box models require a smaller amount of physical data and a reduced calculation time, while differently from Black-box models needs lower amount of measured data for the tuning. Particular diffused in this branch are Lumped-Capacitance models, useful to evaluate the thermal behaviour and so to forecast the heating or cooling load of the building.

The research is focusing its attention to the study of simple dynamic models. Grey-box ones, in particular, thanks to their flexibility and low computational time, are being largely studied for Model Predictive Control (MPC) purposes. The latter represent an advanced approach of process control which evaluates the optimal input for a control system, while satisfying a set of constraints. Concerning building applications, an effective application is correlated with HVAC systems and it is used to evaluate at each time step the optimal control input with respect to the forecasted demand of the conditioned spaces [94].

4. How to approach in Buildings

All the features examined in the previous chapters, directly related to Demand-side management or indirectly linked to it through tools and methodologies exploited to forecast and assess its effectivity, suggest the necessity to follow a clear procedure to evaluate its implementation from the preliminary studies, related to its potential, to the practical implementation in a building. Moreover, these frameworks become even more necessary and not so trivial in analysing medium-large buildings in which the application of any program starts with coordination matters among the different actors involved. Therefore, using as starting point the literature analysed, the author aims at providing to the readers, a most general and clear base to follow considering as relevant additional source its experience in the case-study analysed in the following chapter. It will be referred to commercial medium-large buildings, because of the case-study chosen for this thesis work but considering and accounting for the differences related to the use destination, the process presented can be adapted to any situation and building because it mainly represents a guide to the users for the developing of the different phases.

4.1 Commissioning framework

Motegi et. Al [67] proposed a general framework from the gathering of information to the verification of the effectiveness, in order to ensure the main objectives of these implementation strategies: maximize the demand savings while minimizing the impact to the occupants. The process has been slightly integrated in order to be as general as possible, including even the experience made by the author. It can be summarized in the following phases:

1. **Information gathering**. It regards the collection of all the information available and that can be useful in planning flexibility strategies. They may include the building type, the building floor area, the systems installed for the different services (HVAC, lighting, etc.), the Building Automation and Control System (BACS) characteristics and operation methodologies and finally the historical energy consumption data. It represents one of the most fundamental phases about the knowledge of the system analysed. Without the complete knowledge of the system it is not possible to evaluate the reliability of flexibility strategies and the benefits related. This phase will be discussed more in detail in the following paragraph, because even though may seem to be the simple one, it could represent a tough obstacle.

2. **Building performance simulation.** Considering the system applicability of the different flexibility strategies and accounting for the programs chosen, it is necessary to

develop a simulation tool that should be able to assess the benefits and effect of the strategies analysed.

3. **Strategies sequence of operation.** It is the phase in which the strategy implementation procedure, considering the different constraints related to system applicability, comfort, etc., is developed as a detailed control sequence of operation that in the following phase have to be simulated, programmed in the BACS and tested.
4. **Potential estimation.** It includes the simulation of the different strategies chosen and analysed through the developed tool. This phase is necessary to asses two main aspects: the potential energy and cost savings to justify the implementation and eventually the project investment and the eventual burden caused to the occupants by the strategy implementation.
5. **Performance monitoring plan.** The simulation tool may only give a preliminary evaluation of the strategy analysed. The second step is to test practically the implementation. In order to evaluate the good operation during the test it is necessary to monitor the evolution of different parameters involved in the test. Therefore, this monitoring part have to be planned in advance in order to understand and decide which parameters have to be observed, to individuate the necessity of installing additional measurement instruments and how those data have to be collected.
6. **Proof-of-concept Manual test.** It represents the first manual test used to have a first evaluation of the applicability in terms both of effective energy savings and technical problems. Beyond the individuation of operational problem, monitored data have to be collected and their trend analysed. Therefore, the results mast be compared to the estimations obtained from the simulation tool. Programming the manual test is not so easy because it has to be considered different aspects affected by variability as weather, occupancy, etc.
7. **DR strategy proposal.** The control strategy whose simulation and test have result successfully are presented to the building administrator in a proposal together with their sequence of operation and the related economic plan with costs and benefits.
8. **DR strategy installation.** In case of acceptation of the strategies presented, the additional instruments eventually needed are installed and the sequence of operation is programmed in the BACS.
9. **Post-installation test.** Test useful to evaluate, after the installation, the correct execution of the sequence of operation and the effective benefits, estimated in the previous phases. The most useful instruments of this phase are the data collected by the BACS. In particular, the parameters directly and indirectly controlled during the

sequence of operation, must show changes in certain moments as planned, otherwise the programming of the BACS have to be checked.

10. **Measurement and verification.** The data monitoring should be continued even after the final tests, in particular when the Demand Response events occurs. This phase is necessary because the post-installation test is done in specific conditions that may vary a lot during days and seasons. The data collected in this phase must be used as a retrofit to calibrate the strategies to maximize the savings while minimizing the burdens to the occupants. As already discussed in the previous paragraph, it is suggested to include in the verification through measures, an interview of the building occupants in order to take into account even the subjectivity of the internal comfort perception.

It is not so trivial to conduce in the proper way the entire commissioning framework. Anyway, it is necessary to follow a structured path in order to minimize the risk of burden to the occupants.

Moreover, there is another aspect that have to be taken into account, in particular for medium-large buildings: the management organization. It is made up of several actors which have different roles in the organization and their coordination is necessary for a good conduction of the building and for the good implementation of any planned intervention. Each of the actors have different roles even in the structured framework presented, whose role is related to their general position in the organization.

4.2 Building Management Actors

It is necessary to identify all the actors that may be involved in the energy management framework of a building, considering their general role and the associated one in a DSM application scenario. It is important to consider that the coordination of all the players is essential for the optimal assessment of all the targets. As already said, the framework presented, and the relative actors involved are mainly related to medium-large buildings (or complexes) as the case-study analysed in the following chapters. Concerning the actors presented, they may vary from case to case even in relation to the size of the building/complexes under observation. As a matter of fact, the single players presented, in some cases, may be aggregate and cover more than a single role.

The first actor individuated is the **Building Administrator**, delegated by the **Owner** for the management of the building, or the owner itself. Its role is to establish and indicate the different goals in terms of energy that have to be pursued. It is the figure that express the approbation for all the eventual intervention and programs that have to be applied even considering the eventual necessary investments. Obviously, the main interest remains to ensure the buildings occupants comfort. In a DSM scenario, the main role of the Building Administrator is to coordinate all the figures involved in pursuing the target established by the Owner. These targets may be related to the cost savings or to the prestige related to the application of DSM strategies in the building.

Then, one of the most important agents in the energy framework of a building is represented by the **Energy Manager**, whose role in Italy is specified by the UNI CEI 11339 [97]. It is hired by the Owner/Building administrator and its main role is to monitor the energy consumption of the building and promote energy efficiency interventions and adoption of renewable energy sources. It conduces accurate analysis for the optimization of the consumption looking at the state of art of the equipment installed and the regulation and control strategies adopted. As a matter of fact, in addition of having energy efficient plants installed, it is even essential to optimize their operation. In a DSM context its role is to evaluate if the strategy analysed may lead to benefits in terms of energy savings and so costs. It is the Energy manager that have to choose the optimal strategies, in case there are effective ones, and prepare reports to present the Administrator the results of the analysis, the eventual benefits related to its application and the costs for its implementation.

Facility managers, which for complex institutions may belong to the so-called technical office, includes all the responsible for the management and regulation of all the technical systems installed in the building, from the generation to the distribution part. Their main role is to directly, or indirectly through remote control, intervene on the regulation in order to ensure the occupants comfort or to apply energy manager optimized solutions.

With respect to Administrator and Energy manager, which are always interested in the application of DSM that can lead to benefits, Facility managers may be the most reluctant. It is not related to the benefits associated to DSM but to the fact that it need intervention on the automation system and so on the operation of the equipment. Buildings may be very complex system and ensure their correct operation may not be so trivial. This is the task of the Facility managers who must ensure the correct operation of all the equipment installed to guarantee the comfort of the occupants, therefore they may result unwilling in operating modification to the automation systems. Usually, to provide access of the monitoring system to all the interested parties, they prefer to separate it from the automation system to avoid conflicts and malfunctions.

The **Controls contractor** is often represented by a company specialized in the control and automation of the technical systems of a building. They are hired by the owner/building and install and programs the BACS, that automate the operation of the equipment and at the same time allow the user to have a remote control and to monitor the operation through the installed sensors. Operating on the BACS installed by the controls contractor it is possible to set-up the operation of the different equipment following different strategies, as for example changing the temperature set-point of the HVAC or the on/off times of the ventilation system. Buildings are not always equipped with automation and monitoring systems. As a matter of fact, even though those kinds of systems are incentivised and sometimes are required by the regulation, not all the existing building have been renovated and dispose of such systems. In a DSM scenario, they have to provide the building of all the necessary control systems for the application of the strategies evaluated. Moreover, charged by the administrator, they have to program, or support the facility managers in programming the Building Automation and control System (BACS).

In case in which an automation and monitoring system is present, for large buildings and complexes, as for example university campuses or big industrial sites, there could be present the **Energy Monitoring Staff.** These team are mainly composed on experts in automation and communication and their main mansion is to collect and make accessible all the data related to the points monitored to the other parties of the building organization. Considering big building and complexes, their work is very useful to easily and quickly detect anomalies in the energy consumption of the system under observation. In DSM commissioning phases, their role is to have access to the monitoring system in order to collect and provide to the other parties all the measurement data requested in the different phases, from the development of the simulation model to the verification of the effectiveness of the strategies implemented.

In complex organizations, there could be even the presence of **External Partners.** Obviously, they are represented by expert company in the sector of energy. They could be represented by ESCO companies, Flexibility Service Providers (FSPs), Aggregators or more in general by players that provide energy services. Considering DSM application, external partners may represent third parties that are charged to study and implement the strategies, so may substitute several roles presented, or can be useful to support the other parties in specific tasks. For example, in order to make the building internal organization independent with respect to the controls contractor in energy monitoring, external partners may provide an additional independent system for the monitoring. In this context, in terms of competition, the intervention of External partners may be cheaper than controls contractor leading the user to reduce the costs. Moreover, considering medium-small building and their reduced management organization, the different players may not have the necessary competence to lead the work independently. In this case, the hiring and intervention of specialized external partners becomes necessary.

Finally, in the context of energy monitoring, study and application of DSM strategies and more, there is another figure that is not always present in the building organization: **Researchers.** They can be part of the framework in particular in University campuses applications, as for the case-study analysed, research centres. Their role is principally academic and aims at contributing to the university research. At the same time, they can support the other actors in suggesting and providing analysis instrument and conducing more accurate studies. Concerning DSM, their role is approximately the same because their aim is always to conduct research study. Anyway, they can provide different contributions to the other players during the different phases as for the development of the simulation tool or the study of the different strategies and methodologies used in other application cases presented in literature.

In the following paragraphs, the authors will refer to internal staff which includes the administrator, the energy manager, the facility managers and the energy monitoring staff, actors that belong to the building organization.

As already said, the coordination of all the actors presented is necessary within any scenario in which the building systems is involved, from the normal operation to any intervention and program that would be implemented. In the author has tried to summarize the principal roles of the different actors presented in a general context and in a DSM application scenario.

Therefore, it is important to assess and correlate the different phases presented with the different actors which may have different roles in each phase. As already said, the framework and the actors discussed are mainly related to medium-large building contexts, so even the relations are principally correlated to those cases. Anyway, all the discussion keeps its value because for different application cases would be necessary to reconsider the eventually aggregated roles in single actors.

The involvement of the different actors presented in each phase mainly depends on their general role discussed in Table 9.

	General	DSM
Building Administrator	Coordination of all the figures and resources at disposal. Follow owner indications.	Charge the different actors to study and implement DSM and coordinate their work in the whole commissioning framework.
Energy Manager	Monitor energy consumption while proposing energy efficiency interventions and use or Renewable energy sources.	Evaluate the effect of the application focusing the attention on cost savings or any other target established by the owner/administrator.
Facility Managers	Manage the scheduling and operation of equipment. Program technical system manutention.	Act to modify the operation set-up of the equipment.
Control Contractors	Install hardware and software automation and control system.	Provide support to program the BACS and modify initial algorithms.
Energy Monitoring Staff	Collect monitoring data making them accessible to other players.	Collect the data of the monitored points during the whole process.
External Partners	Directly charged to study and implement interventions or can provide support to internal players.	May be directly charged to conduce the whole work of study and implementation or may provide support during specific phases.
Researchers	Exploit all the resource available to contribute to the academic research.	Use the building as case-study to develop simulations models or evaluate new DSM strategies.

Table 9. Actors' role in a general perspective and in a DSM scenario.

Therefore, in the following Table 10, the author tries to provide a general overview of the phases and the respective actor which may be involved in.

	1	2	3	4	5	6	7	8	9	10
Building Administrator	X									
Energy Manager	X	X	X	X	X		X		X	X
Facility managers	X		X			X		X	X	X
Controls contractors					X			X		
Energy Monitoring staff	X				X	X		X	X	X
External Partners	X	X	X	X	X	X	X	X	X	X
Researchers		X	X	X	X		X		X	X

Table 10. Actors-phases interaction.

As it is possible to observe, for the External partners, the table indicate that they may participate to all the phases. This is due to the fact that, as already mentioned previously, their involvement depends on their field of specialization and the motivation that led the administration to their hiring.

4.3 Information gathering

As mentioned in previous paragraphs, this phase is fundamental because without the necessary information it is impossible to conduce any analysis and so make any evaluation about the possibility to apply DSM. In addition to the development of the simulation tool, the knowledge of all the information related to the building system is necessary to understand even the applicability of certain strategies and the level of automation that could be implemented. Obviously, the analysis conducted, the choose of a certain simulation tool methodology and so on, depend on the availability of data. In general, more data are available and more accurate are the data, more accurate analysis can be conducted. It is possible to distinguish different kind of information that could be necessary to assess the applicability and potential of the strategies that the user would investigate, among which the first two are mainly related to the factors that affects the energy consumption, discussed in Paragraph 3.2.1. Therefore, in the following will be presented the three main phases suggested by the author, which represents the three main source of information that the user should consider.

1. **Design Information**. They can regard both the building, or the system installed. In addition to the development of the building energy model, they could be useful to assess loss in efficiency of the equipment and/or the possibility to substitute the system with a more efficient one. Regarding the design characteristics of the envelope, they could be useful to evaluate renovation interventions with respect to their thermal behaviour. Among the principal information about the design phase of the building, it is possible to individuate:
    - Energy vectors that are used or available;
    - Equipment installed: information about all the equipment installed in the building necessary to satisfy the different services which need energy to work, including production, transformation and distribution.;
    - Thermophysical characteristics: walls stratigraphy with the respectively thermal properties and windows characteristics;
    - Spaces subdivision and organization with the different service presence or not. (for example, conditioned and unconditioned spaces)
2. **Operation Data**. These kinds of data are strictly related to the operation and occupancy consumption factors exposed in the energy modelling chapter. As a matter of fact, it is possible to summarize as most important information:
    - Architecture and set-up of BACS system;
    - Set-up values of the technical systems;

- Technical systems scheduling;
- Occupancy profiles of the different areas of the building;

3. Moreover, as already mentioned in the previous paragraph another important kind of information regards the energy historical data. Even in for this kind of information, there could be different types of data that can be generally individuated as, **Monitoring Data**. Depending on the measurement acquired, they could be useful to individuate and investigate the presence of peaks in the load curve or to assess the electricity consumption brake-down, individuating the most energivorous services, and could be used as input, calibration or verification data for the simulation tool.

Whole building	Whole building power demand	
HVAC system	Zone control	Zone temperature Zone setpoint temperatures VAV damper position VAV airflow Reheat valve position
	Air distribution	Supply air temperature Return air temperature Outside air temperature Outside air damper position Fan power Fan status Fan VFD percent Fan airflow Duct static pressure
	Central plant	Chiller power Chiller status Chilled water supply temperature Chilled water return temperature Chilled water flow Cooling tons
Lighting system	Lighting power Light levels	
Other equipment	Power of target equipment Status of target equipment	
Weather	Outside air temperature Outside air humidity	

Figure 18. Recommended data collection points. [67]

Depending on the capillarity of the Monitoring System, it could be possible to dispose of different kind of data as:

- Energy consumption measurement for each meter installed in the building. Depending on the presence and distribution of the monitoring system, it could be possible to have the energy consumption for each energy vector or, better, of all the major energy services installed in the building, allowing to make a breakdown of the overall consumption.
- Load profiles both overall and for the different energy services.
- Energy related parameters, which includes all the parameters monitored that can be linked to the energy consumption and can be useful in assessing the comfort and for the development or verification of the simulation tool. The most important are represented by rooms temperature, presence or access sensors or the measurement of the sensors installed on the different technical systems.

Following the presented and discussed strategies, Motegi et. Al [67] proposed a set of recommended data collection points, reported in Figure 18, that can be used as a starting point for the gathering of monitoring information and to evaluate the necessity to install additional meters.

4.3.1 Information sources

The disposal of all the information presented could not be so obvious. In addition, for medium-large building the not so simple structure of their organization could make the gathering of such data not so trivial. By the experience of the author, it has been possible to individuate different **sources** that can provide the data searched by the user:

- The Building Automation and Control System (BACS): it usually presents the possibility to log the monitoring data locally or in a server.
- Documentation: that can regard project documentation, or any other relation that tells about any modification made to the building. The two main source of documentation are represented by:
  - Technical relations: related to all the building components, from the envelope elements to the equipment installed;
  - Technical diagrams.
- Technical Staff Interview: Different actors previously presented may have already done inspections and other works that could provide important information. Most important figures may be considered the Energy Manager, the Facility managers and the monitoring staff.

- Inspections: both to fill up the lack of information mainly usually due to poor documentation but even to verify the information available.

Even though the technical staff interview has been proposed as an additional source, their contribution is essential even to have access to the previous two information sources because they can have direct access to the BACS of the building, and they can have collected the project documentation. In other cases, when this kind of information is not available for the internal staff of the building, the user has to follow a different path in order to obtain such data. In the following Table 11, the authors try to provide a general overview of the main data needed, the source of this kind of data and the actors that can be involved in their gathering as a guide that can be used to understand “where” to find the information needed.

Information	Source	Actors involved
Design information	• Documentation. • Technical staff interview. • Inspections.	• Facility Managers • Administrator • Energy manager • Municipality Technical Office
Operation Data	• BACS • Technical staff interviews.	• Facility Managers • Controls Contractor
Monitoring Data	• BACS • Independent monitoring system.	• Facility Managers • Controls Contractor • Energy Monitoring Staff

Table 11. Information, source and actors correlation.

It is possible to observe that in the previous table it has been mentioned an actor which is completely external with respect to the framework presented for DSM implementation, the Municipality Technical Office. Anyway, the availability of the needed Documentation, in particular relative to design information or any other intervention made to the building, by the internal staff is not an obvious thing. In such case, different technical documents and, in particular, technical diagrams can be collected by the Municipality Technical Office, where the responsible of the project or the interventions have deposed them.

Another aspect that the authors consider important to be specified regards the reliability of the information contained in the documentation. First of all, documentation availability is influenced by the age of the building, because newer is the building, higher is the possibility to have a more complete and reliable documentation at disposal. Moreover, the most important documentation that is needed, but not always available, is the As-built one. Considering the five main general phases individuated in the documentation of a building from the initial project to the construction (Figure 19) it is essential to consider that, older is the document with respect to the framework less reliable are the information contained.

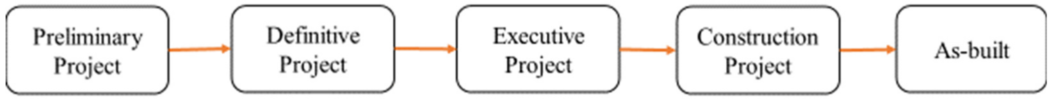

Figure 19. Phases of building project documentation.

The As-built documentation is the only one that contain all the modification that have eventually been done to the building during the construction phase. Therefore, as often suggested in literature and regulations, the best way to assess the reliability of documentation information, in particular to the ones that are drafted before the construction, is to perform inspections.

5. Case-study: The Energy Center

The Energy Center is an office building of Politecnico di Torino built in the ex-Westinghouse area, at the address of Via Paolo Borsellino, 18 in Turin.

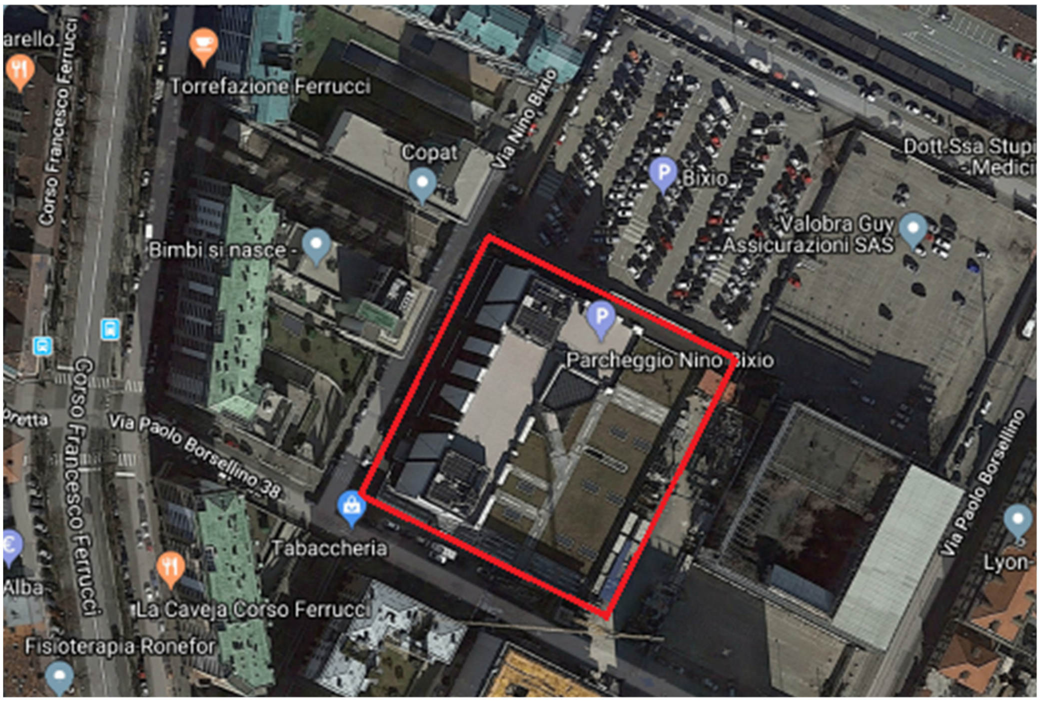

Figure 20. Satellite Map of Energy Center site location. [98]

The idea of the construction of an Energy Center go back to 2008. It has been conceived as an environment whose aim is to collect places, actors and knowledge which pursue the innovation in energy and environmental field. The conceived role was to represent a reference at European and national level for innovative programs and plans in relation to the energy sector. Therefore, it should collect the different needed knowledge in a single place coordinating public and private entities, promoting study and technologies evaluation and providing support to both public and private institutions. As a matter of fact, in 2017 the Polytechnic University of Turin launched the Energy Center Initiative (ECI) to develop a series of actions and projects that will provide support and advice to local, national and transnational authorities on energy policy and technology starting from the City of Torino. Demand-side Management represent an opportunity for the Energy Center Initiative in pursuing its mission. As discussed in Chapter 2, the practice is not so diffuse in Italy, therefore the Energy Center could represent both a reference for knowledge and competence but even a practical example of implementation in a real building of DSM strategies.

Therefore, in this thesis work it has been investigated about the flexibility potential of the building. Considering the commissioning framework presented in Paragraph 4.1, it has been performed some of the phases discussed, focusing the attention of the “preparation” to eventual future implementation of Demand-side Management practices.

At the beginning, great deal of effort has been dedicated to the first phase of the process, the information gathering. As already explained, having a complete knowledge of the whole building system is essential for the study of DSM potential and its future implementation. The steps performed in this phase and the main critical aspects encountered has been furtherly discussed in the following paragraph. Then, for a more complete knowledge of the “energy behaviour” of the building, an energy monitoring phase has been conducted. Therefore, following the gathering of information and data, an analysis of the available data has been conducted in order to have a clearer understanding of the actual operation of the systems installed and their contribution to the building energy consumption.

Due to high complexity of the building and lack in completeness of information and data provided, the development of a simulation building energy model has been excluded. Anyway, exploiting the available information and the overall view of the building systems acquired, an analysis on the potential effects of different DSM strategies has been conducted. In particular it has been speculated about the possible effects on the consumption profiles, but even on the consequent possible internal discomfort.

Moreover, in a view of a future implementation of DSM practices, all the strategies analysed have been discussed even in terms of controllability and observability. Therefore, it has been performed a preliminary step of the performance monitoring plan phase, in order to understand the potential of applicability of the strategy analysed and the eventual deficits in the monitoring system.

5.1 Information and Data collection

Following the planning methodology presented in Paragraph 4.3, it has been collected several kinds of information about the building. It has been not so easy to perform this work due to the different figures involved in the Energy Management of the University organization.

Firstly, the work has been focused on the first phase discussed in the methodology presented: the acquisition of all the available design information. It has been conducted a time-consuming study on Project documentation provided by the Living Lab. Anyway, it has been suddenly individuated the first critical aspect represented by scarce organization of documents and lack in clearness of information presented inside them. Therefore, following the prescriptions presented in Paragraph 4.3.1 the first work conducted has represented the cataloguing of the different documentation at disposal differentiating them with respect to contents and date of drafting. In this way, it has been possible to select the most reliable documentation, usually represented by the most recent one, and so As-built documentation.

Moreover, during the study of the documentation, that includes even equipment technical data sheets, it has been founded several inconsistencies in information provided. Therefore, in order to solve such inconsistencies two main source of information have been exploited:

- Technical Staff Interview: it has been organized several meetings with Facility managers, the staff responsible of University buildings technical systems O&M.
- On-field inspections: it has been performed different inspections to check or correct the information provided by the technical documentation.

In addition to project documentation, staff interviews have been necessary to carry out even the second phase of Information gathering, described in Paragraph 4.3.1: Operational data collection. It has been necessary to have an overall idea of the actual set-up of the different plants and equipment and so to rebuild their scheduling. Moreover, in order to a have a better idea of the typical occupancy profiles, it has been performed a simple interview to the reception staff.

Finally, considering the last phase of information gathering, which regard historical measurements, the main data source exploited has been the monitoring staff, represented by the Living Lab. At the beginning, the data provided were the one acquired by data loggers installed by Politecnico staff and mainly regarded the electricity vector, in particular the measurements available included:

- ➢ Electricity Withdrawal;
- ➢ Electricity Injection in the grid;
- ➢ Electricity Consumption of Polyvalent Group;

- Electricity Consumption of Absorption Chiller;
- Electricity Consumption of fluid Distribution System;
- Electricity Production of PV panels.

Anyway, even for historical data it has been suddenly encountered a critical aspect about the quality of available measurements. As a matter of fact, different missing was identified for several variables monitored, particularly regarding PV plants, as will be further discussed in Paragraph 5.3.1.1.

In addition to the not so good quality of available historical data, the monitoring system lack of different information useful to rebuild the overall energy consumption of the building, in particular regarding the heating system. Moreover, the presence of a sophisticated Supervision system, further discussed in the following paragraphs, suggests a high potential in terms of monitoring that it is not already completely exploited due to the recent construction of the building. Therefore, it has been organized several meetings with all the figures involved in the Energy Management of the building, in order to understand the state of art of the internal monitoring system and to plan the necessary improvement. During the work conducted, two main interventions have been conducted regarding the monitoring system:

- Request to the District Heating supplier of building monitored consumption data;
- Organization of meetings with Controls Contractor in order to clearly understand the potential of the BACS system installed and to perfectionate its state in terms of variables monitored;

Thanks to technical staff request it has been possible to have access to District Heating supplier web portal and to acquire the related consumption measurements. While, about the internal monitoring system, the first meetings with Control Contractor have led to a first setting-up of monitoring system through which it has been possible to acquire the internal temperature measurements of several ambient controller installed in building rooms. Anyway, the system still needs more and more improvements. Temperature measurements presents lots of outliers and the location of related controllers is not already exactly known. As a matter of fact, those data have been used only for initial rough and simple estimations.

In the following paragraph, the authors will present the main information collected about the Energy Center, focusing the attention on its energy systems.

5.2 Description of the building

The building is constituted of a single block, of about 30000 m^3 of gross volume and 5441 m^2 of net surface. It is developed on four floors and a basement whose main areas partitioning is reported in Table 12. The **Basement** presents an underground parking area of about 50 parking spaces, equipped with two charging stations for electric vehicles, and an internal space that will hosts the Energy Center Lab, an office area for researchers. Moreover, the basement presents the technical rooms that host heating and cooling plants, fluid distribution system (pumps), two of five Air Handling Units (AHU) installed, the Uninterruptible Power Supply (UPS) group and the emergency diesel generator. The **Ground Floor** hosts an exposition Hall, that develops for all the other three floors, with a reception station, an Auditorium with approximately 150 seats, and a Laboratory. The **Mezzanine level** present the control room where it is installed the PC Room through which it is possible to manage the Supervision system of the building. Finally, the first, second and third floors present the Offices spaces that accommodate private enterprises and researchers of the Politecnico di Torino.

<table>
<tr><th colspan="2">Intended Use</th><th>Surface [m²]</th></tr>
<tr><td colspan="2">Basement Office (EC Lab)</td><td>327</td></tr>
<tr><td colspan="2">Hall</td><td>270</td></tr>
<tr><td colspan="2">Control Room (Mezzanine level)</td><td>80</td></tr>
<tr><td colspan="2">Laboratory</td><td>460</td></tr>
<tr><td colspan="2">Auditorium</td><td>160</td></tr>
<tr><td rowspan="3">Offices and relative services</td><td>Floor 1</td><td>985</td></tr>
<tr><td>Floor 2</td><td>986</td></tr>
<tr><td>Floor 3</td><td>997</td></tr>
</table>

Table 12. Summary of main areas subdivision.

In the following paragraphs main energy systems installed at the Energy Center will be presented. Generally, the energy services of the building are satisfied through two main energy vectors:

- Electricity, through the connection to the medium-voltage electricity grid;
- Heat, through the connection to the District Heating network of the city of Turin.

Moreover, the Energy Center presents other two on-field Renewable energy sources:

- A Photovoltaic system with a total installed Power of 47 kW for the production of electricity;
- A Solar thermal plant of 30 m^2 for hot water production, mainly destinated to DHW use.

5.2.1 Photovoltaic System

The Energy Center presents a grid-connected PV system of about 47 kW of power installed, which is subdivided, as showed in Figure 21, in four smaller plants, whose main characteristics are reported in Table 13. In particular, it is possible to individuate two free-standing installations in correspondence of Stairs A and B and two building integrated solutions for Hall Façade and Coverage.

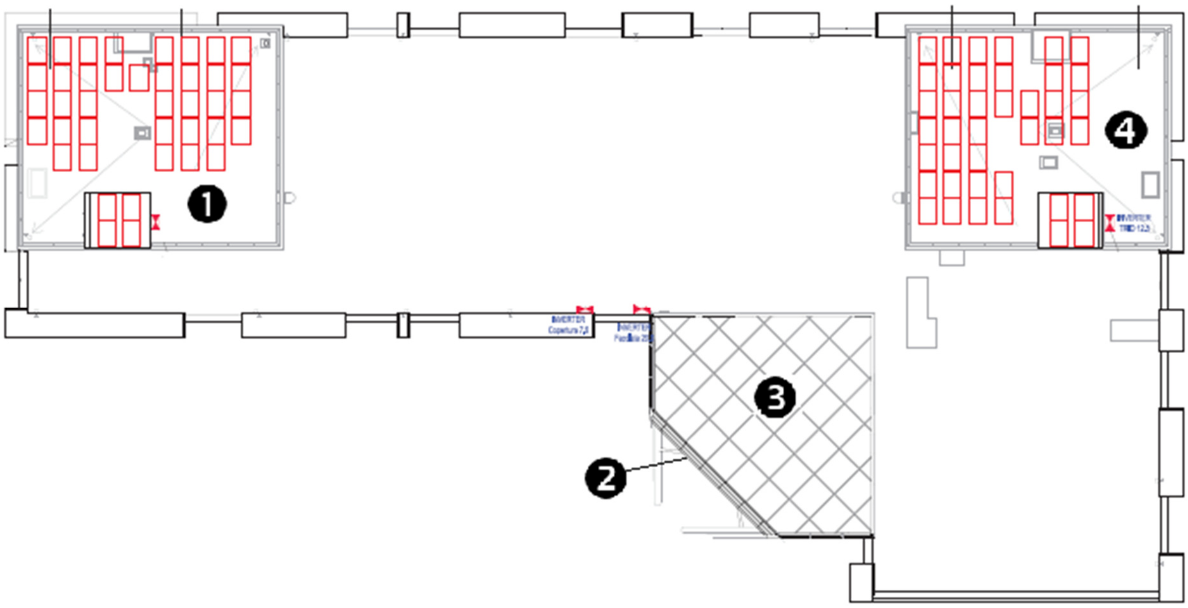

Figure 21. PV plants Map.

ID	PV Plant	P_n (As-built) [kW]	Surface [m^2]	Tilt Angle	Azimuth Angle*
❶	**Stair A**	13,08	~ 65 m^2	10°	+27,5°
❷	**Hall façade**	13,23	~ 80 m^2	80°	-18°
❸	**Hall Coverage**	8,02	~ 51 m^2	5°	-18°
❹	**Stair B**	13,08	~ 65 m^2	10°	+27,5°

**Positive through West.*

Table 13. Main installation data of PV plants.

Concerning the declared power, there has been founded different inconsistencies in the project documentation at disposal. Therefore, in order to confirm the one declared in the As-built documentation and better characterize the PV plants, an analysis on the power and surface installed has been performed, as reported in Appendix A.

5.2.2 Central Plant Room

This technical room is situated in the basement and hosts different systems, whose main energy characteristics are summarized in Table 14, dedicated to the satisfaction of building energy services as heating, cooling and DHW.

Firstly, the Geothermal Polyvalent Group, showed in Figure 22, exploits the aquifer as heat source, during the winter, or heat sink, in the summer to produce respectively heating or cooling. Therefore, it has been created two wells, with a 70 cm diameter and 45 m width, that can operate both as withdrawal or rejection. The machine is constituted by two independent circuits, with R134a as working fluid, that makes it able to satisfy contemporary request of heat and cool. As a matter of fact, in addition to two screw compressors, one for each circuit, it presents three shell and tube heat exchanger, two on the user side that operates respectively as evaporator for the production of cool water and as condenser for the production of hot water, and one on the source side, the aquifer, that operates as condenser or evaporator depending on the load request. The machine is equipped with a regulation system that act on the two hydraulic circuits modulating their operation with respect to two aspects: a thermoregulation with a step logic with respect to the return temperature and a variable primary flow regulation to control its power with respect to the requested flow.

Figure 22. Geothermal Polyvalent Group Installed in Energy Center.

Then it is possible to find the heat exchangers for the connection to the District Heating network. In particular there are three heat exchangers for three different intended uses: one for heating purposes, one for DHW production and one for feeding of the absorption chiller.

Equipment		Parameter	Value
Geothermal Polyvalent Group (water-water)	Heating Mode	COP	4,44
		Heating Capacity	473,7 kW
		Power Absorbed	104,7 kW
	Cooling Mode (without Recovery)	EER	5,65
		Cooling Capacity	442,7 kW
		Power Absorbed	73,7 kW
	Cooling Mode (with Recovery)	TER	7,94
		Cooling Capacity	362 kW
		Power Absorbed	103,4 kW
Absorption Chiller		EER	0,7
		Heat Absorbed	~ 200 kW
		Power Absorbed	2,5 kW
District Heating (Heat Exchangers)	Heating	Nominal Power	350 kW
	DHW	Nominal Power	50 kW
	Absorption Chiller	Nominal Power	255 kW
Thermal Energy Storages	Hot Water	Capacity	4000 l
	Cold Water	Capacity	4000 l
	Solar Thermal Plant	Capacity	1000 l
DHW Boiler	DHW	Capacity	1500 l

Table 14. Main Energy Characteristic of equipment installed in Heating/Cooling Plant Central Room.

The latter is represented by an indirect-fired LiBr absorption chiller. Its main characteristic is that it requires heat to operate but a small amount of electricity. In this case, as anticipated previously, feeding heat is provided by the district heating network. Actually, it has been just tested after the construction of the building, but never used in normal operation for three main reasons:

- It represents a very sophisticated system that require a high and frequent maintenance, in particular to guarantee the vacuum necessary for its operation.
- It presents strict requirements regarding the temperature of the feeding fluid (90-110 °C) that the supplier of the DH is not always able to guarantee.
- Its refrigeration capacity could not be sufficient to cover the entire cooling demand in Summer period.

It is necessary to go deeper in its functioning and evaluate the technical feasibility of its integration with the Polyvalent Group, to reduce the electricity consumption, or its use during mid-season period when the cooling load is lower.

As it is possible to see in Figure 23-Figure 24, it has been even installed two Thermal Energy Storages of in order to accumulate respectively hot and cold water and so provide thermal inertia to the Polyvalent Group. Then, in the Central Plant Room it is possible to find even the inertial TES of the solar thermal plant and the DHW boiler fed by the District Heating. The solar thermal main purpose is the production of DHW, but in case of excess heat at a certain temperature, it is delivered to the 4000 l TES.

Besides all the systems presented, used to produce and store heat and cool, the Central Plant Room hosts even the pumps that belongs to the primary fluids distribution system, apart the ones of the aquifer which are submerged in the wells. The intended use of the different pumps and the nominal power absorbed has been summarized in Table 15.

Pump ID	Purpose	Installed Power [kW]
EP1	Aquifer – Well A	30
EP2	Aquifer – Well B	30
EP3	Polyvalent Group – Cooling	4
EP4	Polyvalent Group – Heating	5,5
EP5	Absorption Chiller	2,2
EP6	AHU – Cooling	2,2
EP7	Radiant ceiling panels	3
EP8	Radiant floor panels	0,43
EP9	Radiators	0,75
EP10	AHU – Heating	4
EP11	Fan Heaters	0,13
EP12	District Heating – Heating	2,2
EP13	District Heating – DHW	0,39
EP14	Recirculation Pump	0,03
EP15	Solar thermal circuit	0,35
EP16	Cooling Water – CED/UPS	0,12
EP17	AHU - Antifreeze	0,75
EP18	Absorption Chiller - Dissipation	/

Table 15. HVAC fluid distribution systems installed pumps.

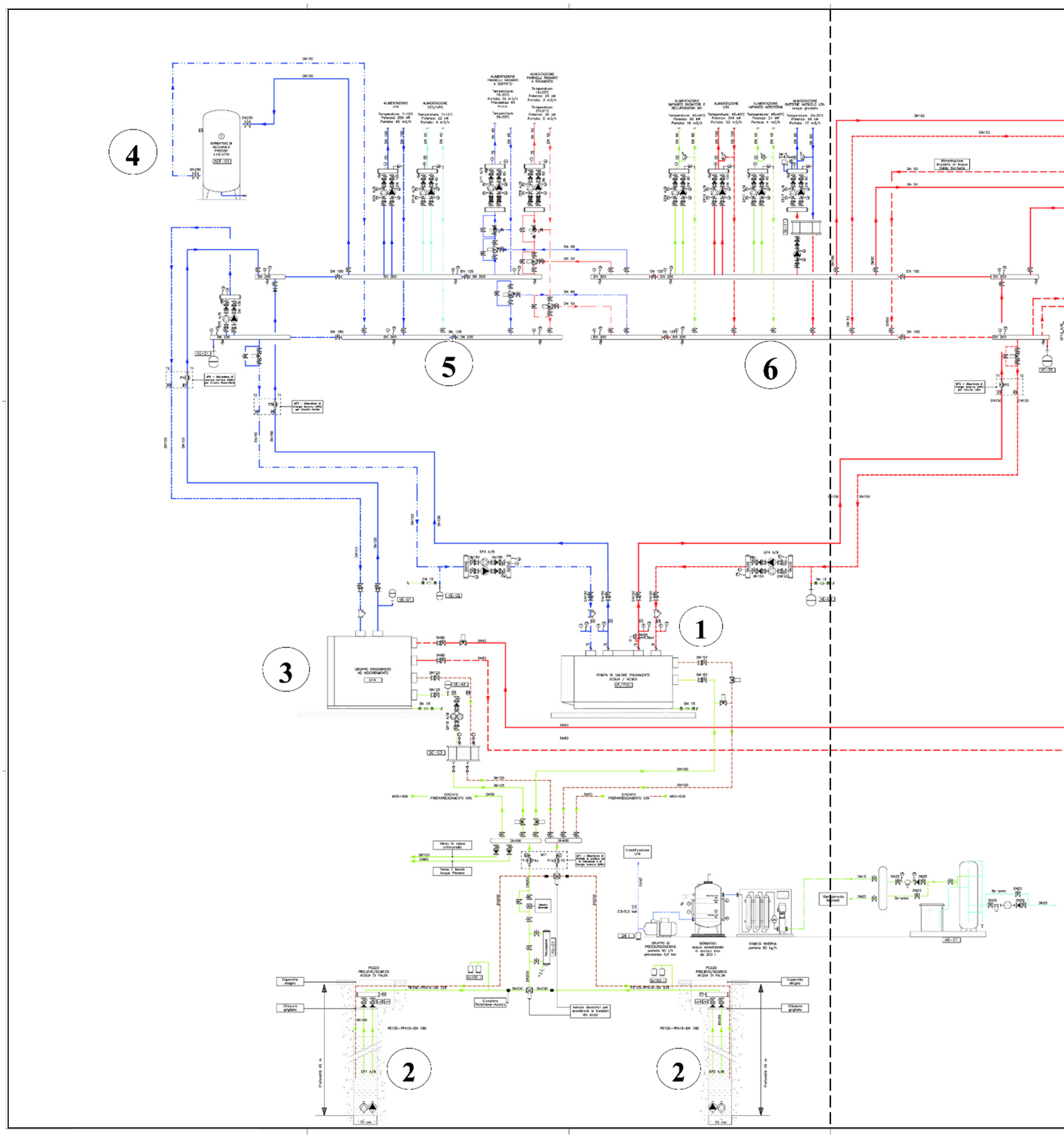

Figure 23. Central Plant Room Technical Scheme. Part 1.

1. Geothermal Polyvalent Group
2. Aquifer Wells
3. Absorption Chiller
4. Cool Storage
5. Cooling System Manifold
6. Heating System Manifold

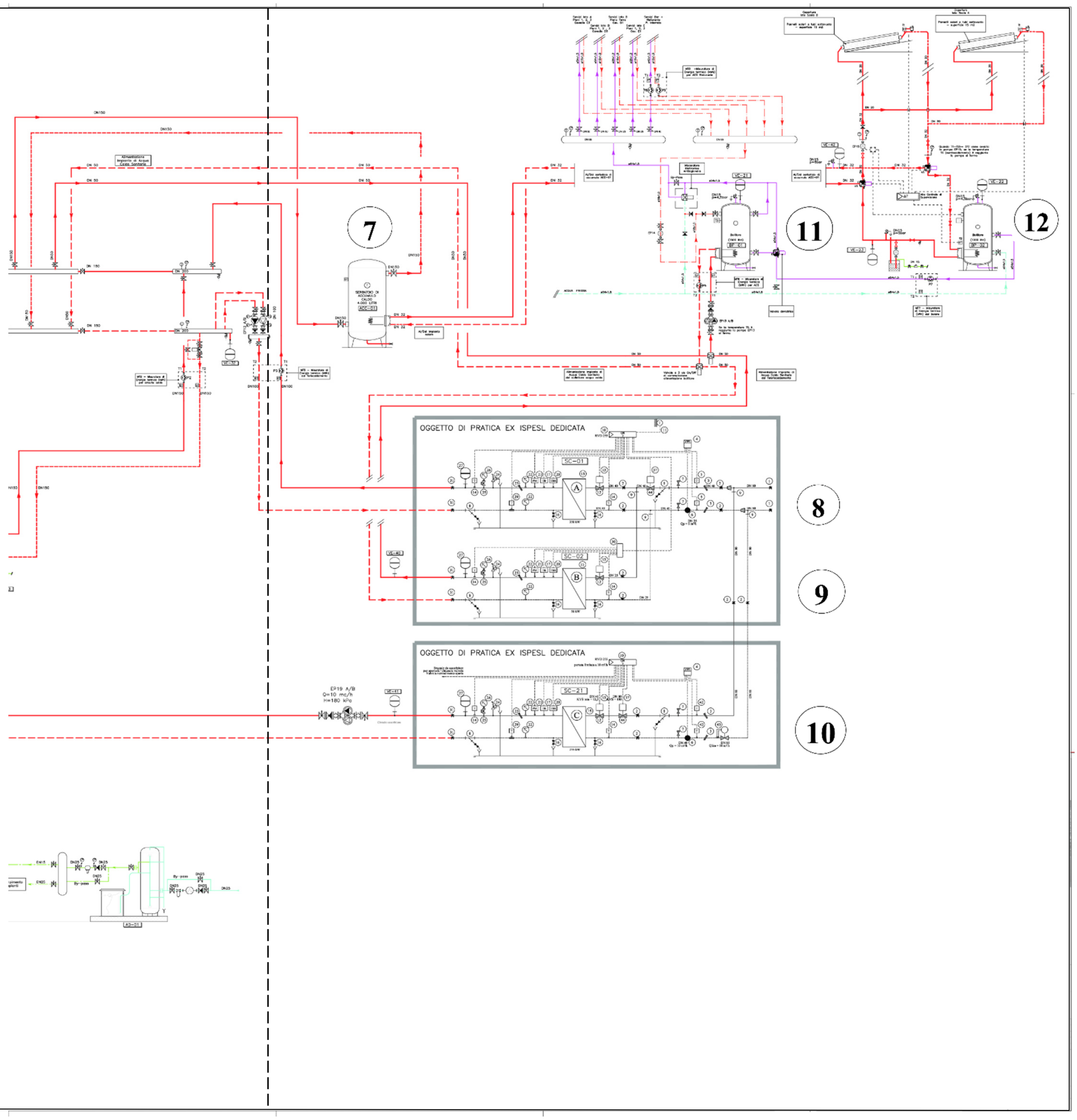

Figure 24. Central Plant Room Technical Scheme. Part 2.

7. Heat Storage

8. DH heat exchanger – Heating

9. DH heat exchanger - DHW

10. DH heat exchanger – Absorption Chiller

11. DHW boiler

12. Solar Thermal Storage

5.2.3 HVAC System

Heat and cool produced by the equipment present in the Central Plant Room, described in the previous Paragraph, is then distributed to the different Utilities. Considering the areas distribution and the related intended use, Energy Center HVAC system has been differentiated and presents specific characteristics depending on the area served. Therefore, it is possible to distinguish:

- The basement: characterized by an all-air system[4] with a dedicated AHU located in one of the technical rooms in the basement.
- The Hall: served by a primary air system[5] with a dedicated AHU located in the basement. The sensible heating or cooling load is satisfied through floor radiant panels located at the ground floor and in the expositions parts of Floors 1,2 and 3.
- The Auditorium: served by an independent all-air system with a dedicated AHU.
- Laboratory: served by fan coils only for heating purposes.
- North-west Offices: characterized by a primary air system with a dedicated AHU (for all the three floors) and radiant ceiling panels.
- North-east Offices: characterized by a primary air system with a dedicated AHU (for all the three floors) and radiant ceiling panels.
- Sanitary Facilities: served by Radiators and a dedicated ventilation system for IAQ purposes (Table 17).
- Technical Rooms (1-2-3 floors), Control Room and UPS Room: all served by dedicated direct expansion split systems that operates independently to guarantee the correct internal conditions, generally to balance the heat load produced by the electronic components (Table 18).

About the Hydronic systems constituted by radiant floors and ceilings, that serve the Offices and the Hall, it represents a two-tube system. It means that, when necessary, facility managers operate the commutation from heating to cooling mode because the supply and return conduits are univocal. The commutation is operated remotely through the management system, respecting the authority prescription about the heating season that for Turin goes from the October 15th to April 15th. It is done operating on the BACS system that consequently acts on the commutation valves.

[4] A type of HVAC system, that use only the supply air, with a certain value of temperature and humidity, to satisfy both IAQ and thermal comfort requirements.

[5] A type of HVAC system in which the supplied air is used only for the hygrometric control and for air quality purposes. The sensible load, and so the temperature desired, is satisfied through hydronic diffusion systems (radiators, radiant panels, fan coils, etc).

Actually, the Supervision system control all the equipment related to the HVAC system following a timer mode of a single clock. Therefore, all the equipment turns on and off at the same time. Approximately, the scheduling applied by facility managers has been:

- Turning-on 7:00;
- Turning-off 19:00;

Beside the timer, the system is even designed in order to regulated itself depending on the load. For example, considering the spaces equipped with radiant panels (floor or ceiling), each room presents its own valve. Following the set-point of the room and considering the actual temperature, the ambient control regulates the opening of the valve following a proportional logic.

AHU served area		**Power Absorbed [kW]**	**Nominal Flowrate [m^3/h]**
Offices North-West	Supply	6,03	12000
	Return	3,61	11000
	Humidifier	41,46*	/
Offices North-East	Supply	2,2	4000
	Return	1,15	3500
	Humidifier	9,27*	/
Hall	Supply	3,04	6000
	Return	1,7	5000
Auditorium	Supply	1,99	7200
	Return	3,23	6900
Basement	Supply	2,29	5000
	Return	1,43	4700

*Estimated in design phase. No technical sheet at disposal.

Table 16. Summary of AHU main characteristics.

Location	Number of Units	Unit Power [kW]
WCs – Basement	4	0,35
WCs - Ground Floor	2	0,35
WCs – Floor 1	3	0,35
WCs – Floor 2	3	0,35
WCs – Floor 3	3	0,35
MT/BT cabin room	1	0,35

Table 17. Summary of air extractors installed power.

Location	Number of Units	Unit Nominal Power absorbed [kW]
Control Room	3	1,875
UPS Room	1	2,18
Floors Technical Rooms	2	2,79

Table 18. Summary of technical rooms independent split systems installed power.

5.2.4 Lighting System

The lighting system of the Energy Center has been conceived with a sophisticated technology in order to reduce as much as possible the related energy consumption. As a matter of fact, it has been installed only lamps with high efficiency, so fluorescent and LED lamps. Moreover, excluding the technical rooms, the parking and the laboratory, great part of the lighting system is controlled through the DALI system, a protocol technology for lighting that allows a very high granularity of control. The lamps installed in Energy Center that are controlled with DALI technology are dimmable and are controlled with different logic depending the intended use of the ambient. For example, in the offices the lights are regulated with respect to natural lights and presence sensors. Table 19 summarize the main light equipment installed in the building.

Main Area	Location	Lamp ID	Unit Power [W]	N. pieces [#]
Basement	Parking	A10	33,4	57
	Stairs	A15	28	16
	Extern	A14	0,4	35
		A15	28	1
		A26	41,3	2
	Internal Open Space	A33	4,2	15
		A1	31	10
		A5	112	26
		A16	47	2
Ground Floor	External	A24	6,4	49
		A25	46	12
	WCs	A1	31	13
	Hall	A16	112	15
		A5	112	5
		A33	4,2	16
		A21	18	3
Mezzanine Level	Control Room	A18	108	15
Floors 1-2-3	Offices and corridors	A30	53	252
		A1	31	27
		A33	4,2	42
	WCs	A1	31	102
	Emergency Stairs	A15	28	30
	Hall access	A16	47	30
		A33	4,2	15

Table 19. Summary of main lighting equipment installed.

5.2.5 Others

In addition to the main equipment, it is necessary to consider other installations that, as will be seen in the following paragraphs, influence the electricity consumption of the building. They include:

- **Elevators**: one panoramic elevator and two goods lift (Stairs A and B). They totally present an installed power of 20 kW.
- **Plug-in**: which are represented mainly by PC loads for offices. In project phase it has been estimated a total load of 10 kW for plug-in. Moreover, there are printers and vending machines.
- **Technology Installations**: which includes different equipment whose load, estimated in design phase, is about 16 kW. Principal systems included are:
  - Wi-fi access points;
  - Telephones and data;
  - Safety systems (Anti-fire, anti-intrusion, surveillance);
  - Control Room Equipment;

This last, as will be seen in the following paragraph, represent a consistent contribution to the baseline of the electricity consumption because of their continuous operation.

5.2.6 Supervision system

The Energy Center is equipped with a sophisticated Building Automation and Control System (BACS), designed to perform three principal functions:

- Safety
- Security
- Automation

Its network is organized with a tree structure that goes from the central control to the so-called level 0, which includes the field devices. In particular, the Energy Center is equipped with Siemens hardware components that, through the network, are then interfaced to the software management system, Desigo CC [99], that allow the control, regulation and monitoring of all the equipment associated, even remotely. Considering the Automation part, which is the most interesting one for Demand-side Management, it is divided in three main sub-systems:

- **HVAC control, production and distribution of primary fluids.** It regards the control and regulation of all the systems that are involved in the production and distribution of the primary fluids of the HVAC systems. For the systems that already present a dedicated regulation system, the Supervision system must be able to communicate with them in order to coordinate completely the operation of the entire system.

- **Ambient Regulation.** That regards the control and regulation of the comfort parameters of the single ambient (rooms) of the buildings. Therefore, each room is equipped with a system that is able to interact with sensors and actuators installed in the same room. As a matter of fact, it is the room system that register the room temperature that comes from the sensor and regulate the opening of the room valve in order to follow the desired temperature setpoint.
- **Electrical System.** Finally, it represents the control of the lighting system and the plug-in load. Great part of the lamps installed in the building are interfaced with the DALI technology protocol. It allows to operate a different control, programming the supervision system.

Therefore, the Supervision system is conceived and designed in order to allow an easier control of all the equipment installed in the building, even pursuing the energy saving. It is able to coordinate all the operations making all the sensors and actuators able to communicate in a closed loop system.

Moreover, in addition to automation, regulation and control, the Supervision System has been even conceived for the energy monitoring of the building. As a matter of fact, the building has been equipped with multimeters and heat meters whose purpose is to acquire measurements about both electricity and heat production and consumption. Anyway, the setting up of the monitoring system has not been already completed, therefore there is a lack of data about several possible available measurements. At the moment, heat meters and multimeters measurements can only observed in real-time on the energy management software Desigo. Table 20, summarize the heat meters installed in the building whose measurements are not already historicised. They are represented by flowrate and temperature sensors, connected to a microprocessor that account for the energy.

Meter ID	Intended Use
MT1	Aquifer Circuit
MT2	Polyvalent Group - Hot Circuit
MT3	Polyvalent Group - Cold Circuit
MT4	Absorption Chiller – Cold Production
MT5	District Heating - Heating
MT6	District Heating - DHW
MT7	Solar Thermal Plant Circuit
MT8	DHW for Basement

Table 20. Heat Meters installed in Energy Center.

The historicization of these heat meters could allow the assessment of several evaluations. For example, it could be possible to evaluate the real contribution of Solar Thermal to the DHW. Moreover, it could be possible to close the energy balance of the Polyvalent Group and evaluate the real evolution of its performances (COP/EER).

5.3 Energy Monitoring

5.3.1 Electricity Consumption Analysis

Considering the electricity consumption of the building, as already discussed previously, the contributions actually measured are represented by:

- Withdrawal from the electricity grid;
- PV plant production;
- Electricity injected in the grid;
- Polyvalent Group absorbed power;
- Fluid distribution system absorbed power.

Observing the availability of the measurements that starts from November 2017 and considering an effective total occupancy and so normal operation of the building since the first months of 2018, it has been decided to analyse the year 2018.

Therefore, in order to have a measure of the overall consumption of the building, it is necessary to sum-up the profiles of the electricity withdrawal and the PV production. In order to do this, it is necessary to make the assumption that all the electricity produced by PV plant is self-consumed. Evaluating the electricity injected in the grid, it results to be only the 0,2% of the PV yearly energy production, therefore the assumption is reliable.

Anyway, in this case it has not been so easy because of the not so good quality of the measured data. As a matter of fact, it has been necessary to perform a reconstruction of the PV profiles, discussed in detail in the following paragraph, in order to subsequently rebuilt the consumption of the building.

5.3.1.1 PV System Production Analysis

Analysing the measures at disposal that regards the production from the PV plants, it could be possible to exploit two different paths to re-build the overall production:

- Using the meter "EC Produzione FV" which should measure the overall production of the PV panels. Unfortunately, this meter has been unavailable for great part of the monitored period, therefore its measure can't be used for our purpose.
- Using the four meters associated to the inverter of the four PV plants, which are organized as follow:
    - ❶ Stair A → Inverter 1
    - ❷ Hall Façade → Inverter 2
    - ❸ Hall Roof → Inverter 3
    - ❹ Stair B → Inverter 4

Important: the name of inverters associated to the plants are the one used in the monitoring system. With respect to As-built project documentation Inverter 2 and 3 have been exchanged.

Therefore, it has been decided to perform the analysis using the second source of data. Anyway, having a first look of overall aggregated results it is possible to understand that there are some critical aspects that must be analysed. As a matter of fact, comparing the overall energy consumption expected, reported in the APE certification, and the one resulted from the monitored measures, as showed in Table 21, it is possible to suddenly observe that something is not working so well.

	A.P.E.	**Measures**	**Difference**
Annual PV production	53,7 MWh	25,4 MWh	**-52%**

Table 21. PV plants overall production.

Observing that there is a not so slightly difference, it has been conducted a first rough analysing using the European open source simulation software PVGIS [100], in order to estimate the expected annual production of the single PV plant and compare it to the one obtained from the measures, as showed in Table 22.

PV Plant	**Production [kWh]**	**h_{eq} (measured)**	**h_{eq} (PVGIS)**	**Difference (%)**
Stair A	4430,9	339	1170	**-71 %**
Hall façade	10040,8	759	1000	**-24 %**
Hall Coverage	2160,4	269	1100	**-75 %**
Stair B	8801,4	673	1170	**-42 %**

Table 22. Comparison of PV production measures and PVGIS simulation.

As it is possible to observe in the table above, the differences between the measured values and the one simulated through the tool PVGIS are not so negligible. In particular, the PV plant installed on the Stair A and the one integrated with the Hall Coverage presents a difference in the yearly production of more than 70%.

The differences individuated could be related to different problems and malfunctioning that can be grouped in two main classes:

- Measurements

- Malfunctioning of data logger/energy meter

- PV system
  - Malfunctioning of Inverters;
  - PV modules non-connected;
  - Damaged PV panels;

Therefore, in order to investigate about the possible causes and take approximate but at the same time consistent decision for the reconstruction of the profiles it has been conducted a deeper analysis comparing the measured data with the simulations performed. Moreover, considering that the real values measured refers to 2018, while the most recent PVGIS weather database is for 2016, it has been decided to simulate the PV profile with a MATLAB script, following the methodology discussed in Appendix B, using as weather input (for ambient temperature and irradiance) data measured by the weather Station of the Politecnico di Torino and collected by the Living Lab.

5.3.1.1.1 Free-standing PV plants of Stairs A and B

Concerning the two PV plants installed in correspondence of the Stairs A and B, as showed in Figure 21, they constitute two identical plant with same characteristics of module installed, installed capacity, orientation and inclination, as even reported in Table 13. Therefore, it is wired that, neglecting at this stage other possible sources of difference as for example a possible shading, there is a gap in the annual production of about 50%.

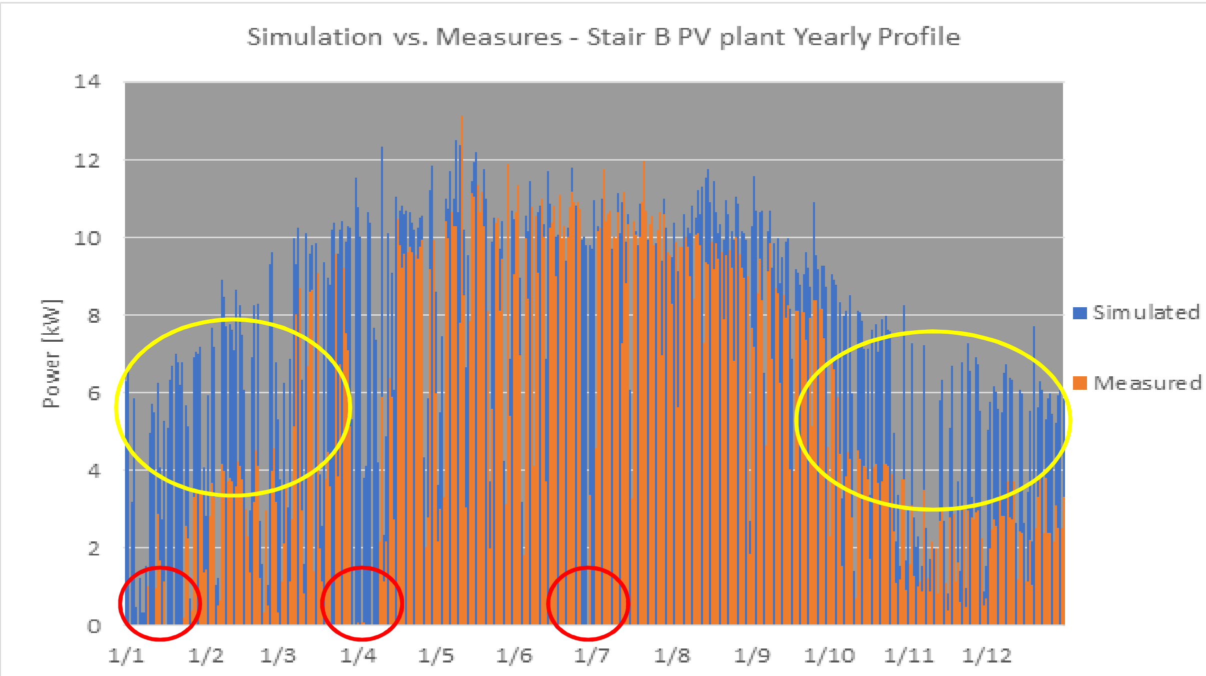

Figure 25. Stair B PV plant power production comparison between measured and simulated results.

As a matter of fact, observing the comparison with the simulated profile showed in Figure 25 and Figure 26, it is possible to understand that there has been problem related to the inverter or the meter approximately from May to August, as highlighted by the red circle.

Moreover, both of plants measures presents some “holes” highlighted with smaller red circles that can be mainly related to measurements errors.

In addition to the measurments errors, it is possible to individuate a reduction of the plant performances, for both Stair A and B, durign the colder months (from October to March). This gap in performances between measures and simulations may be related to a possible problem of shading that interest the two plants, already identified and reported by the Professors Spertino and Pons.

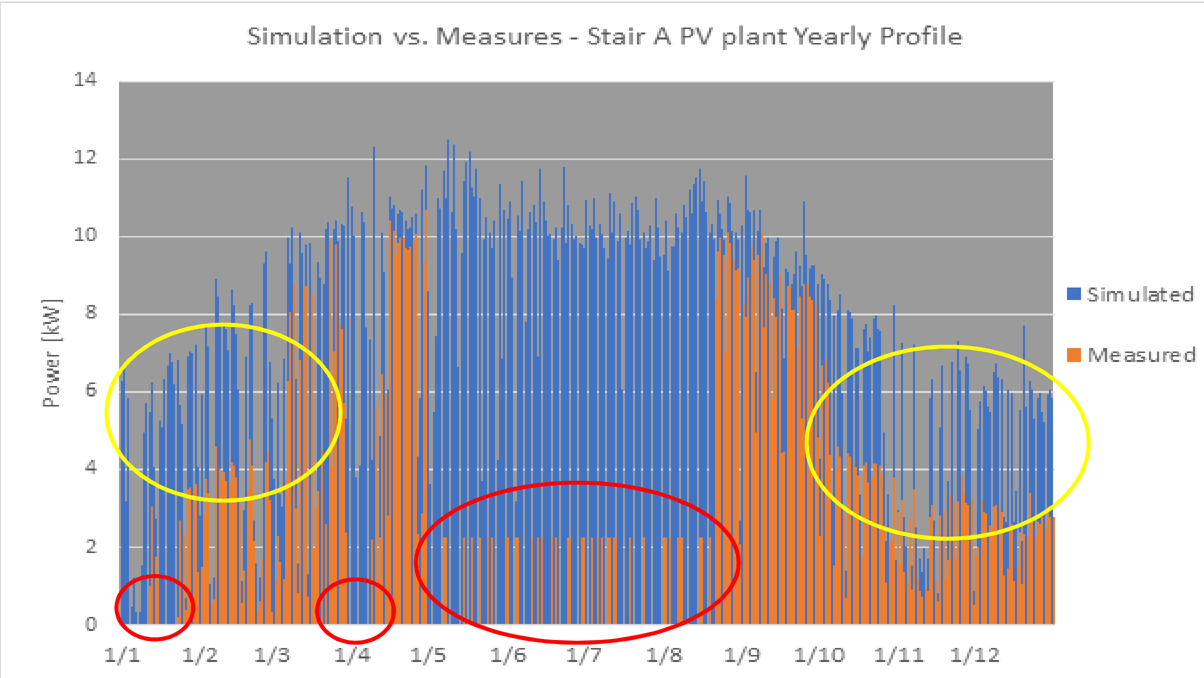

Figure 26. Stair A PV plant power production comparison between measured and simulated results.

Therefore, considering the almost identical configuration of the two PV plants it has been decided to reconstruct the production profile starting from the simulation and using as reference the measures acquired for Stair B, that appear more consistent, for both the PV plants. In order to avoid an overestimation of the electricity production of the PV, some correlation factors have been evaluated considering the different performances in the different periods. As a matter of fact, as already discussed previously, the Stair PV plant presents a higher scaling factor during colder months. Analysing the relation between measures and simulation and subdividing them into different periods, it has been founded four main periods with four different scaling factors that goes from 0,43 to 1. The rebuilt profile obtained is showed in Figure 27.

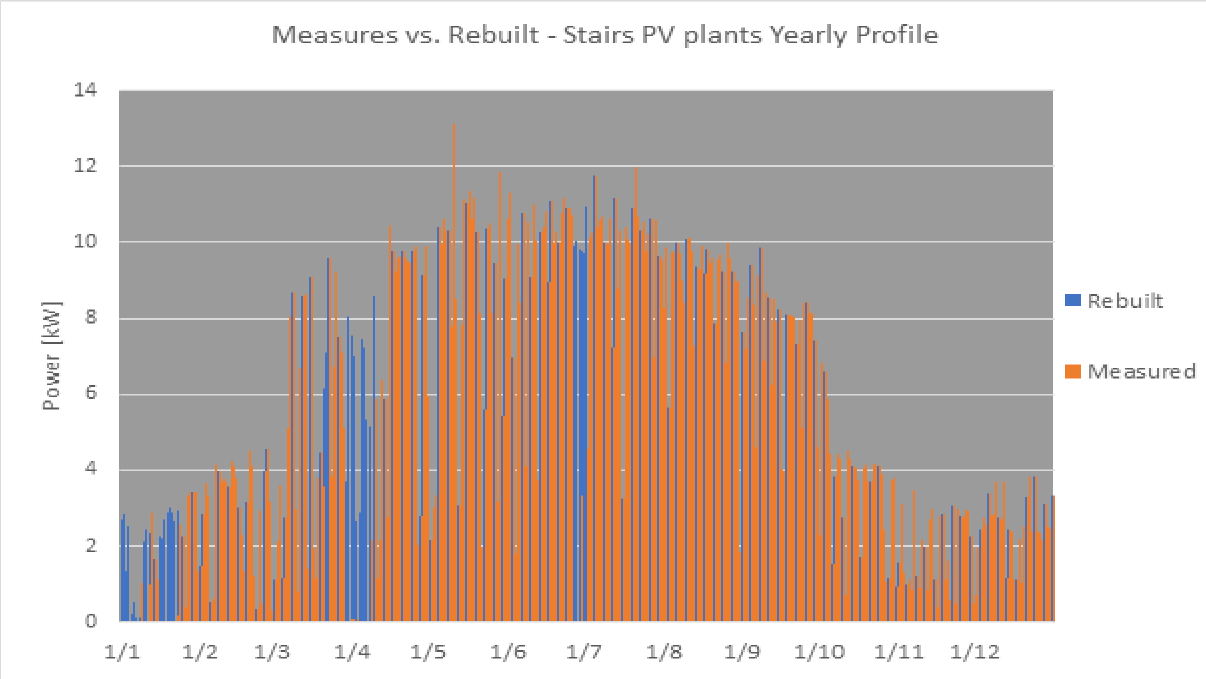

Figure 27. Comparison of measured and rebuilt power profiles of Stairs PV plants.

5.3.1.1.2 BIPV plant of Hall Façade

The photovoltaic system integrated to the Hall Façade do not present critical aspects, as it is possible to observe in Figure 28, as a matter of fact it results the plant that works better.

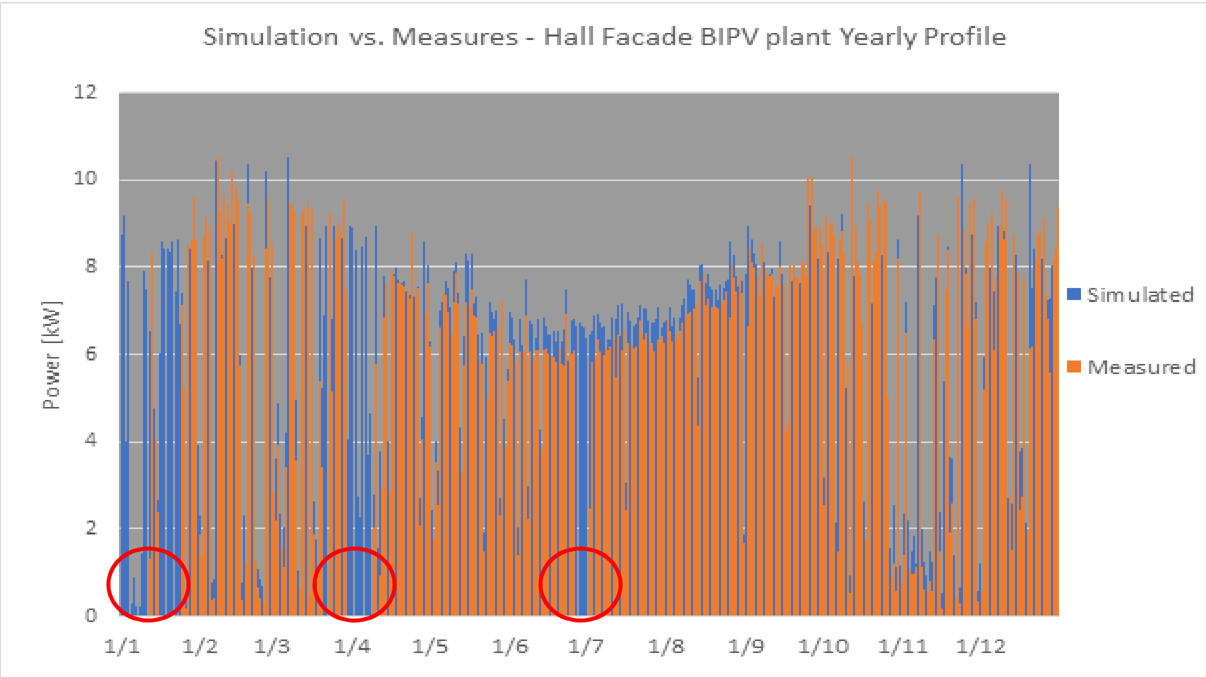

Figure 28. Hall Façade PV plant power production comparison between measured and simulated results.

It presents just some holes in measurements in the same periods of other PV plants, as highlighted on the graph with the red circles. Checking that mostly of those days presented favourable radiation conditions, it is possible to suppose that there has been a problem which has involved the whole measurement system of PV plants.

Therefore, for the reconstruction of production profile, it has been proceeded in the same way followed for the Stairs PV. Anyway, as it is possible to observe in Figure 29, in this case it has been necessary to evaluate a single scaling factor through a simple linear regression, thanks to the good operation of the Plant, obtaining a value of 0,95.

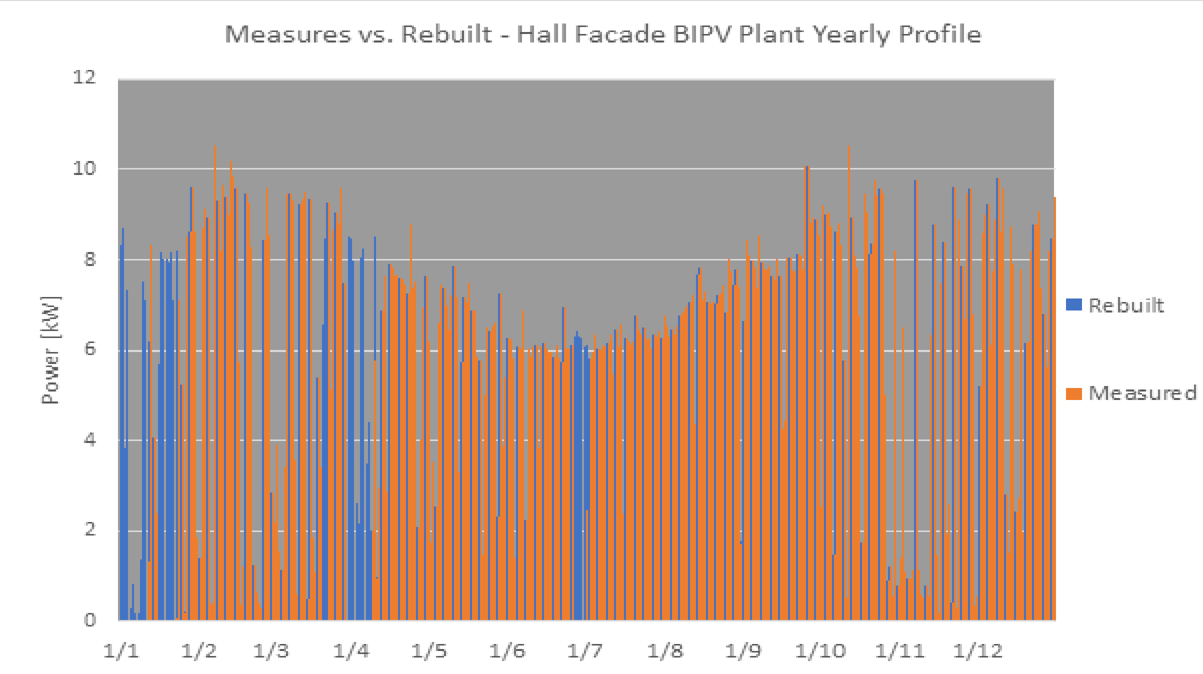

Figure 29. Comparison of measured and rebuilt power profiles of Hall Façade PV plants.

5.3.1.1.3 BIPV plant of Hall Coverage

The Integrated plant installed on the Hall Coverage, as was already discussed with the Monitoring staff of the Living Lab, has had problems related to the associated energy meter during great part of the period analysed. As a matter of fact, a great missing related to a measurement instrument malfunctioning can be individuated by the red circle on the graph showed in Figure 30.

Moreover, as already discussed for the other PV plants installed, there are different “wholes” in the measurements, highlighted with red circles, that cover several days and are distributed during the year. Those kinds of errors are probably related to measurement instrument errors and mostly occur in the same periods for all the four PV plants.

On the other hand, it is probably that this PV plant presents even other problems directly related to the PV system. In fact, it is evident a great difference in the peak powers during all the year. Supposing that in the range highlighted by the yellow circle the measurement instrument has properly worked, there is still present a scaling factor between the two curves that cannot be linked to the differences between the two years and so to radiation conditions because it is supposed to have at least similar peak values.

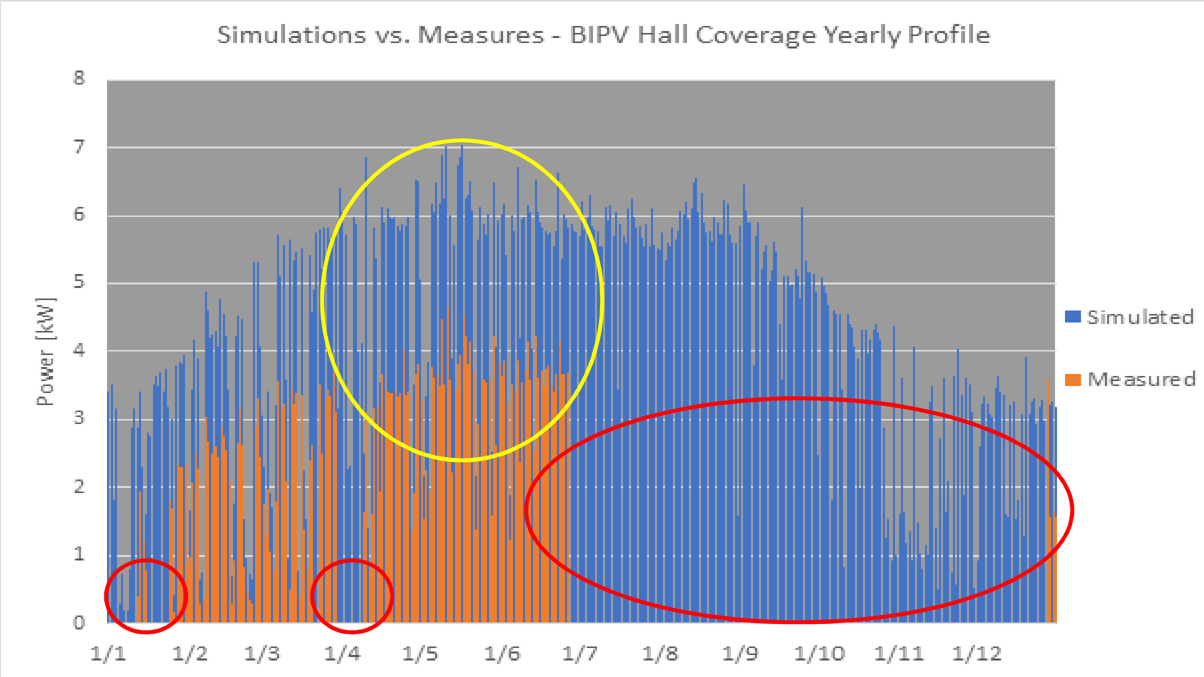

Figure 30. Hall Coverage PV plant power production comparison between measured and simulated results.

In order to avoid the overestimation of the power production and consequently the building consumption, it is not possible to assume the yearly production equal to the one simulated. At the same time, it is not possible to consider the acquired measures as correct.

Therefore, it has been decided to calculate the production profile scaling the one obtained from the simulation through a factor evaluated through a simple linear regression in the range highlighted by the yellow circle, in which it is supposed that the measurement instrument has correctly worked.

Performing the calculation, it is resulted a mean scaling factor of approximately **0,6**. Therefore, neglecting the big measurement error, the Hall Coverage PV plant presents a productivity 40% lower with respect to the one expected, calculated through the simulation, which can be related to PV system problems. The rebuilt profile can be observed in Figure 31.

Successively, it has been investigated deeper in the possible cause of the reduction factor that characterize the performances of Hall Coverage PV plants. During a day with favourable irradiation condition, in the central hours of the day, it has been performed an inspection. Firstly, comparing the value of power acquired by the inverter and the one registered by the data logger there is a matching, therefore for what concerning the observed reduced performances of the plant during the whole year it is probably not related to an error in the monitoring system.

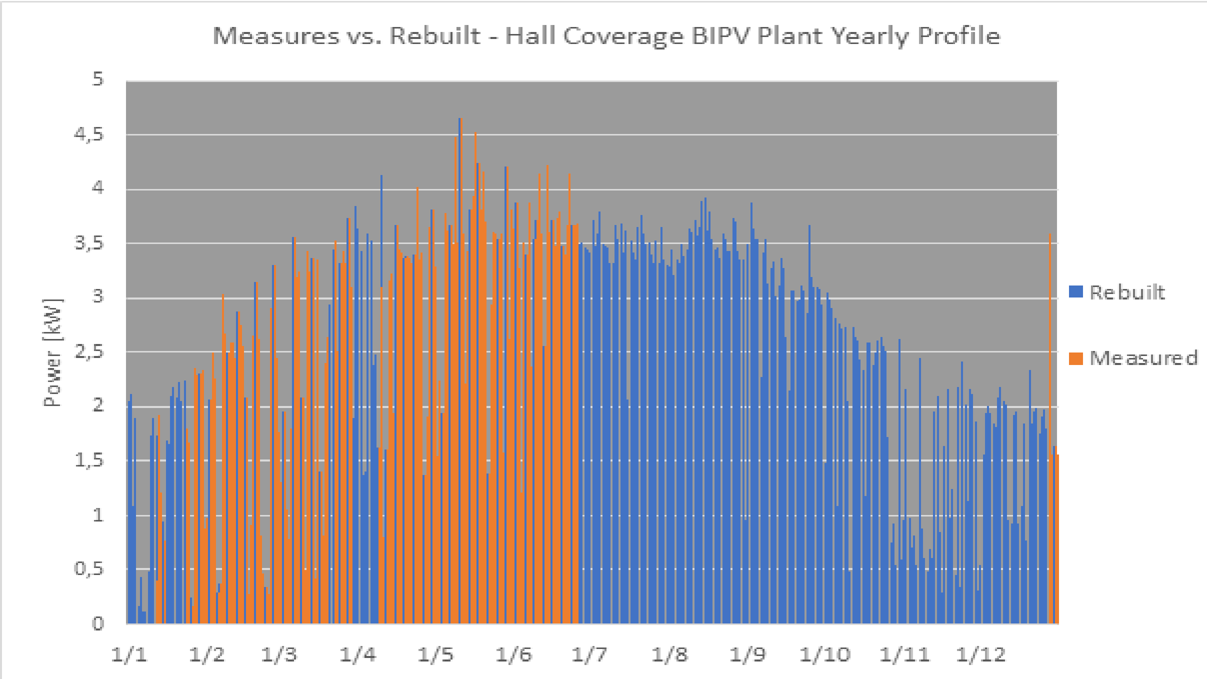

Figure 31. Comparison of measured and rebuilt power profiles of Hall Coverage PV plants.

Anyway, the inverter allows to have a look in "real-time" of the variable monitored. In particular, it shows the value of power, voltage and current of two group of modules, 1 and 2. Looking at the electrical cabinet of the inverter, it is possible to understand that the group 1 refers to the string 1 and 2 of the plant, while the group 2 refers to the string 3.

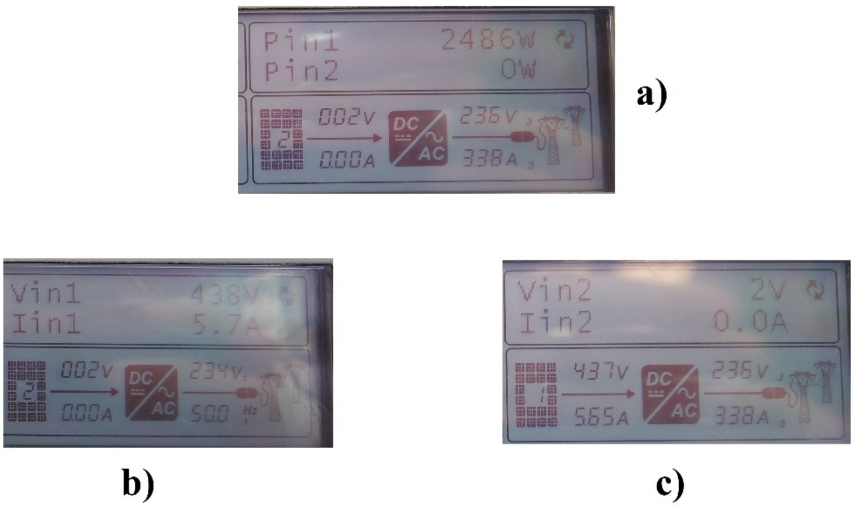

Figure 32. Instant Measures registered during inspection of Hall Coverage PV inverter. a) Power, b) Group 1 voltage and current, c) Group 2 voltage and current.

Looking at the instant measurement reported in Figure 32, it is possible to observe that even with favourable conditions, while group 1 (strings 1 and 2) presents a value of voltage, current and so power, for the third string the inverters provide a null value for the current and a very low voltage of 2 Volts. Therefore, the observed reduction in performances during the whole year could be related to the mulfunction of the the third string of the plant. The main cause could be the damaging of a cell that belongs to that string or an errated connection of the panels. Looking at the strings configuration reported in the As-built documentation, as showed in Figure 33, it is possible to easily localize the string that require maintenance.

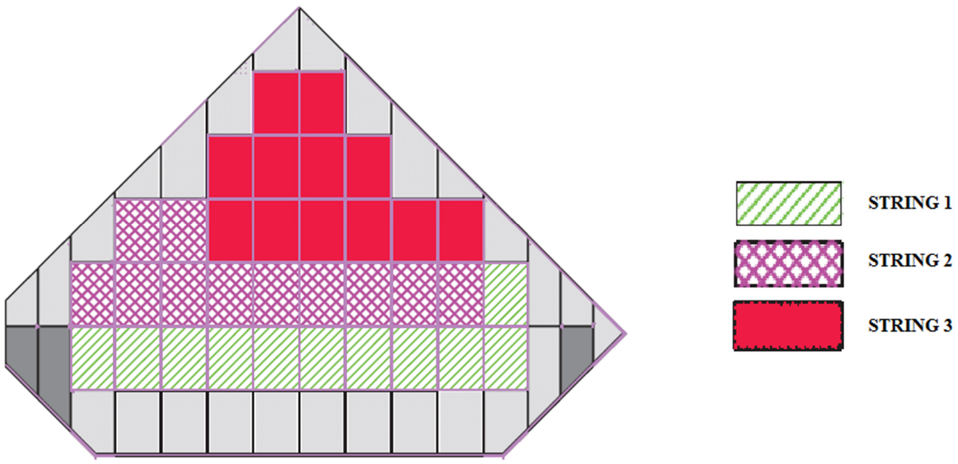

Figure 33. Hall Coverage PV plant Strings Configuration.

Finally, in order to summarize the results obtained through the analysis of the electricity production of the PV plant it has been compared the rebuilt production to the one expected reported in the APE certification and obtained from the simulation, which are in line with it.

	A.P.E.	**Measures**	**Simulation**	**Rebuilt**
Annual PV production	53,7 MWh	25,4 MWh	49,5 MWh	36,6 MWh

Table 23. Comparison of Annual PV production.

As discussed previously for each PV plant installed in the building, the rebuilt power has been evaluated in order to calculate the overall electricity consumption of the building. Therefore, to avoid an overestimation of the consumption, the rebuilt power has been evaluated reconstructing the missing created by the malfunctioning of the Data Logger, so for that periods in which the PV produced electricity, but it has not been correctly measured.

Anyway, for the correct operation of the plants installed, it is necessary to programs interventions of maintenance in particular for the BIPV plant installed in Hall Coverage. Its malfunctioning and the consequent exclusion of the String 3 has led to a reduction in annual energy production that has been estimated comparing the simulated with the rebuilt profile, obtaining a value of 4 MWh that represents about 10% of the rebuilt annual production. Assuming a complete self-consumption of the electricity produced by PV and a medium unitary cost of electricity for medium-voltage of 0,2 €/kWh, this missed production would have led to an additional monetary saving related to the self-production of approximately 800 €.

Therefore, it has been requested maintenance to facility managers in order to recover the malfunctioning string of Hall Coverage plant and evaluate possible interventions to avoid shading on Stairs A and B plants. Obviously, in order to have a clear measure of the energy produced by the PV plants, it is necessary to perfectionate the measurement acquisition systems, in order to avoid the missing observed during the year analysed.

5.3.1.2 Typical Consumption Day Evaluation

After the rebuilt of PV production curve, it is possible to rebuild the consumption profiles of the building. Considering the assumption that all the produced electricity is self-consumed, as discussed in Paragraph 5.3, the electricity production by PV represents approximately the 9% of the total annual electricity consumption of the building, as showed in Figure 34., which results to be 405,3 MWh.

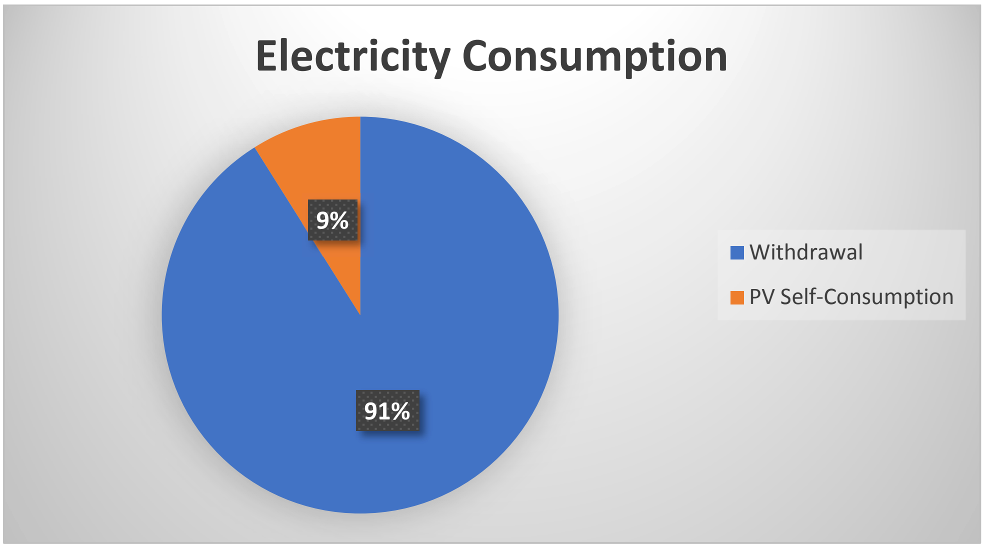

Figure 34. Electricity Consumption Sources.

Then, the subsequent phase has regarded the rebuilt of the consumption curves, and so the overall annual consumption, starting from the construction of some sample days during the year. The intention is to find some representative days of building electricity consumption in order to have a more simple and direct observation of the profiles to then estimate the eventual opportunities of Demand-side Management. This phase has been performed following different steps that are further discussed in the following.

1. **Construction of the Calendar map.**

It represents a very useful tool to have a simple and direct observation of the distribution of electricity daily consumption during the time-frame observed. It has been used as a guideline in order to evaluate through observation, the clustering subdivision to which then associate the sample days. For the first approach, the calendar map has been created dividing the days in 8 clusters, whose consumption range has been simply evaluated dividing the interval between the maximum and the minimum daily consumption into 8 ranges, whose result is shown in Figure 35, that goes from the higher level in red through the lower one in dark blue. Here, it is possible to observe the first main subdivision: heating and cooling season. Due to the use of Polyvalent Group only for cooling purposes, during cooling season it is expected a higher electricity consumption. Moreover, it is possible to notice that great part of the days that belongs to the lower level are represented by Sundays and Holidays.

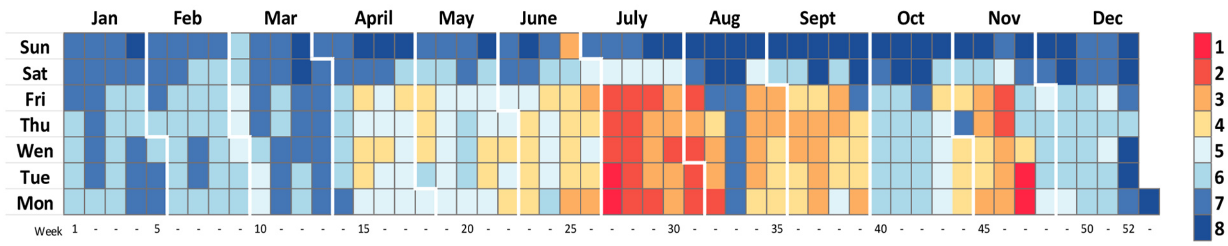

Figure 35. Calendar Map of Daily Electricity Consumption with 8 levels.

Finally, through the calendar map it has been identified a possible anomaly in the electricity consumption in the period of November. It presents a daily consumption which is comparable to the summer season. Considering that the major difference expected in the consumption is related to the use of Polyvalent Group, and that facility managers chosen to use it only for cooling purposes, that period presents a too high daily electricity consumption. Checking the weather conditions of that days, it has been registered a mean external temperature of 8-10 °C that completely exclude the necessity of cool.

2. K-means clustering.

Then, trough the software RapidMiner [101], the 15min profiles of electricity consumption has been analysed, applying one of the unsupervised clustering techniques at disposal, the k-means clustering, whose principles are presented in Appendix C. In particular, the aim of this phase has been to find the number of cluster necessary to describe in a proper way the electricity consumption behaviour of the building.

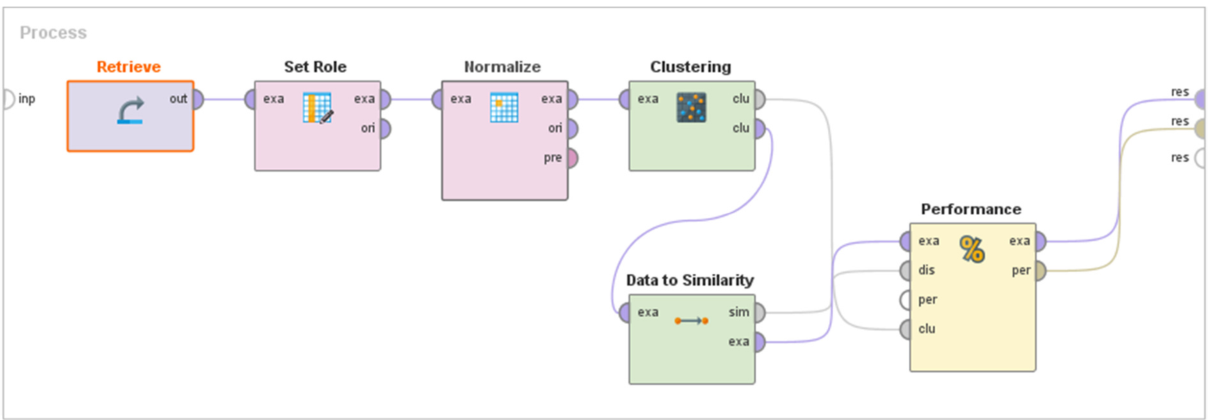

Figure 36. RapidMiner Process for k-means clustering.

Therefore, using RapidMiner interface, as showed in Figure 36, it has been created a process that perform the clustering and then evaluate a performance parameter in terms of density of the clusters (calculated with the Euclidean distance). The process has been re-executed considering different number of clusters and then the density performance as function of the number of clusters has been observed, Figure 37. This allow to evaluate a trade-off between the number of cluster k and the performance of the clustering. Indeed, observing the figure, it is possible to consider as appropriate number of clusters the elbow of the curve, located in the range of 7.

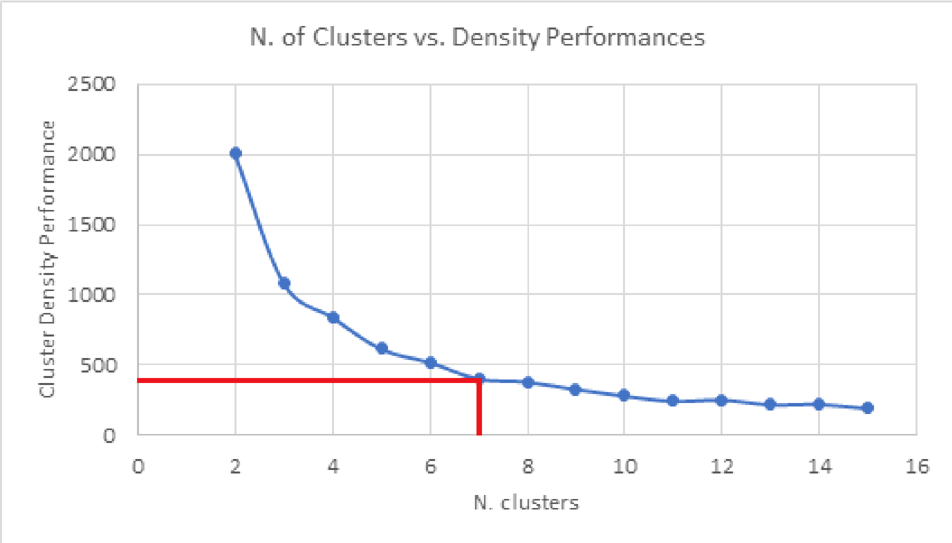

Figure 37. Evolution of clustering density performance as function of number of clusters.

3. Building Operational Consideration

Finally, an additional criterion has been considered represented by the different operation levels of the building systems during the year. As already discussed, occupancy and consequent operation of the different system can strongly affect the building energy consumption. Moreover, as will be seen in the following, the observation of the calendar map created with the daily energy consumption is very useful but not sufficient to take into account the differences in the electricity daily profiles. Therefore, the observation of the calendar map in Figure 35 and k-means clustering results have been integrated into a final supervised clustering, together with the main building operational information collected, summarized in the following:

- The use of the Polyvalent Group during the cooling season and the DH connection for heating purposes, will have a strong impact on the electricity consumption profiles;
- Turin belongs to the zone "E", therefore the heating season goes from October 15th to April 15th;
- On Saturdays, the building is occupied only half-day, therefore the main energy service systems operate from 7:00 to 14:00;
- On Sundays and Holidays the building is closed.

4. Clusters individuation

Finally, considering all the steps previously discussed and the information obtained, through a supervised clustering, the following clusters has been chosen:

Cluster 1- Sunday and holidays.

Cluster 2- Heating season Saturdays.

Cluster 3- Cooling season Saturdays.

Cluster 4- Weekdays from 15 April to 30 June, first mid-season period.

Cluster 5- Weekdays from 1 July, to 15 September, cooling season.

Cluster 6- Weekdays from 15 September to 15 October, second mid-season period.

Cluster 7- Weekdays from 15 October to 15 April, heating season.

In Figure 38 , it is possible to observe the distribution of the different clusters during the year. It is important to specify that in this case, the different colours do not reflect the electricity daily consumption but just the membership of the day to the cluster chosen. It is possible to individuate two main groups among the clusters that distinguish Weekdays and Weekends. Moreover, it has been decided to do a further distinction among Sunday and Saturday because in the first day the building is closed, while it is open until midday on Saturday. Concerning the distinction between heating and cooling season, great differences are expected, because as already discussed the Polyvalent Group is used only during the cooling season, while during the heating season the service is satisfied through the District Heating network.

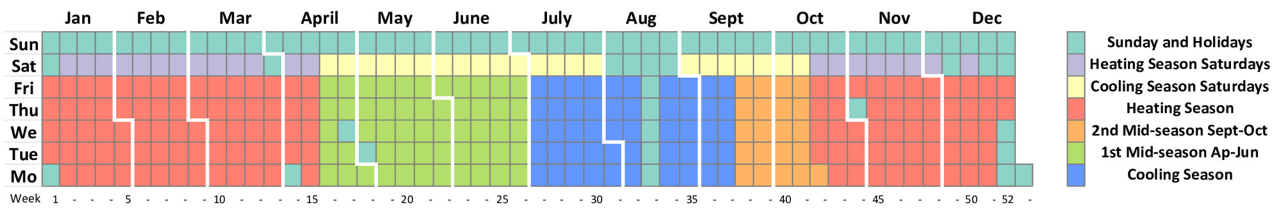

Figure 38. Clusters distribution of the final clustering applied.

Finally, observing the electricity daily consumption distribution of the final clusters chosen it is possible to understand why the only observation of the daily consumption is not sufficient to make a proper clustering of the profiles. As a matter of fact, as showed in Figure 39, differently from clusters that show a daily consumption level completely different, there are clusters that presents similar daily electricity consumption but, as will be seen in the following step, strongly differences in electricity profile of the correspondent typical day. In particular, while Heating Season and Cooling Season Saturday shows a very similar level of daily electricity consumption, it will be showed that their electricity profile is strongly different, mainly due to the fact that on Saturday, the building is open only half-day. Moreover, through the useful graphical instruments of box plots, it has been possible to individuates clusters outliers that have been excluded for the calculation of the Typical Consumption Day of the respective cluster.

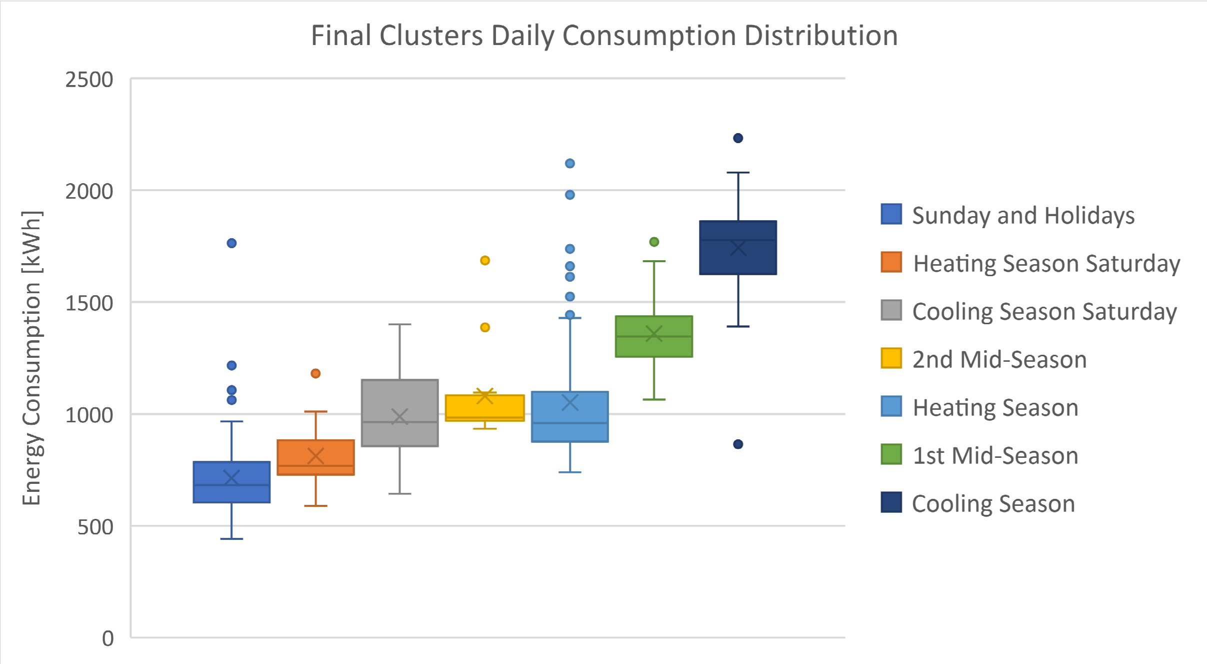

Figure 39. Daily electricity consumption distribution in final clusters.

5. Sample days individuation

Therefore, after the subdivision in several clusters, it has been performed the evaluation of the typical consumption day representative for each cluster individuated.

For a first approach, it has been used the following simple methodology, which has been replicated for each cluster:

a) Selection of the 15min profiles that belong to the individuated cluster;

b) Evaluation of the average profile of the cluster;

c) Evaluation of the Root-mean-square deviation, Equation (1), of each profile with respect to the average one;

d) Choice of the real profile with the smaller Root-mean-square deviation as typical consumption day of the cluster.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x}_i)^2}{N-1}} \quad (1)$$

Where,

σ = Root-mean-square deviation;

x_i = Power value of the real profile;

$\bar{x}_i$ = Power value of the cluster average profile;

N = 96, number of quarters of an hour during the day.

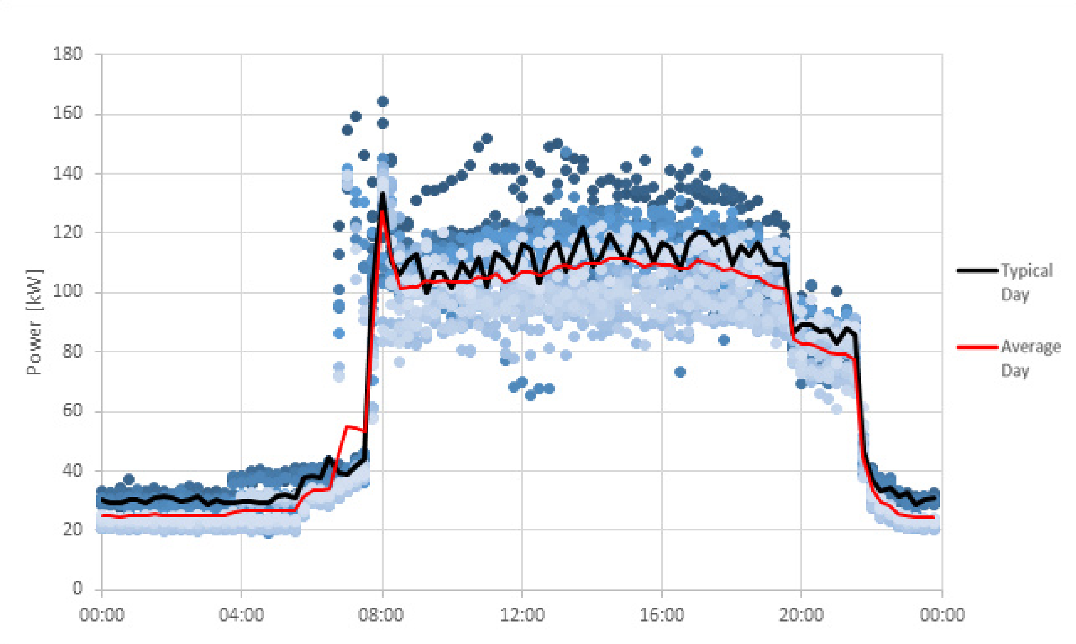

Figure 40. Graphical example of the methodology applied.

Figure 40 shows presents a graphical example of the methodology discussed. The blue points represent the dispersion of the different profiles that belongs to the cluster, while the red solid line represents their average and the black solid line the real day closest to the average, so with the smallest root mean square deviation. Therefore, Table 24 report the resulted typical day and the related weight on the year, given by the ration between the number of days of the cluster over the 365 days of the year.

Cluster	Typical Consumption Day	Cluster Weight
1 – Sunday and Holidays	03/06/2018	33,7%
2 – Heating Season Saturday	1/12/2018	5,7%
3 – Cooling Season Saturday	26/05/2018	13,8%
4 – First Mid-Season	31/05/2018	14,5%
5 – Cooling Season	18/07/2018	5,7%
6 – Second Mid-Season	05/10/2018	5,7%
7 – Heating Season	22/11/2018	20,9%

Table 24. Sample day individuated for the clusters.

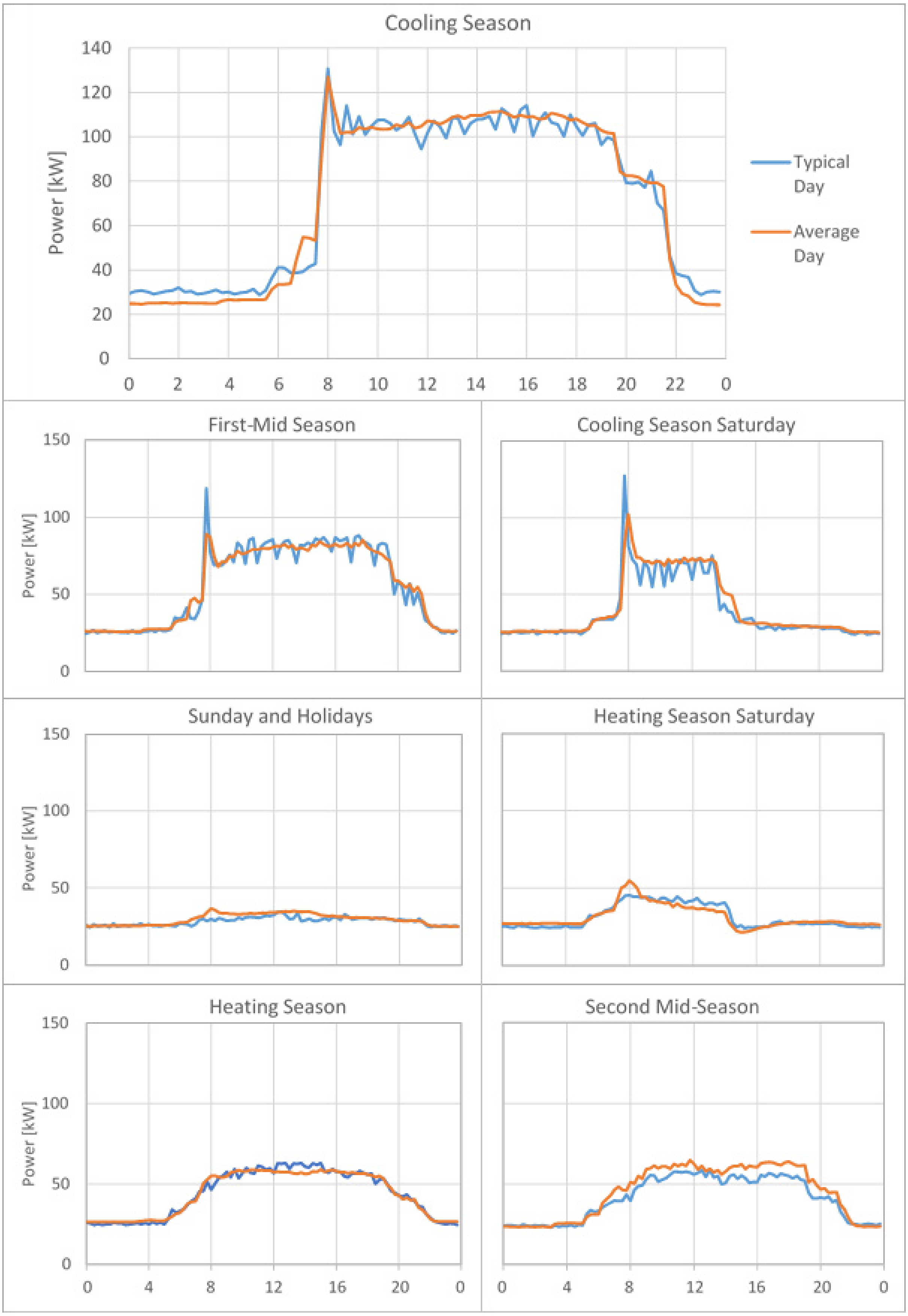

Figure 41. Comparison of Average and Typical day consumption profiles for the different clusters.

Figure 41 shows the graphs with the comparison between the average profile of the cluster with the profile of the sample day individuated, for each of the cluster chosen, are presented. Here, it is possible to observe through the different profiles all the observation discussed previously for the final choice of the clusters.

6. Verification

Considering that the final objective is to rebuild the consumption of the building through individuated typical days, it has been performed a verification of the methodology applied comparing the overall annual consumption profile obtained in two ways:

- Summing up the real profiles acquired with the measurements.
- Multiplying the Typical days profiles, obtained in the previous phase, for the respective number of days included in each cluster.

The result, reported in Figure 42, showed that the methodology used is sufficiently consistent. As a matter of fact, it has been evaluated a maximum percentage error between the two profiles of about 12% and a difference on the total yearly energy consumption of 0.4% as reported in Table 25.

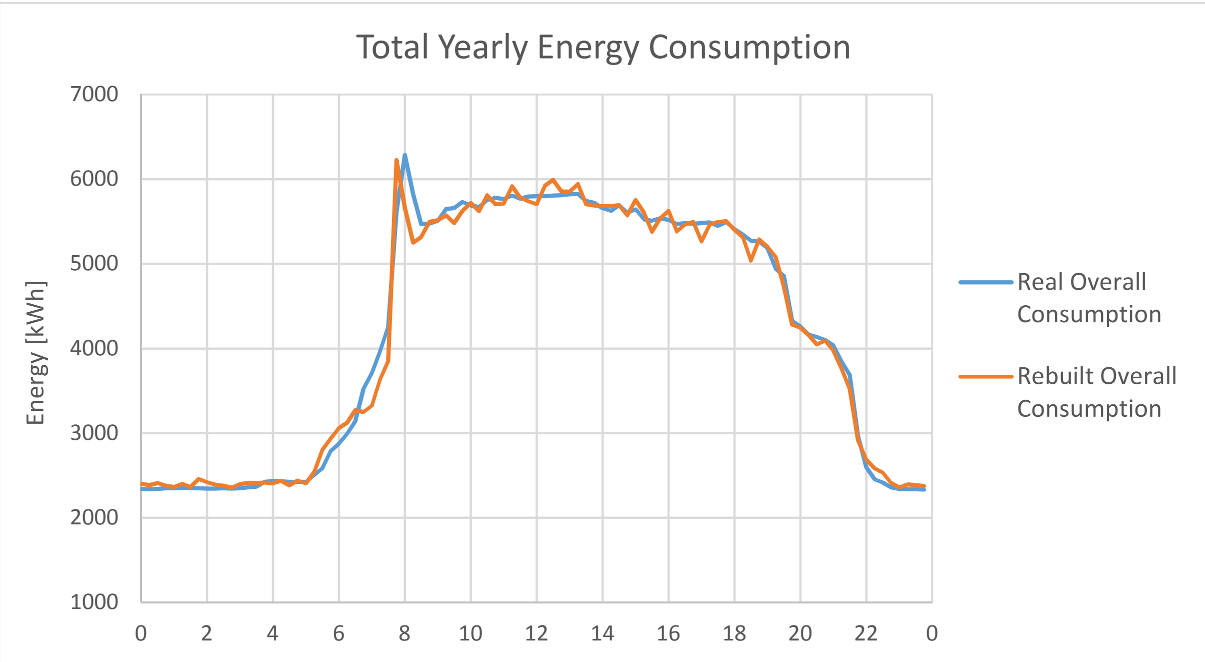

Figure 42. Comparison of Measured and rebuilt overall 15 minutes energy consumption in the year.

Real yearly Electricity Withdrawal	Rebuilt yearly Electricity Withdrawal	Difference
405,3 MWh	404,4 MWh	**-0.2%**

Table 25. Comparison of real and rebuilt yearly total electricity withdrawal.

5.3.1.3 Electricity Consumption Breakdown

The obtained typical day profiles have been then exploited to investigate about the behaviour of the system in terms of electricity consumption. Therefore, through the measures at disposal and the design information gathered it has been investigated about the different systems that contribute to the electricity consumption of the building.

As already discussed previously, actually the equipment whose electricity consumption measures are at disposal and so could be used to perform the consumption breakdown are represented by:

- Polyvalent Group
- Fluid Distribution System (Pumps)

Therefore, it is not possible to operate a complete breakdown just using the measurements at disposal. As a matter of fact, in order to have a starting point for the observation of the of the different profiles obtained and to investigate about the possible unknown contributions to the electricity consumption, a graphical representation of the different equipment power installed has been developed, as showed in Figure 43.

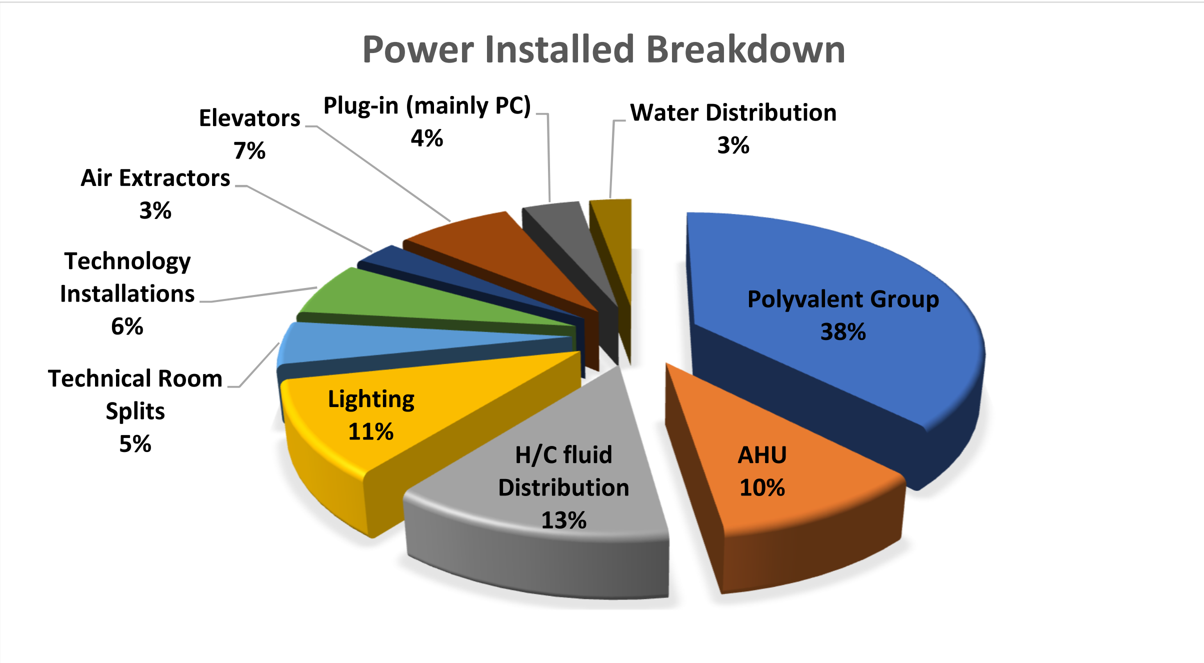

Figure 43. Power installed Breakdown.

Anyway, it is necessary to specify that the power installed may not represent more than a guideline for the consumption breakdown. It is mainly related to the fact that some of the equipment installed does not present a continuous operation during the year. The Polyvalent Group is used only for cooling purpose, so during the heating season its contribution is absent. Strictly correlated to it, there is a part of the fluid distribution system which is dedicated for cooling purposes and another one that operates during heating season. Moreover, some of the AHU installed, Auditorium and Basement, operates only when the respectively areas served are occupied. In order to have an idea of which contributions could provide ventilation and fluid distribution systems, it has been considered an average of the power installed that could work at the same time. In addition, considering the high automation level of the building systems, through thermostatic regulation, presence sensors and so on, it results impossible to properly rebuild the missing consumption contribution starting from the power installed.

Therefore, for this first analysis it has been decided to perform the quantitative consumption breakdown of the typical consumption days using only the contributions already known through measurements, Figure 45 - Figure 44, and to observe qualitatively which could be the sources of the other contributions.

Firstly, observing the Sunday and Holidays typical day profile showed in Figure 44, it is possible to observe that, as expected, great part of the systems of the building are at rest. This profile mainly represents the baseline of the building. Analysing the different systems installed, it is possible to speculate it is mainly constituted by technology installations, technical rooms independent split units and, during night ours, a contribution by external lighting systems.

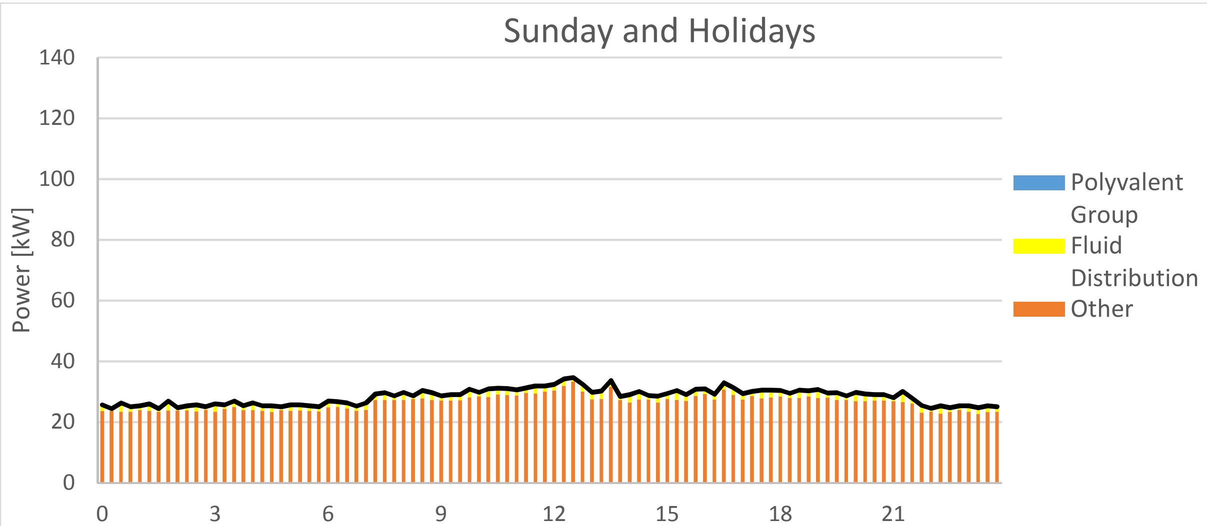

Figure 44. Sunday and Holidays Typical Day consumption profile breakdown.

While, comparing Cooling Season (Figure 45) and First-Mid Season (Figure 46) with Heating Season (Figure 47) and Second Mid-Season (Figure 48), it is possible to observe that, as already said in the discussion of the clustering, the Polyvalent Group is used only for cooling purposes. It represents, as expected, a big contribution to the electricity consumption of the building. Moreover, through the consumption breakdown it is possible to easily notice that the morning peak is completely cause by the operation of the Polyvalent Group.

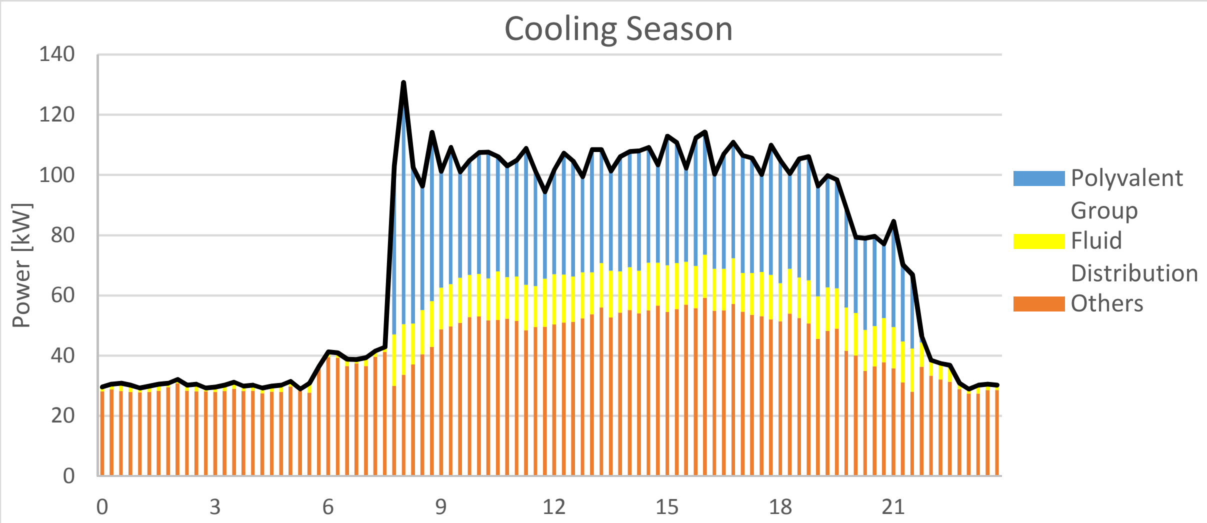

Figure 45. Cooling Season Typical Day consumption profile breakdown.

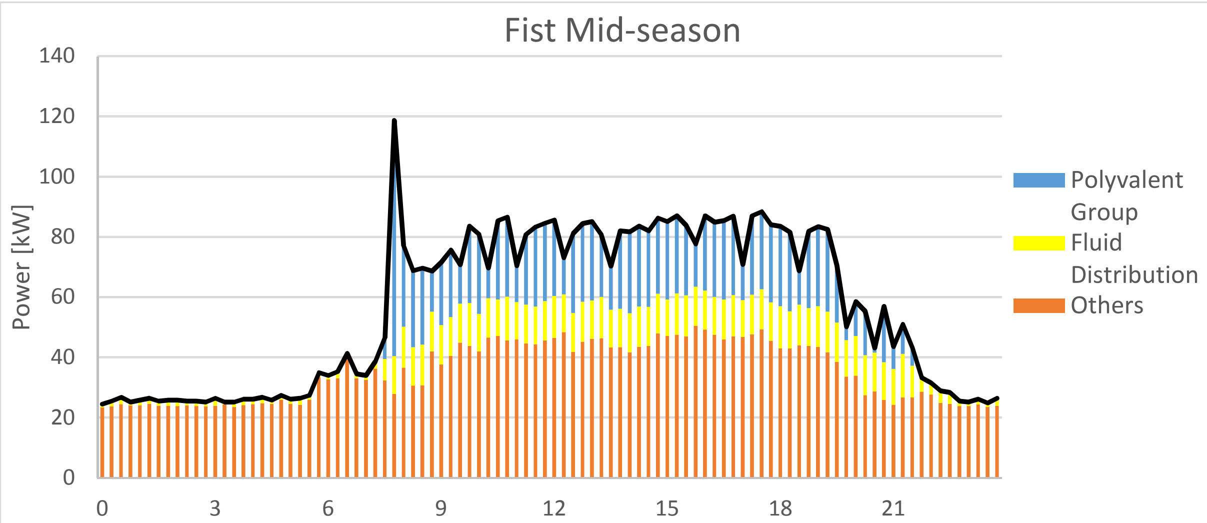

Figure 46. First Mid-Season Typical Day consumption profile breakdown.

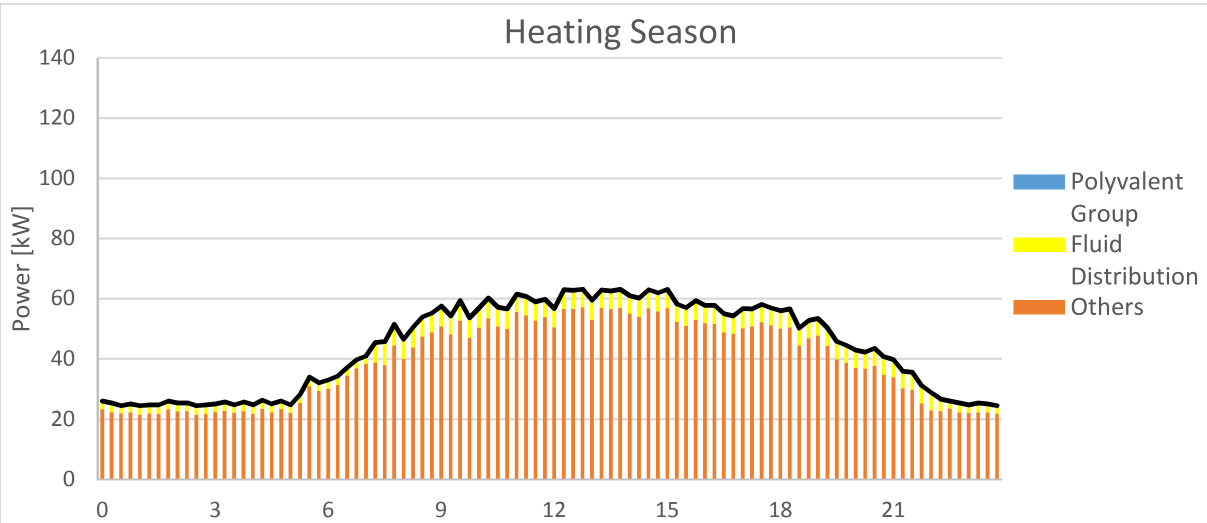

Figure 47. Heating Season Typical Day consumption profile breakdown.

Looking at the profiles of the cooling periods, it is possible to observe that the Polyvalent Groups operated beyond the occupancy hours. This is probably related to the wrong setting-up of the energy management system.

It is interesting to observe that, during working hours, even the fluid distribution systems present a clearly higher electricity consumption during the summer period, which is probably direct connected to the Polyvalent Group operation. As a matter of fact, looking at the fluid distribution pumps power installed, presented in Table 15, it is possible to see that aquifer pumps (EP1 and EP2) which operates only when the Polyvalent Group is used, represents the higher contribution in terms of installed power. On the other hand, during night ours, fluid distribution consumption in almost zero during cooling periods, while it is slightly higher than zero in heating periods. This could be mainly related to the presence of anti-freeze systems that works even during the night.

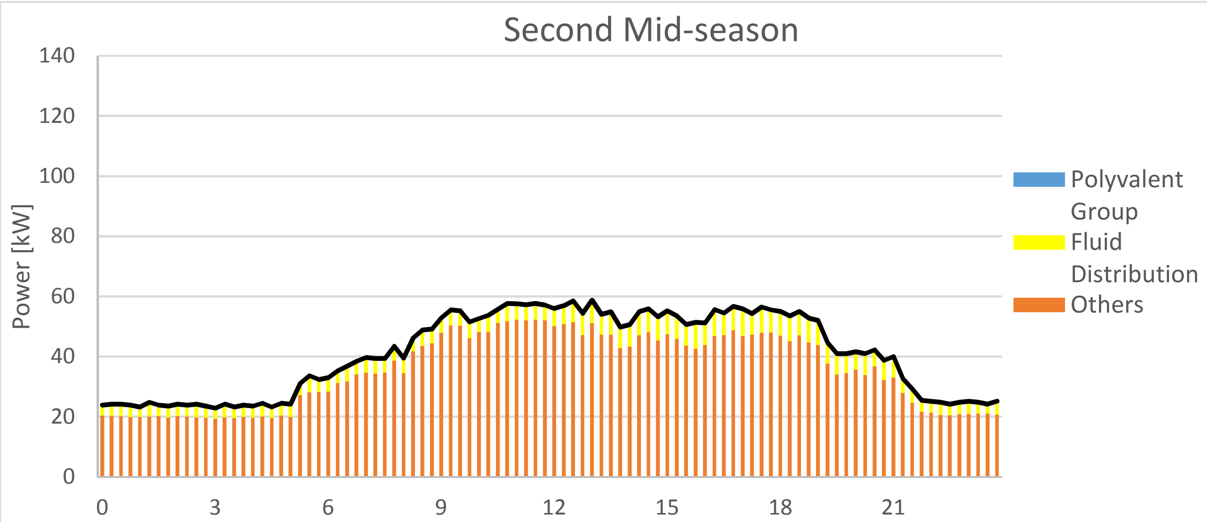

Figure 48. Second Mid-Season Typical Day consumption profile breakdown.

In others contribution, apart the baseline individuated for Sunday profile, it is possible to suppose that the higher contribution will be represented by ventilation (AHU) and lighting. In addition, there will be the variable contributions of water distribution, air extractors, elevators and plug-in.

Finally, observing Heating Season Saturday (Figure 49) and Cooling Season Saturday (Figure 50) profiles, apart the observations already done for the other profiles, it is possible to confirm the considerations made about the occupancy of the building. As a matter of fact, as discussed in the previous paragraphs, on Saturday the building is open only half-day and so the systems are turned off approximately at 14:00.

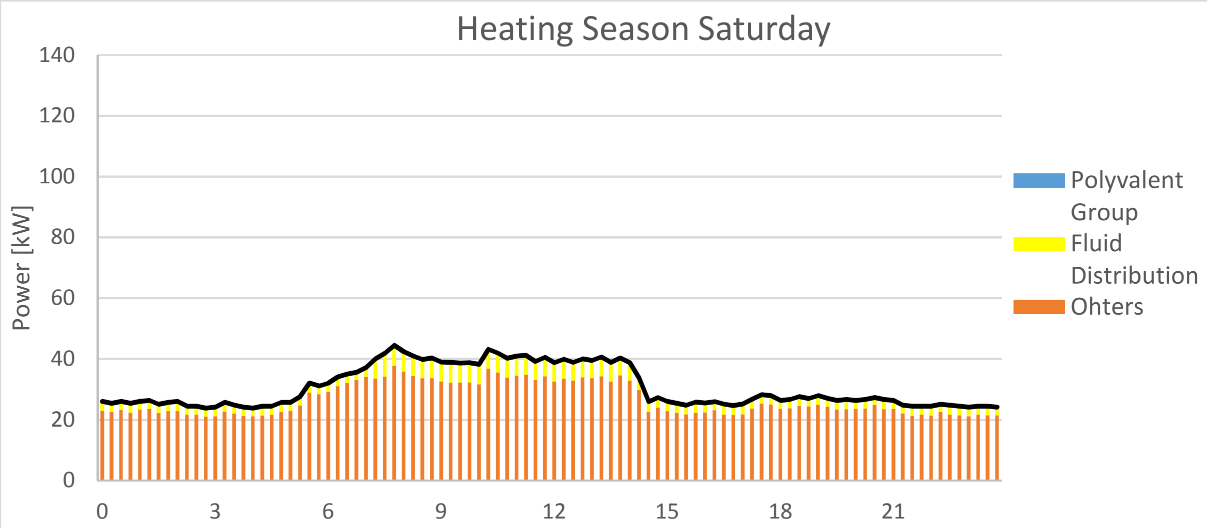

Figure 49. Heating Season Saturday Typical Day consumption profile breakdown.

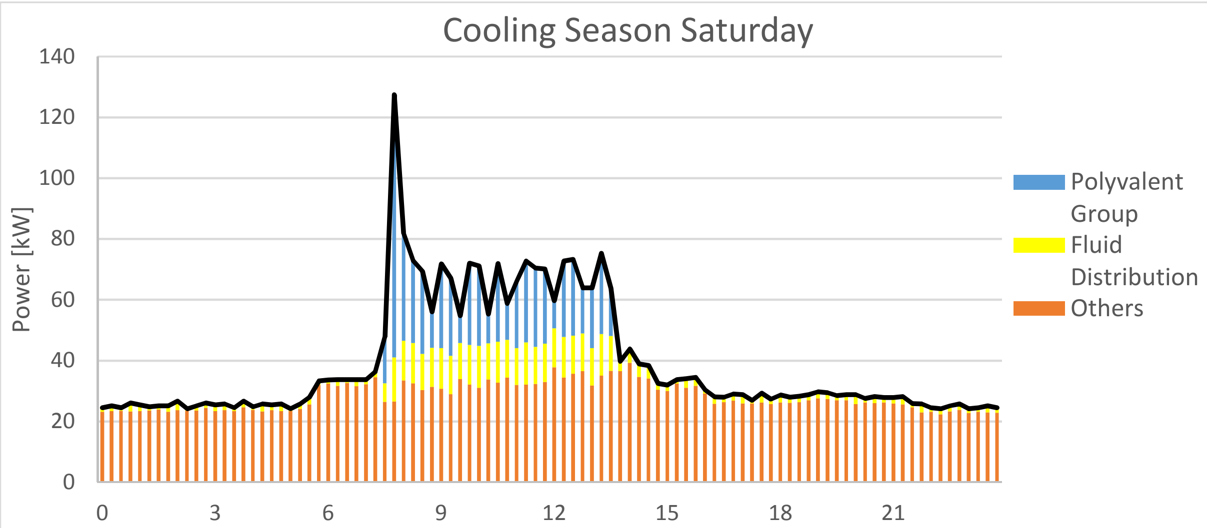

Figure 50. Cooling Season Saturday Typical Day consumption profile breakdown.

5.3.2 District Heating Consumption Analysis

As already discussed previously, the building is connected to the District Heating Network of Turin with three different heat exchangers for different purposes:

- Heating;
- Domestic Hot Water (DHW);
- Absorption Chiller Feeding (Cooling).

Considering heating and cooling, as it is possible to understand, the system has been designed in order to exploit the DH network both in summer and in winter. Anyway, up to date the absorption chiller has been never used, therefore that heat exchanger has never worked (excluding the initial test). After the request to the DH supplier, it has been possible to have at disposal the measures of the District Heating Consumption of DHW and Heating heat exchangers. Anyway, about DHW it is not possible to make a detailed analysis due to lack in measurements related to the Solar thermal plant contribution. The plant is provided with a dedicated heat meter, but it is not already historicised.

Therefore, for this initial assessment, it has been analysed only the DH consumption related to heating purposes. The suppliers allow the access to the measurements through its dedicated web portal, in which each consumer can log in with personal credentials. The DH measurements available are characterized by Power and Energy measurements acquired every 5 minutes and 23 seconds. Therefore, in order to have a more accessible data, a simple resampling technique with linear interpolation has been applied to the data set available. Using the conversion factors indicated by the Ministero per lo Sviluppo Economico (MISE) [102], it is possible to compare the consumption of the two energy vectors used by the building systems. Even though electricity is used during the whole year, the heat part represents a consistent contribution to the energy consumption of the building standing for the 31%.

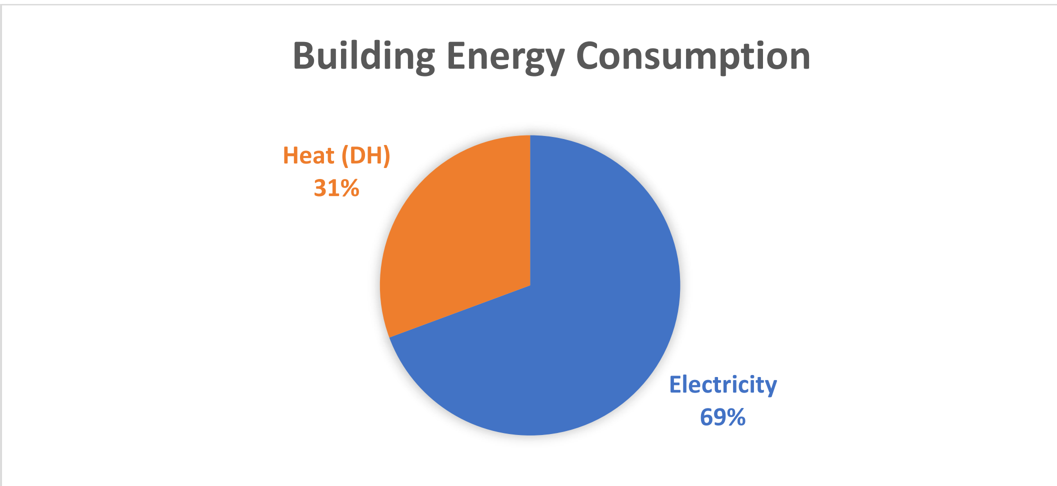

Figure 51. Electricity vs. Heat Consumption in the building.

In terms of typical consumption days, the assessment for the DH is different. As a matter of fact, considering that it is used only for heating purposes, the characteristic season is only one, the heating season. In terms of profile, it is just possible to distinguish three main typical days which are strictly related to the scheduling of the systems, previously discussed. In particular, it is possible to individuate a Working Day, the Saturday and the Sunday as representative days. Figure 52 shows three samples of the possible typical days discussed.

As expected, with respect to the Working Day, the Saturday follows the building occupancy, therefore it is possible to observe the systems shutdown approximately at 14:00. About the sample for the Sunday, it is important to specify that it has been represented with a different scale with respect to the other two samples. The purpose is to show that power is very low but not equal to zero, probably because of the presence of anti-freeze systems that operates even when the building is closed, and the other systems are off.

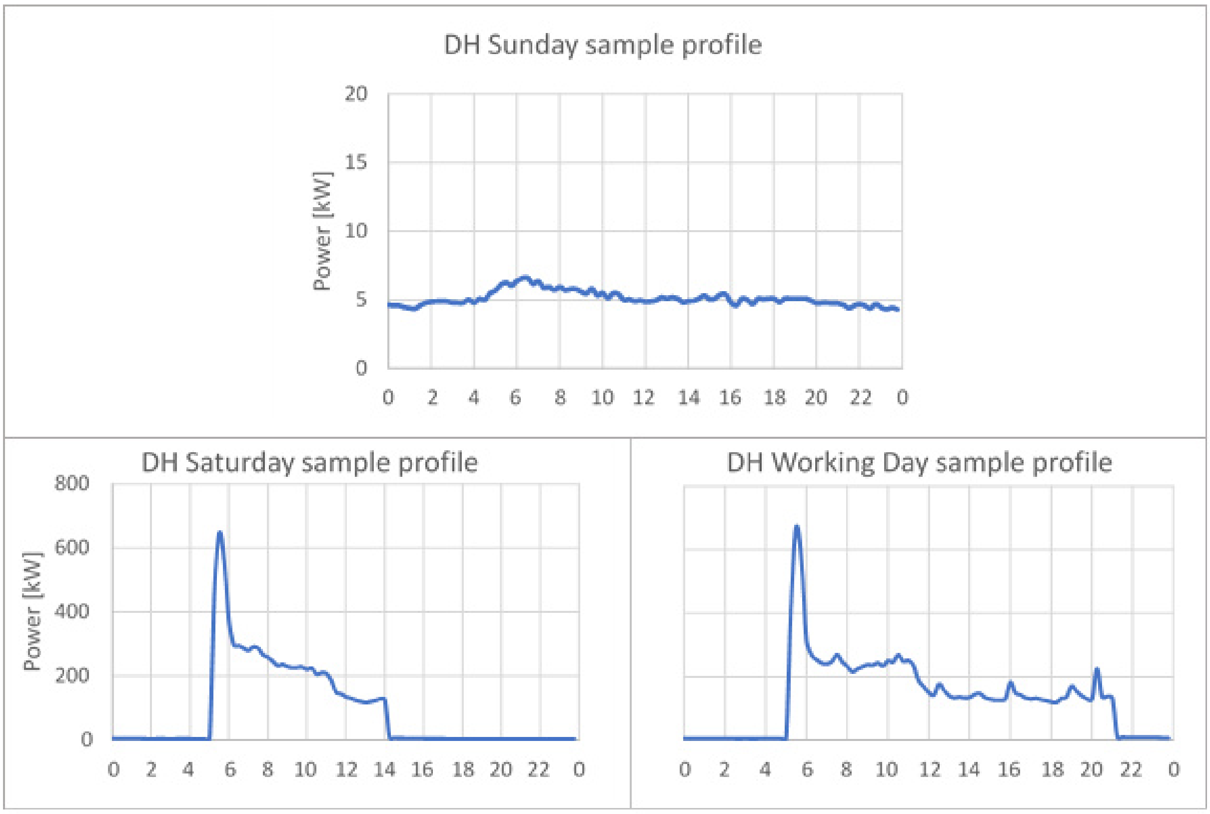

Figure 52. District Heating typical days samples profiles.

In this work it has not been possible to perform a detailed analysis of the District Heating consumption, but it has been simply tried to answer to the following question:

➢ *Could be the Polyvalent Group, highly efficient equipment, more convenient than the DH for heating purposes?*

It has been performed a simple calculation in order to estimate the possible potential benefits related to the use of the Polyvalent group even during the heating season, substituting the use of the District heating network.

Month	Consumption [kWh_t]	Unitary price [€/kWh]	Tot. Cost. [€]	
Dec. - 18	66870	0.0876894	5864	13281 €
Jan. - 19	83820	0.0884909	7417	

Table 26. District Heating accounted Consumption and costs for December 2018 and January 2019.

In Table 26 are summarized the thermal energy consumed during the months of December 2018 and January 2019 with the related cost paid to the supplier.

As already discussed, up to now the Polyvalent Group has been used only for cooling purposes, therefore it is not possible to accurately evaluate its convenience considering its real behaviour in heating mode. Moreover, as discussed in Paragraph 5.2.6, heat meters of energy withdrawn from the aquifer and energy produced by the Polyvalent Group are installed but the measurements acquired can be only visualized in real time without the availability of the historical data. Therefore, for this first analysis it has been considered a constant COP for the Polyvalent group, equal to the one declared by the manufacturer for the heating mode (**4,44**). The related estimated electricity consumption and costs have been calculated and reported in Table 27.

Month	Consumption [kWh_e]	Unitary price [€/kWh]	Tot. Cost. [€]		Potential Saving
Dec. - 18	15061	0.2	3012	6787 €	**-50%**
Jan. - 19	18878	0.2	3775		

Table 27. Polyvalent Group estimated electricity consumption and related cost for heating purposes.

For the evaluation of the cost related to the potential electricity consumption, it has been evaluated, trough the bills, a mean unitary price of 0,2 €/kWh including all price components except for the fixed ones which are paid even without using the Polyvalent Group.

Therefore, using the result of this simple calculation, taking into account the simplification assumed due to lack of deeper information, it is possible to affirm that there is a maximum potential monetary saving of 50% employing the Polyvalent Group even for heating purposes.

5.4 Proposed solutions of Demand-side Management

Exploiting all information gathered about Energy Center building systems and the ones evaluated through the different analysis performed, the final step has regarded the evaluation of possible Demand-side Management opportunities. Firstly, it has been performed a simple analysis about the possibility to extend the actual PV plant size with the aim of increase the self-sufficiency of the building but maximizing self-consumption of electricity produced. Then, through direct observation of consumption profiles it has been evaluated the possibility to apply some demand flexibility strategies, speculating about the possible effects on both profiles path and building internal comfort. The intention is to provide a starting point for future detailed evaluations and eventual implementation tests of the discussed DSM strategies. Considering demand flexibility strategies, at this stage, it has not been possible to exploit the evaluated typical consumption days profiles because of the unavailability of internal temperature measurements for those specific days.

About internal comfort conditions, it is necessary to discuss some considerations. Concerning Indoor air quality and visual comfort, it has not been possible at this stage to quantitatively estimate the possible consequences of the strategies implemented. While, it has been done for thermal comfort using a very simple approach through a linear regression, discussed in paragraph 5.4.2.

Moreover, the author will even discuss all the strategies presented in Paragraph 3.1.3.2 in terms of controllability and observability. As already explained, controllability is intended as the capability of the supervision system to act on the variable necessary to implement the strategy analysed, while observability regard the availability of measurements related to parameters necessary to both evaluate the eventual benefits provided but even to monitor the consequent possible discomfort.

5.4.1 PV plant extension

Exploiting the electricity typical day consumption profiles, it has been performed a simple analysis in order to evaluate the possibility of extension of the PV plant installed in the building. It has been performed a simple optimization analysis on the PV plant size, with the aim of increasing the self-sufficiency of the building while maximizing self-consumption of electricity produced. For this first simple assessment, it has been used the photovoltaic productivity of 2018, but considering the Hall Coverage PV plant working correctly, so its profile has been assumed equal to the one simulated. Moreover, bearing in mind that Hall coverage and Hall Façade surfaces are saturated, it has been assumed for simplicity to increase Stairs A and B PV plants size, assuming installation characteristics identical to the plants already existent. In the following, will be discussed the different phases performed and the assumptions used.

1. PV daily productivity subdivision.

Firstly, daily productivity has been subdivided into four equal ranges which may recall to the four main irradiation conditions that may affects the PV performances: Cloudy, Mostly Cloudy, Mostly Sunny and Sunny. Therefore, considering the maximum daily productivity of the PV plant during the year, the entire range has been divided into four sub-ranges, as reported in Table 28.

Symbol	Interval Name	Daily Production Range [kWh]
	Cloudy	0 – 75
	Mostly Cloudy	75 – 150
	Mostly Sunny	150 – 225
	Sunny	225 – 300

Table 28. PV plants daily production ranges subdivision.

2. Evaluation of productivity levels frequency.

Then, looking at each cluster, the profiles has been furtherly separated in the four ranges individuated. For each cluster it has been evaluated the frequency of occurrence of each level of productivity. It can be considered as a rough probability of the productivity level in a certain cluster.

For example, Figure 53, shows the seven typical day consumption profiles subdivided into PV contribution, so self-production, and grid withdrawal. The PV production profile, for each typical day, corresponds to the one with the higher daily production that belongs to the most probable productivity level. As expected, clusters which includes days of spring a summer season presents higher probability of good irradiation condition, while heating season clusters, whose days mainly belong to winter season, show high probability to present low irradiation conditions.

3. Self-consumption and Self-sufficiency evaluation for each productivity level

Considering the different levels of productivity individuated, it has been evaluated the values of self-consumption and self-sufficiency, considering for each cluster the four PV profiles corresponding to the days with higher daily production in each range.

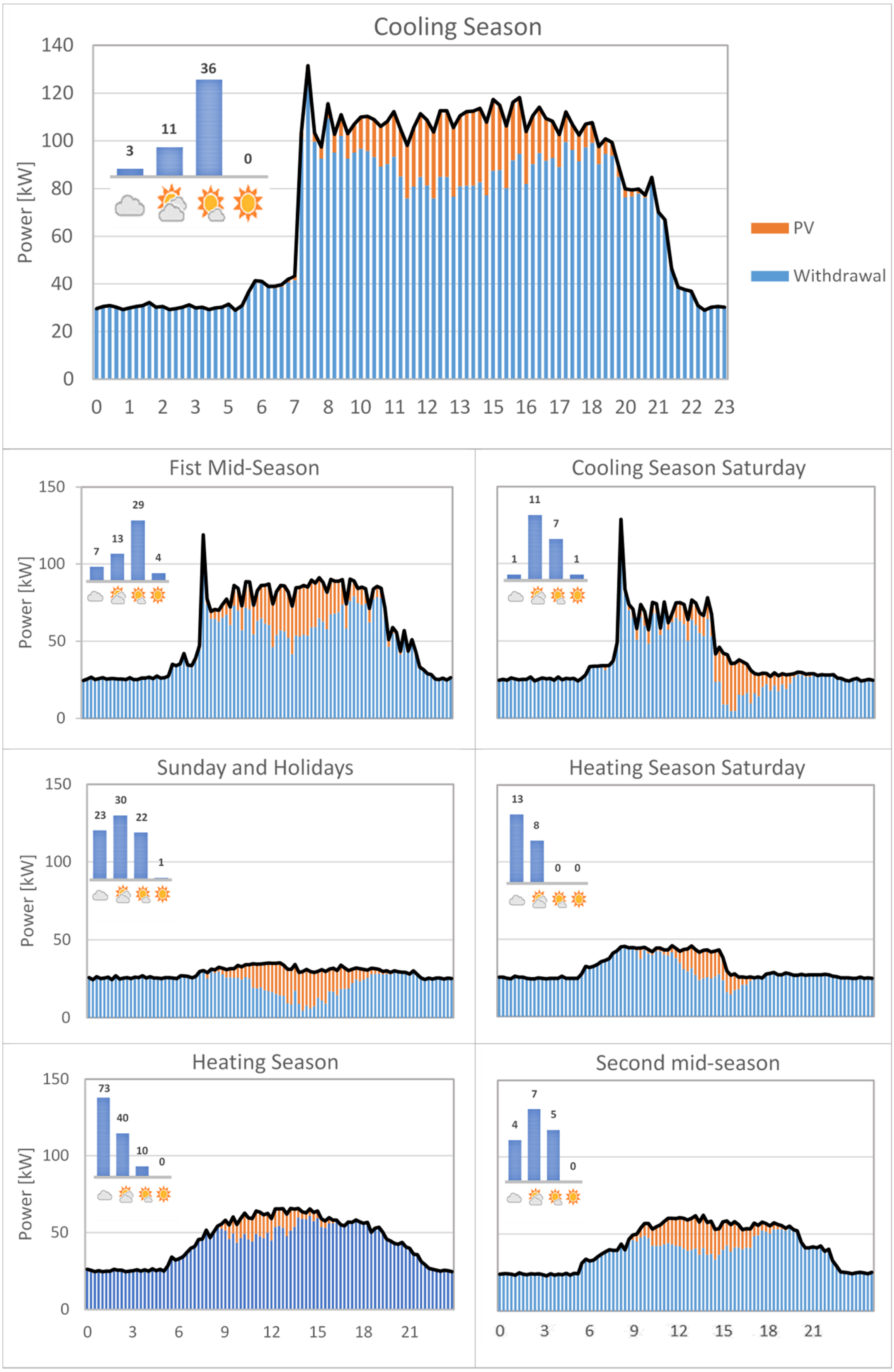

Figure 53. Typical Day Consumption Analysis, PV self-production and withdrawal.

As it is possible to see in Equations (2) and (3), Self-consumption index is considered as the ratio between PV production self-consumed and total PV production, while Self-sufficiency is intended as the ratio between PV self-consumption and the electricity consumption (El_c).

$$SC = \frac{PV_{self-cons.}}{PV_{prod.}} \tag{2}$$

$$SS = \frac{PV_{self-cons.}}{El_c} \tag{3}$$

4. Average clusters indexes evaluation.

Therefore, in order to consider the different levels of irradiation that may occur, it has been evaluated a mean value of the indexes for each cluster performing a weighted average of the indexes evaluated at the previous step for the four productivity levels. The weights are represented by the frequency of occurrence of each productivity level in the clusters.

5. Overall indexes evaluation.

Finally, in order to have a single average value for both the indexes it has been performed another weighted average among the values calculated for each cluster. At this stage, the criterion followed is represented by the weights of the different cluster over the year, as already indicated in Table 24, represented by the ration between the day of the cluster over the 365 days of the year. Therefore, in order to evaluate size factor effect on self-consumption and self-sufficiency, and so to have an estimation of the PV extension potential, the steps from 3 to 5 have been re-executed for different value of the size factor, at this stage assumed between 1(the actual case) and 10. Results obtained are showed in Figure 54.

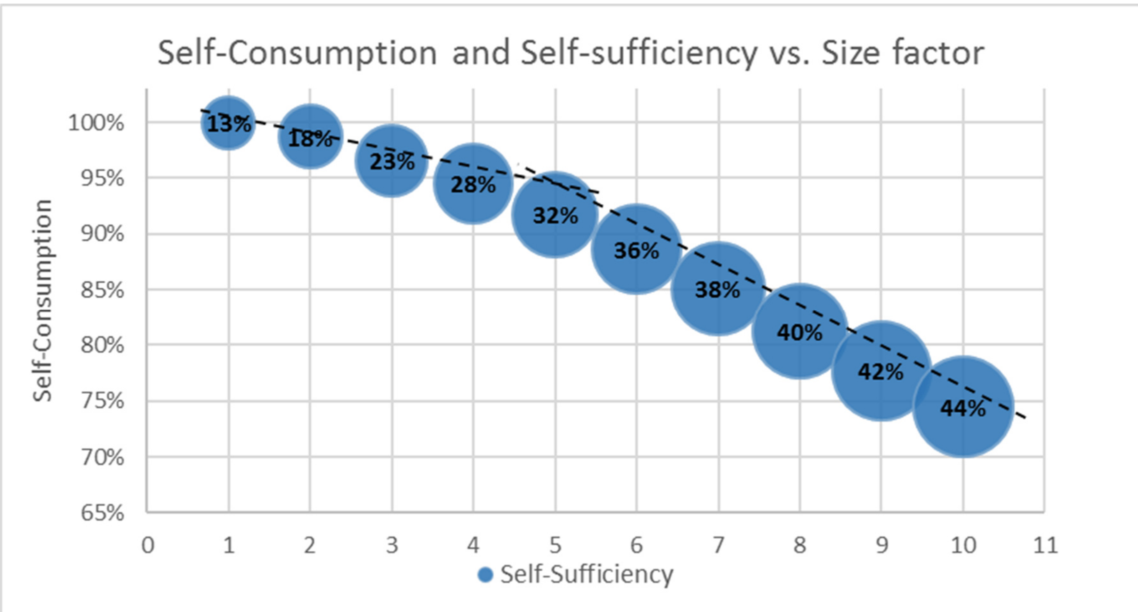

Figure 54. PV size factor effect on self-consumption and self-sufficiency.

It is possible to notice that the evolution of the self-consumption in the range analysed increase its slope after a factor equal to five. Therefore, in order to maximize self-consumption and self-sufficiency, it is possible to assume a maximum increment of Stairs A and B PV areas of five times with respect to the one already installed.

Obviously, the one presented is just an estimation of the extension potential of the PV plant. In particular, in a deeper and more detailed analysis should be considered the real maximum area at disposal and the real optimal installation parameters that could be different with respect to the plants already operating.

5.4.2 Building thermal response estimation

In order to have a rough understanding of the building behaviour in terms of its thermal mass, it has been evaluated a sort of thermal time response using the measured temperature at disposal. For this first assessment, due to lack of information about the exact collocation of sensors associated to available measurements, the building has been considered as a single black box, therefore the following considerations have been done observing the average of the internal temperature actually measured. This assessment has been performed in order to have a first rough measure of building capability to provide flexibility exploiting its good characteristics in terms of thermal mass, having an estimation of the possible consequent discomfort. As a matter of fact, the aim of this evaluation is to provide an experimental reference value of decay (winter) or increase (summer) of temperature consequently to the possible shutdown of the H/C systems.

Firstly, it has been considered a week of December 2018 as sample. Therefore, it has been observed the temperature decay from the shutdown of the plants in the evening (19:00), to the following morning (7:00). It has been evaluated a mean temperature decay of 0,2 °C/h, which represents a conservative estimation because of the worst conditions presented by the time-frame observed:

- Heating plant off;
- Absence of Solar Irradiance. Considering that flexibility strategies are usually applied during the day, for sunny days the temperature decays will surely be lower.
- Unoccupancy. Heat gains related to occupants and their activities led to a reduction in heating load.

It should be necessary to consider another factor that increase the heating load: ventilation. Anyway, as described in previous paragraphs, the AHU installed in Energy Center are all equipped with recovery systems which strongly reduce the heating load related to the ventilation.

Doing the same evaluation for the Cooling season is slightly more trivial. The worst situation available is the Sunday morning with an average internal temperature increase of approximately

0,2 °C/h. Anyway, with respect to the heating season, this value is not conservative because evaluated for the following conditions:

- Cooling plant off;
- Presence of Solar Irradiance;
- Unoccupancy.

While for the previous case Unoccupancy represented a conservative situation, for summer season it is the contrary because Occupancy, and all the internal gains related to the users activities, represent an additional cooling load. Therefore, for this first assessment, it has been considered a value doubled with respect to the one calculated, equal to 0,4 °C/h to avoid an overestimation of flexibility potential.

5.4.3 Electricity Load Curtailing

As discussed in previous Chapters, there are different ways through which utilities could participate actively to the electricity market. One of this is represented by Demand Response programs. In order to evaluate the capability of the building to participate to DR programs, it has been tried to estimate the potential of Polyvalent Group (PG) curtailing, which represents the higher contribution to the electricity consumption in during cooling, speculating on the possible effects on the thermal comfort exploiting the reference temperature increase calculated in the previous paragraph. It has been assumed a flexibility availability period of 120 min, as prescribed by the requirements for the UVAM pilot project discussed in Paragraph 2.4.2.

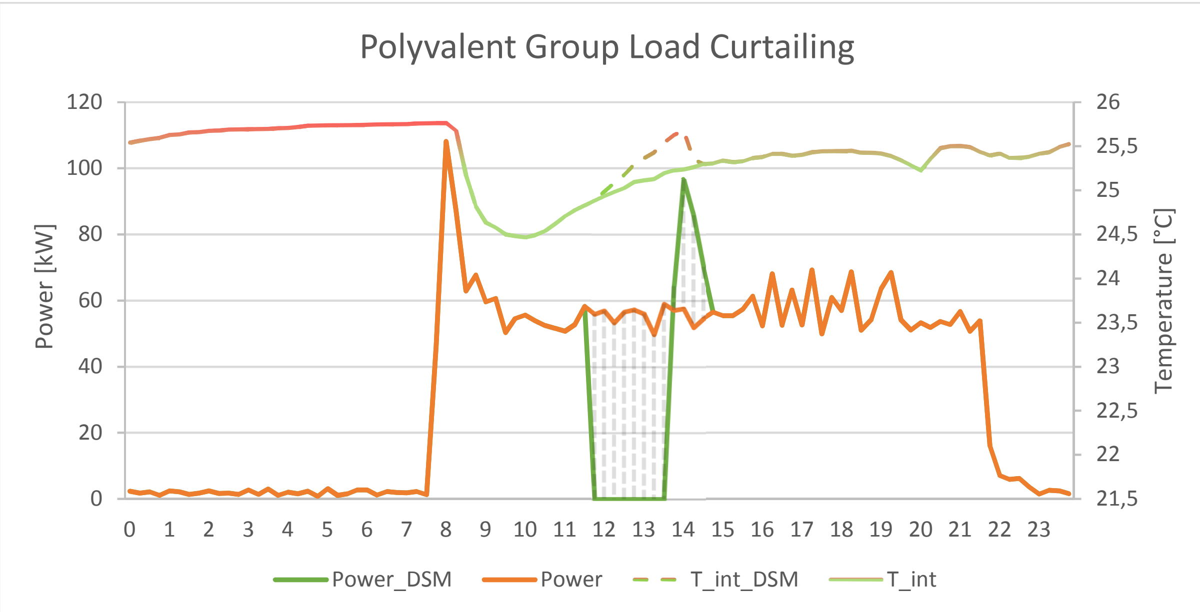

Figure 55. Possible load curtailing effects on a sample day electricity consumption and internal temperatures profiles.

Figure 55 shows the possible effects of the implementation of such strategy. After the beginning of the flexibility event, the reference rate of temperature increase has been applied. It has been chosen to apply the flexibility event from 11:30 to 13:30 because it can be assumed that from 12.30 to approximately 14, occupants may be out of the building for the lunch. As it is possible to observe, the temperature path presents a delay with respect to the load which is related to the thermal mass effect of the building. Therefore, the observed delay of approximately 30 minutes has been kept even for the subsequent observations on the modified path. Then after the restoration to normal operation, a possible rebound peak has been estimated necessary to bring back the temperature to the normal operation (intended as the original path). For this first assessment, the rebound has been evaluated applying a simple energy balance, rescaling the energy necessary to decrease the internal temperature from 7:00 to 9:00 with respect to the temperature difference necessary to restore normal operation. Considering a temperature limit to avoid discomfort of 26 °C (see paragraph 3.1.3.3) it is possible to affirm that this strategy would potentially not affect occupants thermal comfort, with a resulted estimated saving in electricity consumption of the day analysed of approximately 10%.

In terms of controllability and so implementation, the supervision system allows to directly control the Polyvalent Group load shutting down the machine, managing the supply temperature setpoint or it could be even possible to turning off the distribution system unloading the machine. It is suggestable to program such tests in different Weekdays of the summer periods in order to take into account the variability of the cooling load of the building.

In terms of observability, it is necessary to perfectionate the monitoring system in order to control all the comfort parameters that could be affected by the strategy implementation. Therefore, it is necessary to historicize and observe the temperature evolution of the different areas of the building. Particular attention should be paid for area exposed to high irradiation levels that could reach discomfort conditions sooner.

As already discussed in the previous Chapters, it is suggestable to couple the monitoring of the temperature evolution with occupants questionnaire in order to take into account even the subjective nature of the thermal comfort perception. In order to avoid occupants high dissatisfaction, it is suggestable to advise them of the intention to perform tests but to avoid communicating the occupants the exact days and hours of the test, in order to keep the interview results as more objective as possible.

Therefore, in the following will be summarized the suggested steps for the execution of the implementation tests of this strategy:

- Improvement of monitoring system: ensure the monitoring of zone temperature evolution;
- Information of occupants about the future execution of tests;
- Prepare and provide to occupants a questionnaire for comfort assessment (EN 15251 suggestions could be used as starting point [85]).

- Select a set of days in which request the compilation of the questionnaire, during which apply or not the strategy.
- Collect measurements of electricity consumption and comfort parameters monitoring and try to compare days as much similar as possible.

In general, as already discussed, it is suggestable to have even the measurements of the Polyvalent Group heat meters, in order to have a deeper understanding of machine behaviour.

5.4.4 District Heating load curtailing

Even though in this thesis work the author has discussed DSM practices principally for electricity field, it has been even evaluated the possibility to operate on the heating load, and so to provide flexibility services to the District Heating Network. Therefore, in this paragraph it will be proposed the evaluation of a load curtailing strategy applied to the District Heating load. As already discussed for previous paragraph, it represents just a speculation on the possible effects that the strategy could have on both load path and thermal comfort. The latter has been taken into account considering the reference temperature decrease evaluated in Paragraph 5.4.2. For this first assessment it has analysed a January sample working day and it has been assumed again an availability time of the flexibility strategy of 120 min, as showed in Figure 56.

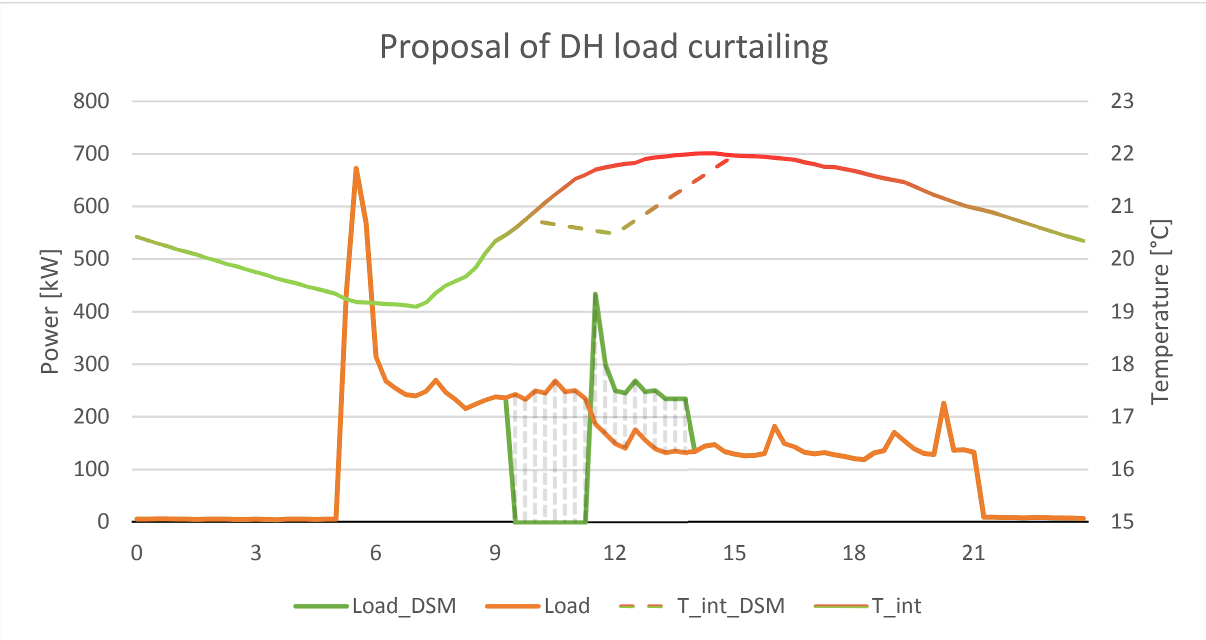

Figure 56. Possible load curtailing effects on a sample day DH consumption and internal temperatures profiles.

The observations that is possible to do are very similar to the previous case analysed. With a delay of about 30 minutes from the starting of the flexibility event, the evaluated reference temperature decrease has been applied to the internal temperature profile. Then, after two hours of curtailing the system has been restored and a rebound has been estimated to bring the temperature back to the ordinary path. Even in this case, the rebound has been evaluated with a simple energy balance, rescaling the load with respect to the temperature difference. Considering a comfort temperature limit of 20°C it is possible to affirm that the strategy presents a good potential of implementation with an estimated energy saving of about 6% of analysed day district heating consumption.

Considering the implementation of such strategy, in order to curtail the heating load, it is possible to proceed in two different ways: shutting down the fluid distribution pumps or acting on supply water temperature.

While, on observability side, it is necessary to consider different variables that need to be controlled in order to both evaluate the eventual benefits and the consequent eventual thermal comfort effects. In particular it is suggestable to monitor:

- District Heating consumption;
- Fluid distribution system power absorption, to evaluate the eventual saving even in electricity.
- Internal air Temperature. As already discussed, it is necessary to perfectionate the internal temperature monitoring.

This strategy is very similar to the previous presented, except for the systems involved and the expected effects. Anyway, the suggested procedure for the implementation can be considered the same to the one previously discussed.

5.4.5 Pre-cooling peak shaving strategy

As previously discussed in paragraph 5.3.1.3, the peak power showed in the cooling periods is completely cause by the polyvalent group. Therefore, in order to reduce that peak, it could be possible to evaluate the implementation of a pre-cooling strategy. Considering the actual thermoregulation of the Polyvalent group as function of the load it could be possible to implement the strategy in two different ways:

- Acting on the supplied water temperature setpoint, and so acting on the temperature difference. In this case, the strategy provides the system turning on in advance with a gradual increase of the supply water temperature setpoint starting from a lower value with respect to the normal operation;
- Acting on the flowrate. Even in this case, the strategy provides the system turning on in advance with a gradual increase of the requested cold-water flowrate.

In particular, considering the second way exposed, it could be possible to act on the different loads served by the Polyvalent Group during the cooling season, whose nominal powers has been reported in Table 29.

The fluid distribution system of the building, considering both pumps and valves, allows to have a good control on the load in terms of flowrate requested. It could be possible both to act on the pumps of the different load utilities, controlling their operating speed and so managed flowrate, or on the load utilities valves. In particular, for the second case, the systems present a very good granularity that would allow a fine regulation of the load. For this first assessment, Figure 57 shows the expected results of the application of a supposed strategy with an observed reduction in load peak of 35%. It is necessary to notice that to evaluate the real consequences to the load it is necessary to perform simulations or implementation tests. In this initial speculation, a simple energy balance has been applied, evaluating the contribution of each load with a simple proportion with respect the nominal load showed in Table 29. Considering the occasional unoccupancy of Auditorium and Basement, the AHU of such areas has been excluded for this first analysis.

AHU	259 kW (56,8%)	Offices NW	106 kW (41%)
		Offices NE	10,6 kW (10,6%)
		Hall	37,8 kW (14,6%)
		Basement	39,5 kW (15,2%)
		Auditorium	48,2 kW (18,6%)
Radiant Floors	20 kW (4,5%)	/	/
Radiant Ceilings	160 kW (35%)	Floor 1	51,2 kW (32%)
		Floor 2	51,2 kW (32%)
		Floor 3	57,6 kW (36%)
Storage	17 kW (3,7 %)	/	/

Table 29. Main cooling loads nominal power.

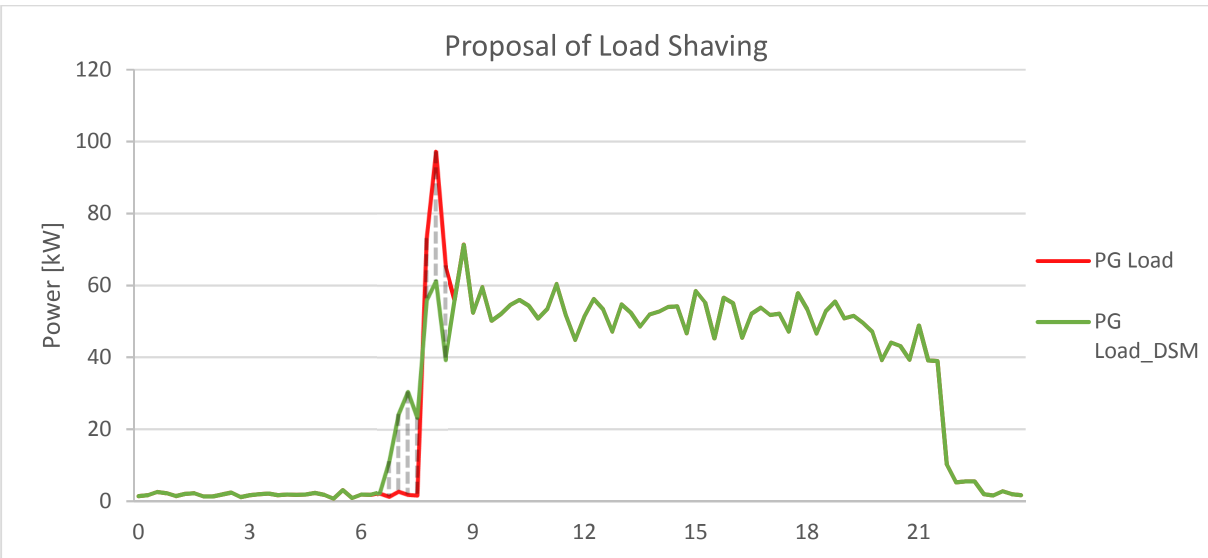

Figure 57. Possible effects of a Pre-cooling strategy applied to Polyvalent Group.

Therefore, it is supposed to shift the different loads in time, anticipating the turning on of the Polyvalent Group but increase in different step the cool water flowrate requested, adding at different time the utilities load, supposing to open the respective valve at different times as follow:

- 6:30 – Third floor radiant ceiling valves;
- 6:45 – Second floor radiant ceiling valves;
- 7:00 – First floor radiant ceiling valves;
- 7:15 – Radiant floor valves (Hall);
- 7:30 – AHU batteries.

Obviously, the order showed is just a proposal that could be perfectionated considering the level of comfort and discomfort of the various floors. For example, Hall and Third floor areas may present a higher cooling load due to their higher exposition. Therefore, could be suggestable to start from these two areas. In terms of applicability, as already discussed previously, actually the HVAC systems are controlled with a single clock. In order to apply such strategy, it should be necessary to separate the systems to different clocks. Higher is the number of clocks for the different systems, higher is the granularity of control and so lower is the rate of increase of the power. But it is suggestable to find a trade-off between the granularity of control and simplicity of systems management to avoid high complexity in setting up the desired programs.

5.4.6 Night Free Cooling Strategy

Looking at internal and external temperature profiles, as showed in the sample week of August presented in Figure 58, it is possible to notice a considerable temperature difference between the internal and external environment during the night ours that may reach even 8°C.

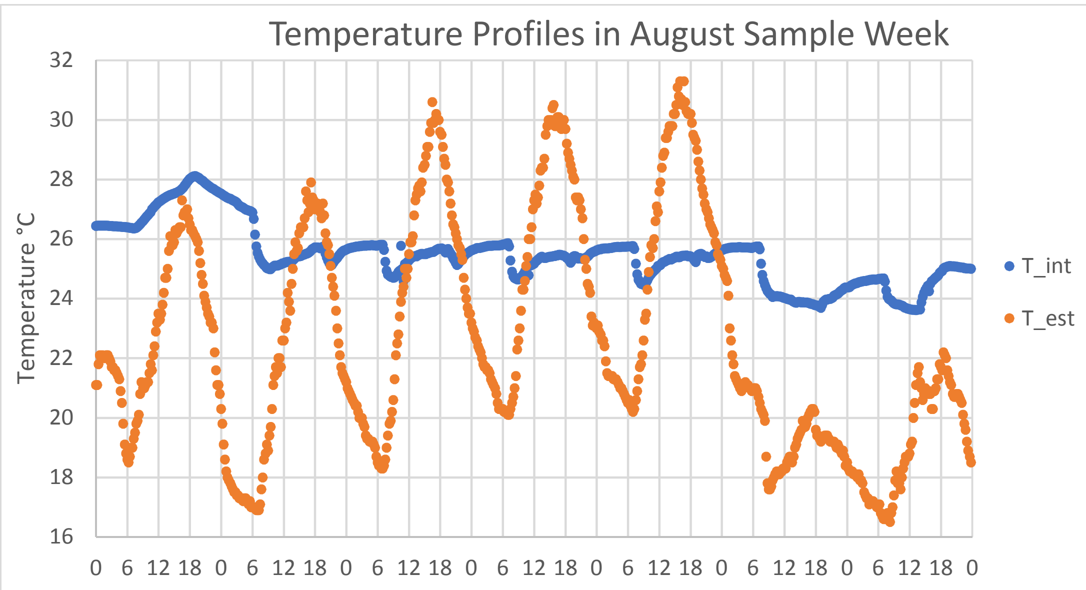

Figure 58. Comparison of External and Internal Temperature of a sample week of August.

As already discussed in previous paragraphs, the internal temperature of the building has been evaluated as the average of the zone temperature monitored, therefore assuming the building as a single black box.

This temperature difference suggests evaluating the possible implementation of a direct free-cooling strategy, which provide the turning on of AHU during the night, excluding the heat recovery system. Therefore, it means to cool the air inside the building through external air that is at a lower temperature, reducing the load necessary to bring the temperature to the set point in the morning. Obviously, for this simple assessment it has been used a mean temperature representative of the whole building. It is necessary to contextualize this observation to the difference zones of the buildings, taking into account the different aspects that may affect its thermal load, as for example the exposition.

Therefore, it has been performed a simple calculation to estimate the time of operation of the AHU necessary to decrease the internal temperature approximately to the external one. Considering the possible application of this strategy, it has been excluded the area of the Auditorium and the basement, which are served by independent AHU, because of their usual unoccupancy. As a matter of fact, as communicated by the technical staff, the AHU of Auditorium and basement operates when there are programmed events that involve their occupancy. In Table 30 and Table 31 are respectively reported the volumetric data and the nominal flow rate which have been used to perform the calculation. Considering an overall volume of 13 000 m^3 of air that have to be completely changed and a potentiality of the AHUs of 22000 m^3/h it has been estimated a necessary time of AHU operation of about 40 minutes. Therefore, for the complete change of the air it has been considered the time to operate 3 air volume changes, so 2 hours.

Floor	**Zone (and respective**	**Volume [m^3]**
Ground Floor	Hall	1946
First Floor	Hall	1920
	Offices NW	735
	Offices NE	665
Second Floor	Hall	1941
	Offices NW	834
	Offices NE	655
Third Floor	Hall	2016
	Offices NW	840
	Offices NE	641

Table 30. Volumes served by the AHU installed in the building.

AHU ID.	Supply flow rate [m^3/h]	Return flow rate [m^3/h]
Offices NW	4000	3500
Offices NO	12000	11000
Hall	6000	5000

Table 31.Summary of AHU nominal flow rates.

Therefore, considering that the lowest external temperature usually corresponds to 7:00 AM during summer, it would be necessary to turn on the ventilation system two hours before the normal operation, at 5:00 AM, excluding during these two hours the recovery system.

For the implementation tests of this strategy it is suggestable to perform two weeks with the strategy and two without in order to be sure to capture as much as possible similar days to correctly compare the results and evaluate the eventual benefits.

In terms of controllability, the supervision system allows to program the presented strategy and it is possible to exclude the recovery system of the AHUs. Anyway, as discussed in previous Chapter, at the moment all systems scheduling is connected to a single clock. In order to turning on the AHU independently with respect to the other systems of the HVAC, it would be necessary to separate the systems to different clocks. Facility manager are already evaluating the separation of the clocks, searching for a good compromise between capillarity of the control and easy management. It will be proposed this strategy, suggesting the separation of at least the AHUs clocks from the other systems.

In terms of observability, it is necessary to perfectionate the monitoring systems before the performance of the implementation tests. While the Polyvalent Group consumption is available, in order to estimate the eventual benefits in terms of reduced consumption, it is necessary to monitor even the consumption of the ventilation system. On the other hand, in order to assess if the expected temperature level is reached, it is necessary to monitor the internal temperature of the different zone of the building. As already suggested for other strategy that involves thermal comfort, it is suggestable to perform even an occupants interview for the entire period analysed, with and without the strategy implemented. It could even lead to an increase in the energy consumption, but a great improvement in comfort for the occupants.

Finally, another opportunity to exploit the free cooling of the night could be to install windows actuators. The idea is to couple the turning on of the AHUs with the opening of the windows. This could lead to a reduction in time necessary for the change of air previously calculated, and so to an additional energy saving.

In the following the author summarizes the suggested step that have to be followed for the tests implementation in:

- Improvement of the automation system. It is necessary to separate the clocks that controls the AHU from the other systems.
- Preparation of Monitoring system.
    - Monitoring and historicization of zone temperature evolution. It needs to be improved, control the association of temperature and rooms and add eventual missing zones;
    - Monitoring and historicization of AHU power absorption, actually historical measures not available;
    - Monitoring and historicization of Polyvalent Group, actually available.
- Prepare and provide occupants a questionnaire for comfort assessment.
- Perform the strategy the first two weeks of July and then compare the results to the adjacent weeks to evaluate eventual benefits.

5.4.7 Others

As final step of the presented thesis work, in this paragraph will be discussed, in terms of applicability, other general DSM strategies, following the prescriptions discussed in paragraph 3.1.3.2, in order to have an idea of their flexibility potential.

5.4.7.1 Global Temperature Adjustment (GTA) Strategy

This strategy presents a considerable flexibility potential. In terms of controllability, the supervision system of the Energy Center allows to control and modify the temperature setpoints. Moreover, the system presents even a very good capillarity that may allowing the user to operate on the single room and so to choose to apply the strategy to specific areas of the building.

To assess the consequences of the GTA strategy it is necessary to consider the differences of conditioning system of the different areas. Considering primary air system, it is possible to operate the adjustment on the single room equipped with ambient control. The supervision system will modify the opening grade of the zone valves, reducing the load requested to the Polyvalent Group or District Heating, depending on the season analysed. While, for all-air systems, it is possible to operate on the set-point of the entire zone served by the AHU. In particular, the BACS system will modify the temperature setpoint of the AHU and consequently adjust the heating or cooling load to the respective batteries.

About the implementation of the strategy, the ambient control systems installed by Siemens present the possibility to program different level of temperature setpoints. For example, to make the implementation of the strategy easier, it could be possible to resetting the temperature setpoint of the program economy, in order to then modify contemporary all the chosen zone controlling the setpoint program.

In terms of observability it is necessary to consider different variables that have to be monitored:

- Internal Temperature. Actually available, but measurements need to be improved.
- Setpoint, available but not historicised.
- Power absorption of systems involved
  - Polyvalent Group/District Heating (depending on the season observed);
  - Fluid distribution systems (pumps);
  - AHU (in particular for all-air systems).

As already suggested for other DSM strategies that involves thermal comfort, even in this case it is better to couple the comfort variable monitoring with occupants interview.

5.4.7.2 Fan Power reduction

Fans installed in AHUs of Energy Center, of both supply and return, presents IE4 engines equipped with inverter. Moreover, observing the controlled points of the AHUs there is an Analog Output variable that control the inverters speed/power through a percentage value. Therefore, it is possible to independently regulate the five AHUs installed, so deciding in which zone apply the strategy. Moreover, the equipment allows to evaluate even a reduction of the Fan Power and not just a curtailing.

In terms of observability, it is necessary to have a disposal the measures of the following parameters. It is important to notice that the comfort parameters that have to be monitored depends on the kind of HVAC interested by the strategy.

- AHU power absorption;
- All air systems
  - Internal air Temperature, available but measurements need to be improved;
  - Internal air Humidity;
  - Internal air Quality (CO_2).
- Primary air system
  - Air Humidity;
  - Air Quality (CO_2).

Internal air Humidity of rooms is monitored but it is not historicised so there is no availability of measurements. CO_2 concentration in internal air is not available, because of the missing of dedicated sensors in rooms. It can be monitored only at zone level, through the observation of CO_2 concentration in AHUs return air.

Therefore, this strategy presents a good flexibility potential but necessity some improvement in the monitoring system. Considering the installed power of the AHUs, the strategy may provide a maximum power flexibility of 27 kW.

5.4.7.3 Distribution valve limiting

It is possible to discuss this strategy at two different levels of granularity of the Energy Center air conditioning system.

1. Adjustment of primary circuit valves.

Observing the controlled points, it not seems to be possible to operate on the primary circuit valves. In order to reduce the H/C operating on the primary circuit, it should be necessary to reduce and limit the power of the related distribution pumps.

2. Adjustment on the secondary circuit.

The BACS of the Energy Center allows to modulate all the valves of the end user loads:

- AHU battery valves. In particular, for NO and NE offices the reheat battery is differentiated for each floor, while for basement AHU it is differentiated for each sub-zone served.
- Radiant floors (for Ground Floor and Floors 1,2 and 3)
- Radiant Ceilings. At each office room is associated a valve for the regulation of the internal comfort. The supervision system allows to operate on the single valve.

Regarding observability, it is necessary to monitor the variables necessary to evaluate the eventual energy saving and the comfort ones that could be affected by the implementation. In particular it is suggestable to monito:

- Internal air Temperature. It may regard all buildings zone or even the specific areas/rooms in which the strategy is applied. For example, in summer season, it could be decided to apply the strategy only to the areas that are affected by low irradiation, reducing the possibility to cause occupants discomfort;
- Heating/Cooling System power absorption.
- Fluid Distribution System Power absorption. Reducing the opening grade of the valves reduce even the flowrate requested.

5.4.7.4 Chiller/Heater Demand Limit

In order to evaluate the applicability and observability of such strategy it is necessary to distinguish the different generation systems installed in the building.

About the Polyvalent Group, the manufacturer technical sheets indicate the possibility to operate demand limit strategies through the dedicated controller of the machine. Otherwise, as already said, it is possible to operates on the primary circuit distribution pumps. As a matter of fact, considering the District Heating system, it is the only way to limit the demand. It is expected that limiting the pumps power, and so the flowrate to the systems it consequently limits the chiller/heater load.

In terms of observability, it is necessary to measures the following quantities:

- Chiller/heater power absorption, to evaluate the eventual energy saving;
- Fluid distribution system power absorption;
- Chiller/heater heat meters. It could be useful to evaluate the reduction in energy provided, and so requested, to the systems. Moreover, considering the Polyvalent Group, it could be interesting to observe its behaviour in terms of evolution of the COP/EER as a consequence of the strategy implementation.

About the possibility to operate a chiller/heater quantity reduction, for the building analysed it has been excluded because of the presence and operation of single units.

5.4.7.5 AHU Humidifier Strategy

This strategy presents a considerable potential, taking into account that electric humidifier often represents an important contribution of the electricity consumption of the building.

In this case, the points of AHU controlled suggests that it is only possible a curtailment of humidifier, through the control of its state on/off. Moreover, it is necessary to consider that only NO and NE Offices AHUs are equipped with humidifiers but during an inspection it has been possible to verify that at the moment these components are at rest and so not used.

5.4.7.6 Lighting system strategies

Considering the strategies presented in paragraph 3.1.3.2.2, it is possible to affirm that the high granularity of the control system installed in the Energy Center would allow the execution of all of them. As a matter of fact, as already discussed in Chapter 5, great part of building lighting system is represented by dimmable lights interfaced with DALI technology. Therefore, it is possible to operate any kind of intervention with different levels of granularity of the regulation, but even to choose specific target areas.

Anyway, the author considers a not so high flexibility potential for such strategy due to two principal reasons:

- The lighting systems control and regulation presents a very high level of energy efficiency. As a matter of fact, considering as example the lighting system of Office areas, the lamps state is controlled through presence sensors while their illumination level is regulated through natural light sensors.
- Great part of the volumes of the building are dedicated to offices. Therefore, guarantee a minimum level of illumination is essential for the productivity of the occupants.

Considering both the aspects, it is expected a consequent low potential saving related to the possible implementation of such flexibility strategy.

6. Conclusion

In this thesis work, it has been analysed the opportunities related to Demand-side Management practices in an office building, considering as case-study the Energy Center of the Polytechnic University of Turin.

Firstly, it has emerged the necessity to follow a structured path to investigate and implement Demand-side Management in most appropriate way. Therefore, coupling the prescriptions founded in literature and the know-how maturated during this thesis work, it has been developed a suggested framework to approach to Demand-side Management in buildings from information gathering to implementation and verification. Considering the case-study analysed, the attention has been focused on commercial/office buildings. Particular consideration has been devoted to the critical phases such as information gathering that results fundamental for study and implementation of DSM practices. However, in medium-large buildings, this activity may be difficult and involves different actors.

This methodological framework has been then applied to the Energy Center exploiting two of the proposed phases: information gathering and potential estimation. They are essential for the preparation of building systems essential knowledge towards future implementation of DSM practices. The information collection step has been performed involving different stakeholders of building energy management organization. This activity showed the difficulties to get precise and consistent information and measurements, which if are not available and validated require additional time-consuming work.

Strictly correlated to information gathering and the purpose of knowledge about building energy behaviour has been the subsequent carried out energy monitoring phase. Due to the presence of measurements errors, it has been necessary to execute a reconstruction of PV plants production, with the aim to rebuild the building electricity consumption. It has allowed to individuate a malfunctioning of one string of Hall Coverage PV installation which have caused an estimated 10% reduction in annual PV production with a consequent loss of monetary saving of about 800 €/year.

Then, to have a more direct observation of consumption profiles it has been performed a clustering through both supervised and unsupervised approach. It has been identified seven typical consumption days of the building with a verified error between measured and rebuilt annual electricity consumption of less than 1%. In addition, it has been analysed the district heating consumption which accounts for 31% of total building energy consumption in terms of tonnes of oil equivalent. Considering the high efficiency declared by the manufacturer of the Polyvalent Group installed, it has been proposed to use the machine even for heating purposes. Assuming a constant value for the COP of the polyvalent group equal to the one declared by the manufacturer, due to missing of detailed information, it has been estimated a potential monetary saving for heating expenditures of about 50%.

In a second phase, we proposed some Demand-side Management interventions, estimating the related flexibility potential on typical consumption days. Strategies analysed and results obtained are summarized in the following:

- Evaluation of PV surface extension potential with the aim of maximize both self-sufficiency of the building and self-consumption of the electricity produced. Extending the installation capacity of Stairs A and B of five times, a 20% increase in self-sufficiency and a value of 92% in self-consumption are estimated.
- Evaluation of a load curtailing strategy of the polyvalent group. Considering a 2 hours curtailment and estimating a rebound energy to bring back the internal conditions to normal operation it has been estimated an energy saving of approximately 10% in the day analysed assuring the thermal comfort.
- Evaluation of a load curtailing strategy of the district heating withdrawal. Considering a 2 hours curtailment and estimating an energy rebound it has been evaluated a potential energy saving of approximately 6% the daily consumption without going below an internal temperature limit for thermal comfort of 20°C.
- Proposal of a pre-cooling peak shaving strategy. It has been estimated a reduction in peak load of 35% anticipating the turning on of the systems by half an hour and adding gradually the different loads.
- Proposal for night free-cooling strategy implementation. An intervention suggested by the observed evolution of external temperature that reaches even values which are 8 °C lower than internal temperature. It has been estimated a necessary time of operation of the ventilation system of 2 hours to bring the decrease the internal temperature to the value of the external one, excluding the recovery system, with a consequent expected reduction in the daily cooling load.

As a general outcome the Energy Center, thanks to his highly sophisticated control and regulation system, presents a high potential for Demand-side Management implementation. At the same time, the monitoring part of the BACS system requires a strong improvement.

The discussed works represent an important starting point for several future works. The evaluation proposed necessity for deeper investigation through more detailed analysis. As a matter of fact, for PV plants extension potential two principal assumptions may be perfectioned, which regard the consideration of the available surface and the real installation parameters of the eventually added PV panels. While for other flexibility strategies it has been discussed the principal aspects related to their implementation in order to evaluate their applicability in terms of controllability and observability of the interested variables. It is suggestable to perform tests coupled with monitoring in order to assess the real consequences of strategies implementation.

It has been individuated two main interventions on Building Energy Management System, necessary to perform strategies implementation tests:

- Separation of the clocks that control the different systems installed, to allow independent interventions;
- Improvement of the monitoring system with the measurement acquisition of variable interested by the strategies.

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8. Appendices

8.1 Appendix A

Photovoltaic Installed Power Check

Concerning the declared installed power found in the technical schemes of the electrical systems and reported in Table 13, it has been performed a check of those values with respect to the ones declared in the project documentation and related to the furnisher data sheets.

In Table 32 are reported the values declared in the technical documentation and the evaluated total power related to the two PV plants of **Stair A and B**.

	P_n* [W]	Dimensions* [mm]	N. modules	P_{TOT} [kW]
Stair A	327	1046x1559	40	13,08
Stair B	327	1046x1559	40	13,08

* The values refer to single modules.

Table 32. Stairs A and B PV plant documentation data.

As it is possible to observe, the power calculated coincide with the one declared in the technical schemes.

Considering the PV plant integrated to the **Hall façade**, the data presented in the technical documentation is collected in Table 33.

	P_n [W] (module)	**N. cells per module**	**Cell dimension [mm]**
Hall Facade	125	32	156x156

Table 33. Hall Facade plant documentation data.

Anyway, observing the technical schemes, as reported in Figure 59, and performing on-site inspections, it is possible to understand that there is no a single kind of module related to the Façade. Therefore, in order to do the calculation of the installed, it is necessary to evaluate the power of the single cell and the number of the cells installed.

Concerning the power of the single cell, it has been divided the power of the single module divided for the number of cells per module declared in the technical documentation, obtaining a power of 3,91 W per cell.

While, through the inspection it has been individuated two type modules, as reported in Table 34, with which it has been evaluated the total number of cells installed.

	N. modules	N. cells per modules	Total N. of cells
Type 1	27	10x10	**3220**
Type 2	13	10x4	

Table 34. Hall Façade, data collected by inspection.

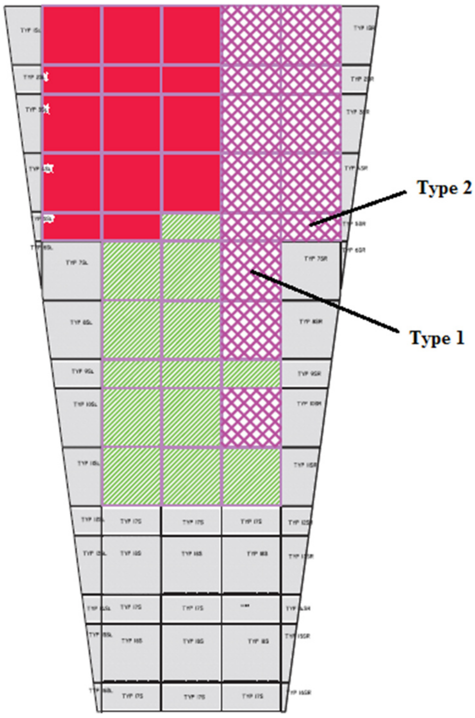

Figure 59. Facade PV plant configuration.

Performing the calculation of the total Power installed through that number of cells and the power of the single cell, it is obtained a result of 12,58 kW which is similar to the one declared in the technical schemes.

Finally, regarding the **Hall Coverage**, the data presented in the technical documentation are the one collected in

	P_n [W] (module)	N. cells per module	Cell dimension [mm]
Hall Coverage	195	50	156x156

Table 35. Hall Coverage plant documentation data.

Anyway, performing the calculation with those data, the resulting total power installed is 12,7 kW which is too much high with respect to the one declared in the technical relations. Moreover, through on-site inspections it is possible to observe that the number of cells per module is not 50 and that, even though the furnisher is the same for the Façade, the dimensions of cells used for the coverage are smaller.

Therefore, with the on-site inspection have been evaluated the real number of installed modules and cells as reported in Table 36.

	N. modules	N. cells per modules	Total N. of cells
Hall Coverage	34	8x12	**3264**

Table 36. Hall coverage PV plant, data collected with inspection.

While, about the dimension of the cells, consulting the documentation provided by the furnisher it has been founded that there are two available dimensions of cells:

- 156x156 mm
- 125x125 mm

Therefore, assuming the same efficiency, the power of the single cell has been evaluated scaling the power of the cell obtained for the Façade for the smaller area of the one used for the Coverage, obtaining **2,5 W** per cell.

Using this unitary power for the calculation of the total power installed on the coverage it results to be 8,16 which is similar to the one declared in the technical documentation.

8.2 Appendix B

PV Electricity Production Simulation Methodology

In the following will be discussed the methodology indicated by Bottaccioli et Al. [103] that has been used to simulate the PV production profiles. Therefore, here are presented the steps followed and the relative equations, while in Table 37 are reported all the parameters used in the equations presented, identifying their definition and origin (if they are assumed, taken from data or evaluated).

1. **Evaluation of the Incident Solar Radiation.**

The weather station provides the measures of the Irradiance on the Horizontal plane. In order to obtain the value of the Irradiance on the tilted surfaces of the PV plants, it is necessary to firstly apply a decomposition algorithm to evaluate the Direct and Diffuse radiation. As discussed by Bottaccioli et. Al, in the area of Turin, the most suitable algorithm is the one presented by Karatasou et Al. [104]. Then, the obtained direct and diffuse radiation has been re-projected on the tilted surfaces of the different PV plants installed.

2. **Evaluation of the Cell Temperature.**

In order to perform a more accurate simulation of the PV profiles, it has been taken into account the effect of the temperature on the cell efficiency. As suggested by Bottaccioli et Al. [103], instead of using the external ambient temperature, it has been evaluated the sol-air temperature with Equation (4).

$$T_{sa} = T_a + \frac{\alpha_{roof}}{h_c} * G_t \tag{4}$$

Then, in order to evaluate the cell temperature, it has been applied Equation (5).

$$T_C = \frac{T_{sa} + \left(T_{c,NOCT} - T_{a,NOCT}\right)\left(\frac{G_t}{G_{t,NOCT}}\right)\left[1 - \frac{\eta_{STC}\left(1 - \alpha_p * T_{c,STC}\right)}{\tau\alpha}\right]}{1 + \left(T_{c,NOCT} + T_{a,NOCT}\right)\left(\frac{G_t}{G_{t,NOCT}}\right)\left(\frac{\alpha_p * \eta_{STC}}{G_{t,NOCT}}\right)} \tag{5}$$

3. **Evaluation of Cell Efficiency in Standard Test Conditions (STC).**

Excluding the PV plants installed on Stairs A and B, for which the value of the efficiency in STC is indicated in the technical documentation of the manufacturer, for Hall Façade and Coverage the value has been evaluated through Equation (6)

$$\eta_{STC} = \frac{P_n}{A_c * G_{STC}} \tag{6}$$

4. Correction of Cell Efficiency with Cell Temperature.

In order to take into account effects of temperature on cell performances, the cell efficiency has been corrected through Equation (7).

$$\eta = \eta_{STC}\left(1 + \alpha_p\left(T_c - T_{c,STC}\right)\right) \tag{7}$$

5. Calculation of the Power.

Finally, it has been evaluated the power produced by the PV plants using Equation that considers the effect of temperature on cell performances through the corrected efficiency.

$$P = \eta * G_t * A_{tot} \tag{8}$$

Depending on the PV plant simulated, the total surface A_{tot} has been evaluated multiplying of the Number of cells for the cell surface or the number of modules for the module surface.

Finally, in order to take into account other possible factors that may affect the power production of the PV plant, it has been assumed a Power Factor of **0,9**. It has been assumed considering the fact that the PV panels were operating since just one year and the effect of temperature, that usually represent a consistent part of Power Factor has been already considered in corrected cell efficiency.

Parameter	Definition	Value
T_a	Ambient Temperature	[°C], Weather station measures
T_{sa}	Sol-air Temperature	[°C], evaluated with Equation (4)
G_t	Solar Irradiance on tilted surface	[W/m^2], evaluated from Weather station measures.
α_{roof}	Absorption coefficient of the surface	Assumed 0,6
h_c	Heat transfer coefficient (convection and long-wave radiation)	Assumed equal to 25 [W/m^{2}K]
T_c	Cell temperature	Evaluated through Equation (5)
$T_{c,NOCT}$	Normal Operating Cell Temperature (NOCT)	Assumed 45°C
$T_{a,NOCT}$	Ambient temperature at NOCT conditions	20 °C
$G_{t,NOCT}$	Solar Irradiance at NOCT conditions	800 W/m^2
η_{STC}	Cell efficiency in STC	Stairs A/B: 20,4 %
		Façade: Equation (6)
		Coverage: Equation (6)
α_p	Temperature coefficient of Power	Stairs A/B: -0,38 [%/°C]
		Façade: -0,5 [%/°C]
		Coverage: -0,45 [%/°C]
$T_{c,STC}$	Cell Temperature at STC	25°C
$\tau\alpha$	Product of transmissivity and absorption coefficient of PV array.	0.9
P_n	Nominal Cell/Module Power	Appendix A
G_{STC}	Solar Irradiance at STC	1000 W/m^2
A_c	Cell/Module surface	Appendix A
N_c	Number of Cell/Module installed	Appendix A
A_{tot}	PV plant total surface	$A_{tot} = N_c * A_c$

Table 37. PV plants simulation parameters.

8.3 Appendix C

K-means Clustering Methodology

K-means algorithm is a partitioning clustering algorithm that belongs to unsupervised learning machines methodologies which aims at grouping unlabelled multidimensional data into K clusters, with respect to an established criterion [105]. The clustering is based on two main concepts:

- The clusters, which are the partitioning groups in which the example sets are then divided. For K-means algorithm, the number of cluster K represents an input parameter established a priori by the user.
- The centroids, which represents the position of the center of the clusters in the n-dimensional space constituted by the different attributes of the example set.

Therefore, K-means algorithm is based on two principal steps:

- Centroids assignment. The algorithm assigns to the example data set K initial centroids.
- Centroids Moving. This second steps represent the core of the algorithm. As a matter of fact, it is constituted by the iterative execution of two sub-steps:
  - ➢ Each data point is examined and assigned to the cluster with the closest centroid.
  - ➢ The new Centroids position is re-assigned for each cluster averaging over all data of one cluster.

The two previous sub-steps are repeated iteratively until no change in the clusters occur or until some stopping criterion is reached (as in RapidMiner, the number of *max optimization steps)* [106].

While, the entire procedure, including even the initial centroids assignment is repeated each time with a different starting set of centroids. This is done because of the algorithm sensitiveness with respect to the initial set of assigned centroids. The algorithm aims at minimizing an objective function, which in this case is represented the squared error function, the sum of squared distances of all the data with respect to their corresponding centroids, as showed in Equation (9).

$$J = \sum_{j=1}^{k} \sum_{i=1}^{n} \left\| x_i^{(j)} - c_j \right\|^2 \qquad (9)$$

Where,

k = number of clusters;

n = number of data points;

$\left\| x_i^{(j)} - c_j \right\|^2$ represents the distance criteria for the cluster assignment to each data point.

One of the most used, applied even in this case, is represented by the Euclidean Distance reported in Equation (10).

$$d(x,c) = \sqrt{\sum_{k=1}^{x} (x_k - c_k)^2} \tag{10}$$

8.4 Appendix D

Clustering Assumed Holidays

In Table 38 are summarized all the holidays that have considered together with Sundays in a single cluster. Their distribution, together with Sundays, is clearly showed in Figure 60.

New Year and Epiphany	01/01/2018
	06/01/2018
Easter	31/03/2018 – 02/04/2018
August Holidays	4/08/2018
	11/08/2018 – 19/08/2018
	25/08/2018
Christmas Holidays	22/12/2018 – 26/12/2018
	29/12/2018 – 31/12/2018
Other Italian festivities	25/04/2018
	01/05/2018
	02/06/2018
	01/11/2018
	8/12/2018

Table 38. Holidays that have been added to Sundays into a single cluster.

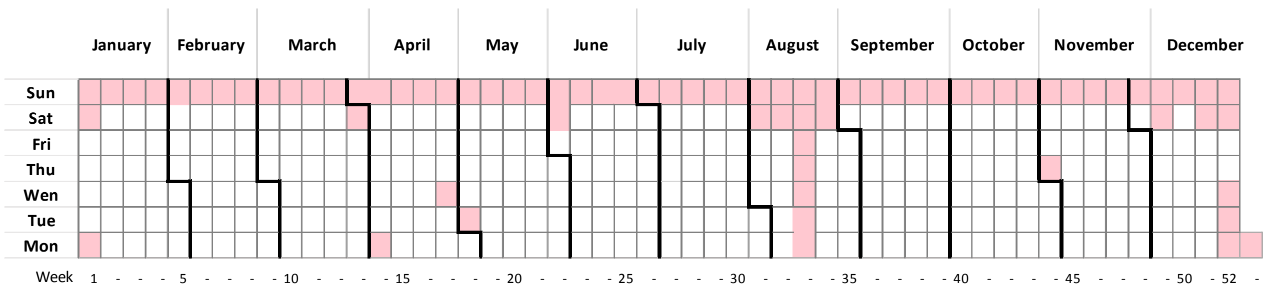

Figure 60. Distribution of Sundays and Holidays during 2018.