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SOFC microCHP Regulation and Application in the Commercial Sector

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Abstract

The regulation of a country can represent a big obstacle for the application of Fuel Cell microCHPs. For this reason, an analysis of the Italian regulation for the building energy efficiency is carried on. The main objective of this study is to find possible obstacles to the diffusion of SOFC microCHP systems and to understand if the higher electrical efficiency of these machines is considered in a positive way for the calculation of the energy demand and the Energy Label of a commercial building.

In the first part, the Italian regulation is analysed, with a focus on the methods for the evaluation of the energy consumption of the building and on the constraints imposed by the Ministerial Decrees. Then all positive and negative aspects about SOFC microCHP in the regulation are presented, considering as reference the SOLIDpower® company's product BLUEgen®, a SOFC with an electrical power equal to 1.5 kW and an electrical efficiency of 60%.

Furthermore, a practical case is presented in detail: the building is the Vinovo's public pool, modelled using the ACCA Software TerMus®. Three different cases are considered and compared:

- The Base Case, related to the first energy audit done by Coesa Srl® company.
- The SOFC Case, where a fuel cell with an electrical power of 10 kW is added to the generation plant of the building. In addition, a comparison between CHPs with different electrical efficiencies is performed starting from the SOFC Case.
- The Improved Building Case, where it is considered also an improvement of the building structure, with the same generation plant of SOFC Case. In this model the building is considered as new and must respect all the constraints imposed by the Italian Ministerial Decrees.

The last part consists in an economic analysis of the SOFC microCHP installation, considering two cost scenarios, PRESENT and TARGET.

The main results obtained are:

- All microCHPs, fuel cells included, are considered as thermal machine and must work with a logic of thermal load following. Being the SOFC a system producing mainly electricity recovering heat as secondary product, the constraint on the thermal production can represent a problem.
- A higher electrical efficiency is always favoured for microCHP systems, making a SOFC a good way to enhance the primary energy saving. The electricity self-consumption is always rewarded, even from the point of view of regulation.

- The simple installation of a SOFC system can rise the Energy Label of a building by one or two classes, depending on the size, increasing the value of the building itself.
- If a renewable energy share constraint must be respected, like in new buildings and important renovations, the application of a SOFC (and in general of a microCHP) working with Natural Gas as fuel is very unlikely.
- From the economical point of view, SOFC microCHP are not so far to be competitive with the Internal Combustion Engine technology.

Summary

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Acronyms List

CHP	Combined Heat and Power
ICE	Internal Combustion Engine
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
SEN	National Energy Strategy (*Strategia Energetica Nazionale)*
PES	Primary Energy Saving
FC	Fuel Cell
FC	Load Factor *(Fattore di Carico)*
EP	Energy Performance factor
DM 26/06/2015	Ministerial Decree 26 June 2015
Nren	Non-renewable
Ren	Renewable
Tot	Total
H	Heating
W	Sanitary hot water
V	Ventilation
C	Cooling
L	Lighting
T	Transport
PV	Photovoltaic
DL 03/03/2011	Legislative Decree 3 March 2011, n.28
DD	Degree Days
NG	Natural Gas
UTA	Air Treatment Unit *(Unità di Trattamento Aria)*
LHV	Lower Heating Value
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
WACC	Weighted Average Cost of Capital
NPV	Net Present Value
IRR	Internal Rate of Return
ROI	Return On Investment
LCOE	Levelized Cost Of Electricity

Symbols List

Q_{nd}	Useful thermal energy	[kWh]
$Q_{hum,nd}$	Useful thermal energy for humidification	[kWh]
E_{del}	Delivered energy	[kWh]
E_P	Primary energy	[kWh]
$q_{ve} \cdot FC_{ve}$	Air flow rate for mechanical ventilation	[m³/s]
ϑ_{sup}	Input air temperature	[°C]
β	Time fraction with active mechanical ventilation	[-]
Q_{tr}	Thermal energy exchange for transmission	[kWh]
Q_{ve}	Thermal energy exchange for ventilation	[kWh]
Q_{int}	The internal energy due to internal sources	[kWh]
$Q_{sol,w}$	Internal energy due to the incident solar radiation	[kWh]
$\eta_{H,gn}$	Utilization factor of the internal energy	[-]
$\eta_{C,ls}$	Utilization factor of the internal dispersions	[-]
$Q_{hr,i}$	Useful effective thermal energy need	[kWh]
$Q'_{H,i}$	Ideal useful thermal energy need	[kWh]
$Q_{l,e,i}$	Emission losses	[kWh]
$Q_{l,rg,i}$	Regulation losses	[kWh]
$Q_{H,du,ls,nrh,i}$	Not-recovered distribution losses	[kWh]
$Q_{H,du,aux,rh,i}$	Auxiliary electricity recovered	[kWh]
$Q_{H,du,in,i}$	Input distribution energy	[kWh]
Qw	Thermal energy need to the user	[kWh]
ρ_w	Water density	[kg/m³]
c_w	Water specific heat	[kWh/kgK]
$V_{w,i}$	Daily water volume needed	[m³/d]
$\theta_{er,i}$	Output water temperature	[°C]
θ_0	Input (cold) water temperature	[°C]
G	Number of days for the considered period	[d]
$Q'_{d,H,in,month}$	Heating demand net of the solar contribution	[kWh]
$Q'_{d,W,in,month}$	Hot water demand net of the solar contribution	[kWh]
$\emptyset_{gn,out,month}$	Monthly useful thermal power	[kW]
$FC_{gn,i}$	Load factor of the i-th generator	[-]
$\emptyset_{max,gn,out,i}$	Maximum useful power	[kW]
$Q_{CHP,p,in}$	Primary energy entering the CHP	[kWh]
$Q_{CHP,ter,out}$	Output thermal energy of the CHP	[kWh]
$\eta_{ter,chp}$	Thermal efficiency of the CHP	[-]
EP_{tot}	Total energy performance factor	[kWh/m²y]
EP_{nren}	Non-renewable energy performance factor	[kWh/m²y]
$E_{P,gl,tot}$	Total yearly primary energy need	[kWh]
$E_{P,gl,nren}$	Non-renewable yearly primary energy need	[kWh]
$f_{P,del}$	Delivered energy conversion factor	[-]

$f_{P,exp}$	Exported energy conversion factor	[-]
E	Delivered energy to the CHP	[kWh]
a_w	Allocation factor for electricity	[-]
W	Electricity produced by the CHP	[kWh]
$EP_{gl,nren}$	Global non-renewable energy performance factor	[kWh/m^{2}y]
η_{el}	CHP electrical efficiency	[-]
η_{th}	CHP thermal efficiency	[-]
$\eta_{el,ref}$	National electrical system efficiency	[-]
$\eta_{th,ref}$	Standard thermal efficiency	[-]
f_P	Energy conversion factor	[-]
U	Transmittance	[W/m^{2}K]
P	Electrical renewable power	[kW]
S	Building Surface	[m^2]
I	Global energy index	[kWh/m^{2}y]
I_{192}	Maximum global energy index	[kWh/m^{2}y]
$\%_{effective}$	Renewable energy share obtained in the project	[%]
$\%_{limit}$	Renewable energy share limit	[%]
$P_{effective}$	Renewable power obtained in the project	[kW]
P_{limit}	Renewable power limit	[kW]
$Q_{SOFC,p,in}$	SOFC input primary energy	[kWh]
$Q_{SOFC,th,out}$	SOFC output thermal energy	[kWh]
$Q_{SOFC,el,out}$	SOFC output electrical energy	[kWh]
$\phi_{SOFC,th}$	SOFC Thermal Power	[kW]
$CHPH\eta$	CHP thermal efficiency	[-]
$Ref\ H\eta$	Reference thermal efficiency	[-]
$CHPE\eta$	CHP electrical efficiency	[-]
$Ref\ E\eta$	Reference electrical efficiency	[-]
S	Layer thickness	[mm]
λ	Layer thermal conductivity	[W/mK]
C	Thermal conductance	[W/m^{2}K]
MS	Superficial mass	[kg/m^2]
P	Vapour permeability	[kg/msPa]
CS	Specific heat	[J/kgK]
R	Thermal resistance	[m^{2}K/W]
ΔE	Hypothetical primary energy added	[kWh]
A'_{sol}	Solar equivalent surface	[m^2]
H'_T	Average heat exchange coefficient	[W/mK]
$EP_{h,nd}$	Useful energy performance index for heating	[kWh/m^{2}y]
$\eta_{G,h}$	Heating average seasonal efficiency	[-]
$\eta_{G,w}$	Hot water production average seasonal efficiency	[-]
$EP_{gl,tot}$	Global energy performance index	[kWh/m^{2}y]
$Q_{w,ren}$	Renewable energy share for hot water production	[%]
Q_{ren}	Total renewable energy share	[%]

CHAPTER 1

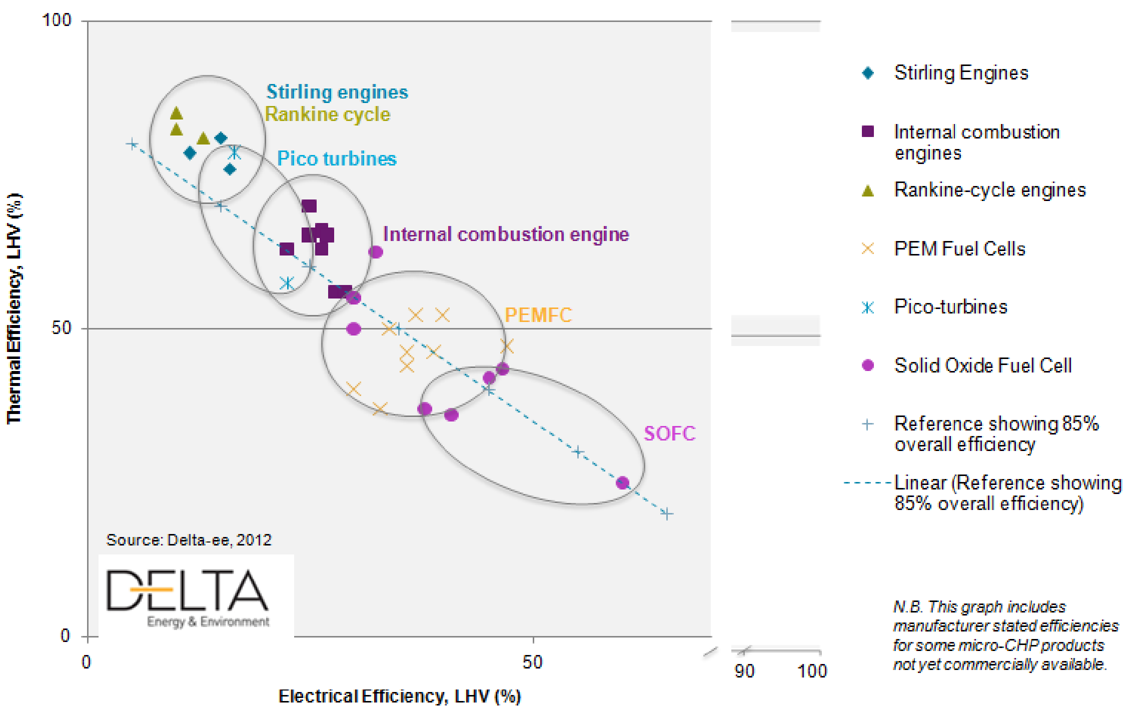
Introduction

A Combined Heat and Power (CHP) unit is a machine that, starting from an input fuel, can produce simultaneously electricity and heat, bringing to significant savings in the primary energy. When the electrical power of a CHP is under 50 kW it is called microCHP. Depending on the type of technology used, different values of electrical and thermal efficiencies are reached. The main types of microCHP are:

- Internal Combustion Engine (ICE);
- Pico (or micro) Turbine;
- Stirling Engine;
- Proton Exchange Membrane Fuel Cell (PEMFC);
- Solid Oxide Fuel Cell (SOFC).

Figure 1 [1] shows how the electrical and thermal efficiencies change depending on the type of microCHP.

FIGURE 1: MICROCHP EFFICIENCIES OVERVIEW [1]



The most used microCHP at the moment is the ICE [2], that have an electrical efficiency around 25%. This value is quite low and normally brings to problems on managing the high quantity of heat produced by the engine. At the contrary, fuel cell systems produce more electricity and less heat. This characteristic makes the fuel cell a very promising technology for microCHP application. Among them, the SOFC is particularly attractive for commercial application in buildings with a high and constant electrical consumption.
A Solid Oxide Fuel Cell (SOFC) is an electrochemical device that converts the chemical energy of a fuel in electricity and heat, working at temperatures around from 500°C to 1,000°C [3] . Thanks to the high operation temperature, this fuel cell can reach very interesting electrical efficiencies, up to 60%. It also has a wide fuel flexibility, making possible the operation with Natural Gas from the grid, the most used fuel in CHP applications in Italy.
The high efficiency makes this technology very attractive for the electricity production, both at centralized level and at distributed level. But, being the electrical efficiency independent from the size of the plant, the distributed application of this machine is particularly interesting both for microCHP systems and for smart grids.
A SOFC microCHP is a SOFC with a small electrical power that works in a CHP asset, reaching an overall efficiency of around 85% (Figure 1). The major constraint for its application is that it must work at a constant load for most of the year, with the minimum possible number of stops. This is related to the fact that each thermal cycle is detrimental for the ceramic materials of the fuel cell. Furthermore, each start and stop cycle requires days to be completed, reducing the hours of operation.
The positive effects of SOFC microCHP [4] are:

- Saving of primary energy thanks to high electrical efficiency and consequently saving of CO_2 emissions.
- Increase of the efficiency of building sector, that is a critical point in Italy, especially for the public buildings.
- Eliminating emissions of NO_x, SO_x, Volatile Organic Compounds (VOC) and Particulate Matter (PM), an advantage considering the high levels of these pollutants in big cities.
- Possibility to boost the distributed generation and to operate in smart grid conditions to balance the electrical load when a high intermittent electrical power share takes place. This aspect will be more and more important in the near future, when Italy power mix will be increasingly dominated by intermittent renewable sources.

1.1 The Italian and European Framework

The Italy's National Energy Strategy 2017 (SEN) sets the goal of achieving the 30% of energy savings by 2030, with respect to their trend in 2030 [5]. To reach this ambitious goal, it is specified a list of interventions, divided by sector of application. For the tertiary sector, the attention is focused on the energy redevelopment of existent buildings, especially in the public sector.

Regarding the thermal energy production plant, the mechanism of tax deductions gives an idea of the intervention suggested to increase the efficiency, as shown by Table 1 [6].

TABLE 1: 2018 ITALY'S TAX DEDUCTIONS FOR ENERGY EFFICIENCY

Type of Intervention	Deduction Percentage	Maximum Deduction
Condensing Boilers with at least class A efficiency	50%	30,000.00 €
Condensing Boilers with at least class A efficiency and Thermoregulation systems	65%	30,000.00 €
Condensing Hot Air Generators	65%	30,000.00 €
Heat Pumps with high efficiency	65%	30,000.00 €
Hybrid Systems composed by Heat Pumps and Condensing Boiler	65%	30,000.00 €
MicroCHP	**65%**	**100,000.00 €**
Heat Pumps for sanitary hot water production	65%	30,000.00 €

It is fundamental for the purpose of this study to underline that the Budget Law 2018 [6] added the microCHP systems to the mechanism of tax deduction if they can guarantee a Primary Energy Saving (PES) of at least 20%. Therefore, it is clear that this technology is considered at a national level an effective way to reduce the primary energy consumption of a building. As will be explained in CHAPTER 4, paragraph "4.5 Primary Energy Saving", a SOFC microCHP can easily respect this limit, taking advantage of the high electrical efficiency and of the low thermal output.

It has been already demonstrated by international projects like Ene.field [7] that the installation of FC microCHP in the residential sector brings to a reduction of greenhouse gases greater than a condensing boiler and a heat pump thanks to the efficiency increase of the building. This project underlined that the barriers to a large market penetration of FC microCHP [8] are:

- **The regulation of European countries, that do not reward adequately these systems;**
- The lack of common European standards;

- The economic cost of the plant;
- The system complexity.

This master thesis concentrates the attention on the Italian regulation, trying to give a framework of the problems and benefits of the current directives taking as example a SOFC microCHP.

1.2 Objectives

The main objective of this study is to understand if the Italian regulation – for what concerning the calculation of building energy demands – considers the SOFC system in a positive and realistic way. Indeed, the Fuel Cells are not still considered in the technical regulations and in the software for the calculation of buildings energy consumptions, because they are still in the early commercialization stage.
The aim of this work is to analyse in detail the technical regulation regarding all microCHPs, in order to identify possible obstacles and problems in case the same regulation would be applied to a SOFC microCHP system.

The second objective is to find if it is possible to have a gain with a SOFC microCHP installation from the point of view of the building Energy Label, a number that shows the non-renewable energy consumption of a building. Furthermore, a practical case, the Vinovo's public pool, is analysed in detail to quantify the improvement and to compare different cases.
The idea is to follow the regulation step by step in the calculations to understand the behaviour of the energy consumption results, understanding how they change if a SOFC microCHP is applied, both from a general and a practical point of view.

The third objective is to compare a SOFC microCHP with an ICE having the same global efficiency and the same input power, to see how the regulation takes into account the electrical efficiency difference. This is important to underline the competitiveness of Fuel Cells from the point of view of performance with very small sizes plants.

The last objective is to analyse economically the Vinovo's pool case, trying to understand the convenience of installing a SOFC microCHP in a PRESENT scenario and in a TARGET scenario, also comparing it with an ICE microCHP installation.

1.3 Structure and Collaborations

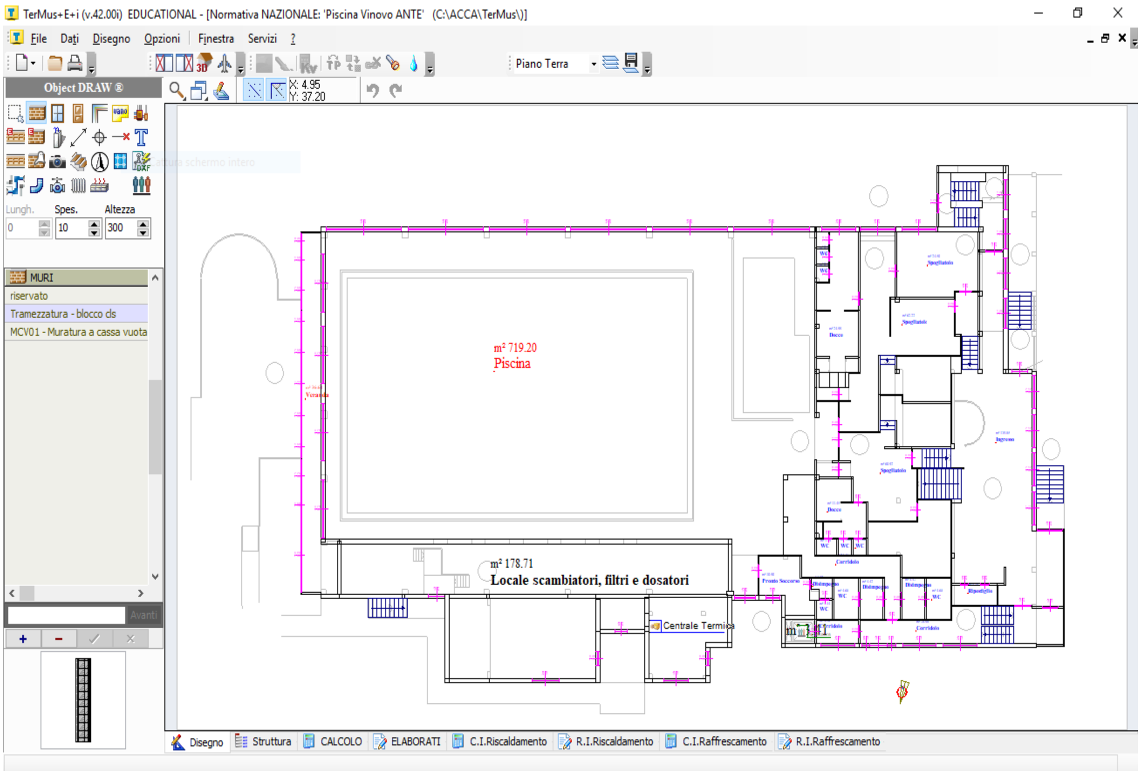
The study is organized in chapters, but it can be divided in two big sections.

The first one is from Chapter 2 to Chapter 4, where the Italian regulation is described, starting from a general framework of the calculation methods, to the analysis of the positive and negative aspects regarding a SOFC microCHP (CHAPTER 4). In particular, the technical regulation UNI/TS 11300, for the calculation of building energy performance, is examined to show the passages for the energy labelling of buildings and for the calculation of the building energy demands (CHAPTER 2); then, the limits imposed by different Ministerial Decrees to the energy generation system are shown (CHAPTER 3).
All information about UNI/TS 11300 have been provided by Coesa Srl® company (http://www.coesaenergy.it/) and by *Politecnico di Torino* university (https://www.polito.it/).
Being necessary to buy this regulation, it was not possible to provide all data in the explanation of the method for the energy demand calculation. Anyway, the necessary information to understand the logic used in the regulation are given, as well as some table with the necessary quantities.
In Chapter 4, several examples are provided to give a clear idea of the concepts explained. To do that, a BLUEgen® unit is considered: this machine is the main product of SOLIDpower® company (https://www.solidpower.com/it/), which provided the necessary data for the analysis, shown in the initial part of CHAPTER 4.

The second big section regards a case study, the Vinovo's Pool, both from the technical and economical point of view. A model is developed using the ACCA software TerMus®, normally used by energy efficiency companies to calculate the Energy Label of buildings. The entire model is built on the TerMus® Educational version of the software, free for students but exactly with the same features of the original TerMus®.
This computer program has the function of following entirely all technical regulations methods, so it is used to validate all general considerations from the Chapters 2-3-4. The final outputs of the model are the specific consumptions for each service (heating, sanitary hot water, ventilation and lighting), expressed in [kWh/m^2y], and the building Energy Label.
Figure 2 shows the main page of the software, with the Vinovo's Pool ground floor already drawn. In the upper left corner, there are the symbols to add components to the project, like walls, windows, doors, zones, roofs, generators and so on. On the left side, all types of selected component are displayed, and it is possible to choose each of them singularly.
The model is obtained overlapping every single component to the ".dwg" file from AutoCAD® software imported in TerMus®; all data and drawings about the Vinovo's Pool have been again provided by Coesa Srl® company, that performed an energy audit on this structure a few years ago.
The TerMus® models are three in total:

1) The Base Case, related to the first energy audit done by Coesa Srl® company.
2) The SOFC Case, where a fuel cell with an electrical power of 10 kW is added to the generation plant of the building. In addition, a comparison between CHPs with different electrical efficiencies is performed starting from the SOFC CASE.
3) The Improved Building Case, where it is considered also an improvement of the building structure, with the same generation plant of SOFC CASE. However, in this model the building is considered as new and must respect all the constraints imposed by the Ministerial Decrees.

FIGURE 2: TERMUS® MAIN PAGE, GROUND FLOOR OF VINOVO'S POOL



In CHAPTER 5, all the information about the real building and all the characteristics of the TerMus® models are listed, while in CHAPTER 6 all results from the software are presented, comparing the Base Case model with the real building and the SOFC Case with the Base Case. In this chapter, it is also presented an analysis based on the electrical efficiency and on the size of the microCHP installed in the TerMus® model and it is shown the Improved Building Case with the corresponding results.
CHAPTER 7 is entirely dedicated to the economic analysis: first of all two scenarios about the SOFC microCHP, PRESENT and TARGET, are described and analysed in detail. Then,

a comparison with two ICE microCHP, respectively with an electrical power of 10 kW_e and 5 kW_e, is carried on.

CHAPTER 2

Regulation UNI/TS 11300

The regulation UNI/TS 11300 [9] is the Italian technical specification for the evaluation of the buildings energy performance. The aim is to give a standard method at a national level according to the European directives, in order to fulfil the objectives of European plans.
The Italian and European references for this regulation are:

- *Decreto Legislativo 19 Agosto 2005, n.192, "Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia"* [10]*;*
- *Decreto Legislativo 29 Dicembre 2006, n. 311* [11]*;*
- *Decreto del Presidente della Repubblica 2 Aprile 2009, n.59* [12]*;*
- *Decreto Ministeriale 26/06/2009, "Linee guida nazionali per la certificazione energetica degli edifici"* [13]*;*
- Directive 2010/31/UE [14].

The regulation UNI/TS 11300 is composed by six parts, each one related to a different topic:

i. Part 1: "Evaluation of energy need for space heating and cooling." [15]
ii. Part 2: "Evaluation of primary energy need and of system efficiencies for space heating, domestic hot water production, ventilation and lighting for non-residential buildings." [16]
iii. Part 3: "Evaluation of primary energy need and system efficiencies for space cooling." [17]
iv. Part 4: "Renewable energy and other generation systems for space heating and domestic hot water production." [18]
v. Part 5: "Evaluation of energy performance for the classification of buildings." [19]
vi. Part 6: "Evaluation of primary energy need for people transportation."

The most important outputs of this regulation are the **Energy Indexes**, that express specific consumptions inside the building, depending on the service for whom the energy is consumed. For each service (Heating, Sanitary Hot Water, Ventilation, Cooling, Lighting and Transport) there are three different indexes, depending on the source of the energy used: renewable, non-renewable and global. The Energy Indexes are expressed in kWh per m^2 per year.

Table 2 [19] shows the main parameters required for the Energy Indexes definition and in which part of the regulation the calculation procedure is explained. The delivered energy indicates the energy transported to the building before its transformation in primary energy.

TABLE 2: UNI/TS 11300 MAIN PARAMETERS

Service	Parameter	Symbol	Measurement Unit	Calculation Reference
Heating	Useful thermal energy for heating	$Q_{H,nd}$	[kWh]	UNI/TS 11300-1
	Useful thermal energy for humidification	$Q_{H,hum,nd}$	[kWh]	UNI/TS 11300-1
	Delivered energy	$E_{del,H}$	[kWh]	UNI/TS 11300-2 UNI/TS 11300-4
	Primary energy	$E_{P,H}$	[kWh]	UNI/TS 11300-5
Sanitary hot water	Useful thermal energy	$Q_{W,nd}$	[kWh]	UNI/TS 11300-2
	Delivered energy	$E_{del,W}$	[kWh]	UNI/TS 11300-2 UNI/TS 11300-4
	Primary energy	$E_{P,W}$	[kWh]	UNI/TS 11300-5
Ventilation	Air flow rate for mechanical ventilation	$q_{ve} \cdot FC_{ve}$	[m^3/s]	UNI/TS 11300-1
	Input air temperature	ϑ_{sup}	[°C]	UNI/TS 11300-1
	Time fraction with active mechanical ventilation	β	[-]	UNI/TS 11300-1
	Delivered energy	$E_{del,V}$	[kWh]	UNI/TS 11300-2
	Primary energy	$E_{P,V}$	[kWh]	UNI/TS 11300-5
Cooling	Useful energy for cooling	$Q_{C,nd}$	[kWh]	UNI/TS 11300-1
	Useful energy for dehumidification	$Q_{C,dehum,nd}$	[kWh]	UNI/TS 11300-1
	Mean yearly efficiency	ε_C	[-]	UNI/TS 11300-3
	Delivered energy	$E_{del,C}$	[kWh]	UNI/TS 11300-3
	Primary energy	$E_{P,C}$	[kWh]	UNI/TS 11300-5
Lighting	Delivered energy	$E_{del,L}$	[kWh]	UNI/TS 11300-2 UNI EN 15193
	Primary energy	$E_{P,L}$	[kWh]	UNI/TS 11300-5
People transport	Delivered energy	$E_{del,T}$	[kWh]	UNI/TS 11300-6
	Primary energy	$E_{P,T}$	[kWh]	UNI/TS 11300-5

The main applications of UNI/TS 11300 are:

1. Evaluation of the respect of regulations in terms of energy objectives for a defined building;
2. Comparison between different project alternatives;
3. Calculation of a conventional level of energy performance for buildings;
4. Estimation of the effects of interventions to increase the energy performance of buildings;
5. Forecast of future national or international energy demands, using models of typical buildings.

The aim of the study is to analyse the way the regulation considers the SOFC microCHP system. For this reason, in the following pages, only UNI/TS 11300-4 and UNI/TS 11300-5 are analysed in a detailed way. All the methods of calculation for the other parameters are shown briefly, with the same order given by UNI/TS 11300, except for the UNI/TS 11300-6, whose content is not available.

2.1 UNI/TS 11300-1

The following procedure [15] is used to calculate the energy needs for heating and cooling:

1. Definition of the borders between conditioned and non-conditioned zones, based on the building plan.
2. Definition of the borders between different calculation zones, based on the building plan. For example, two adjacent zones can have two different ambient temperature, depending on the type of activity done inside.
3. Definition of internal conditions and input data related to the external environment.
4. Calculation, for each month and each zone, of the ideal energy needs for heating ($Q_{H,nd}$) and cooling ($Q_{C,nd}$). They are calculated with the following formulas:

$$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \eta_{H,gn} \times (Q_{int} + Q_{sol,w}) \quad [kWh] \tag{1}$$

$$Q_{C,nd} = (Q_{int} + Q_{sol,w}) - \eta_{C,ls} \times (Q_{C,tr} + Q_{C,ve}) \quad [kWh] \tag{2}$$

The input data, obtained by the building model construction, are:

$Q_{H,tr}$, the thermal energy exchange for transmission for heating;

$Q_{C,tr}$, the thermal energy exchange for transmission for cooling;

$Q_{H,ve}$, the thermal energy exchange for ventilation for heating;

$Q_{C,ve}$, the thermal energy exchange for ventilation for cooling;
Q_{int}, the internal energy due to internal sources;
$Q_{sol,w}$, the internal energy due to the incident solar radiation on glass components;
$\eta_{H,gn}$, the utilization factor of the internal energy;
$\eta_{C,Is}$, the utilization factor of the internal dispersions.

5. Calculation of the heating and cooling seasons as the some of the quantities found at Point 4.
6. If necessary, recalculation of ideal energy needs for the ends of the heating and cooling seasons if only a part of the month is considered and not the entire month.
7. If required, calculation, for each month and each zone, of the energy needs for humidification ($Q_{H,hum,nd}$) and dehumidification ($Q_{C,dehum,nd}$).
8. Unification of the results related to the different zones served by the same plants.

2.2 UNI/TS 11300-2

This section of the rule contains a lot of information for the evaluation of the energy needs of non-residential buildings. So, it requires all data about the energy vectors generation and utilization.
First of all, it is necessary to know the working period of the energy generation plant serving the building. Second, it must be specified the subdivision of the machinery, related to the type of service. This information is useful to evaluate all characteristics of generation, distribution, emission, storage and final user.
The main sections of UNI/TS 11300-2 [16] are:

1. **Calculation procedure**

   A thermal balance is performed on the entire system. For each subsystem, the primary energy need (energy input) is obtained from the energy output, knowing the characteristics of emission, distribution, storage and generation. So, it is possible to find the losses in each section of the plant. Losses can be non-recoverable, recoverable or recovered. For example, a hot pipe put outside represents a not recoverable loss; if it is installed inside it is considered recoverable and, when possible, its contribution will be subtracted to the energy demand. A fraction of electricity can be recovered as useful heat, too, because of joule losses that help to heat the heat transfer fluid.
   With this procedure, also the efficiencies of the subsystems are evaluated.

2. **Thermal energy needs and losses of winter heating subsystems**

   The thermal energy need to the user is found with the following expression.

$$Q_{hr,i} = Q'_{H,i} + Q_{l,e,i} + Q_{l,rg,i} \quad [kWh] \qquad (3)$$

Where:

$Q_{hr,i}$ is the useful effective thermal energy need.

$Q'_{H,i}$ is the ideal useful thermal energy need net of the recovered losses.

$Q_{l,e,i}$ are the emission losses.

$Q_{l,rg,i}$ are the regulation losses.

In this section a few tables give the values for the common systems of emission and regulation.

Then it's considered the input energy to the distribution system:

$$Q_{H,du,in,i} = Q_{hr,i} + Q_{H,du,ls,nrh,i} - Q_{H,du,aux,rh,i} \quad [kWh] \qquad (4)$$

Where:

$Q_{H,du,ls,nrh,i}$ are the not-recovered distribution losses.

$Q_{H,du,aux,rh,i}$ is the auxiliary electricity recovered in the distribution grid.

Also in this case, the regulation gives tables to find the distribution efficiency value, depending on how the distribution grid is built inside the building.

The last system considered is the generation: some tables give common efficiency values of boilers.

3. **Thermal energy needs and losses of sanitary hot water production subsystems.**

The thermal energy need to the user is:

$$Qw = \rho_w \times c_w \times \sum_i [V_{w,i} \times (\theta_{er,i} - \theta_0)] \times G \quad [kWh] \qquad (5)$$

Where:

ρ_w is the water density, 1000 [kg/m^3].

c_w is the water specific heat, 1,162 * 10-3 [kWh/(kg × K)].

$V_{w,i}$ is the daily water volume needed, expressed in [m^3/d].

$\theta_{er,i}$ is the output water temperature, in [°C].

θ_0 is the input (cold) water temperature, in [°C].

G is the number of days for the considered period.

The calculation takes into account the energy needs for water disinfection.

The procedure to calculate the losses and, thus, the input energy to each subsystem is very similar to the one of section 2.

4. **Electrical energy needs of heating and hot water production subsystems.**

   The total electrical energy need of the system is given by the sum of the single needs for emission, distribution and generation. This quantity is expressed in [kWh] but it has to be converted in primary energy to be considered in the total consumption. It is suggested to measure directly the electrical loads of the user to have a better simulation of the building.

   In this case too, all the subsystems are treated with tables containing typical values of electrical consumption.

5. Distribution losses calculation. (Appendix A of UNI/TS 11300-2)
6. Generation losses calculation. (Appendix B of UNI/TS 11300-2)
7. Energy needs for mechanical ventilation and winter air conditioning. (Appendix C of UNI/TS 11300-2)
8. Energy needs for lighting. (Appendix D of UNI/TS 11300-2)
9. Energy performance of buildings without heating and/or hot water production systems. (Appendix E of UNI/TS 11300-2)

2.3 UNI/TS 11300-3

For the calculation of the primary energy for cooling, a similar procedure as UNI/TS 11300-2 is followed. On a monthly base, the regulation determines the useful cooling energy necessary for the conditioning. Then, the efficiency of each subsystem is evaluated from the user to the source, to find the primary energy.

This section contains also useful information about typical machinery for cooling, like fans and refrigeration machines, and about their performances. In the appendixes, calculation methods of losses and of other parameters are described.

The main chapters of UNI/TS 11300-3 [17] are:

1. Primary energy needs for cooling and mean seasonal efficiency calculation procedure.
2. Distribution losses calculation. (Appendix A)
3. Storage losses calculation. (Appendix B)
4. Correction term calculation for machines working away from nominal conditions. (Appendix C)
5. Correction terms for adjustment in real working conditions. (Appendix D)
6. Example of primary energy need calculation for cooling. (Appendix E)

7. Seasonal Energy Efficiency Ratio (SEER) calculation. (Appendix G)

2.4 UNI/TS 11300-4

UNI/TS 11300-4 [18] is devoted to the alternative production of energy for heating and hot water demands. The alternative systems considered are solar collectors, biomass combustion, photovoltaic, heat pumps, cogeneration and district heating. If a system presents more generation subsystem, a certain priority order of intervention must be established, with the aim of minimizing the primary energy need.

TABLE 3: INTERVENTION PRIORITY OF GENERATORS

Priority	Generation Subsystem	Energy Production
1	Solar Collectors	Thermal
2	Cogeneration	Electrical and Thermal
3	Biomass Combustion	Thermal
4	Heat Pumps	Thermal or cooling
5	Fossil Fuel Heat Generators	Thermal

With district heating, normally, the entire energy demand is satisfied but, if solar collectors are present, they have the priority.

The regulation logic is based on the Load Factor, expressed with the acronym *FC* because referred to the Italian language. This quantity is expressed as the ratio between the thermal nominal power of the generator and the thermal power required by the building. If it is equal to one, the power required is exactly equal to the nominal power of the generator.

If *FC* is higher than one for the first generator, it is necessary the intervention of the second system to fulfil the energy demand in the time interval considered. It is also possible to establish other independent parameters to have a more realistic regulation, like a cut-off temperature for Heat Pumps.

CHP systems have a high priority because they are designed to work in base load condition, at constant power. The regulation specifies that they are considered as **thermal machines**, producing electricity as a function of the heat load. This is a critical point in case of FCCHP and will be discussed further on.

UNI/TS 11300-4 gives a general methodology for the following calculations:

1.1 Calculation of monthly energy demand covered by solar collectors, not related to the topic of the study.

1.2 Calculation of electricity needed by the solar thermal system for auxiliaries.

1.3 Calculation of primary energy needed by the solar thermal system for auxiliaries.

1.4 Calculation of heat demand that has to be covered by other generation subsystems:

$Q'_{d,H,in,month}$ is the heating demand net of the solar contribution, in [kWh].

$Q'_{d,W,in,month}$ is the hot water demand net of the solar contribution, in [kWh].

2.1 Calculation of the mean useful thermal power that must be covered by the subsequent generator "i" in the priority scale. This number is useful to understand if it will be necessary to use more than one generator or it is sufficient the first generator in order of priority.

$$\emptyset_{gn,out,month} = \frac{Q'_{d,in,month}}{h_{month}} \quad [kW] \qquad (6)$$

2.2 Cut off temperature verification.

2.3 Calculation of Load Factor (*FC*) for the i-th generator:

$$FC_{gn,i} = \frac{\emptyset_{gn,out,month}}{\emptyset_{max,gn,out,i}} \quad [-] \qquad (7)$$

Where $\emptyset_{max,gn,out,i}$ is the maximum useful power of the generator.

There can be two cases, bringing to different formulations of the useful thermal energy ($Q'_{gn,out,I,month}$):

a) $FC_{gn,i} \leq 1$: there is no need of integration from other systems. The system power depends on the monthly thermal energy demand.

$$Q'_{gn,out,i,month} = Q'_{d,in,month} = \emptyset_{gn,out,month} \times h_{month} \quad [kWh] \qquad (8)$$

b) $FC_{gn,i} > 1$: it's necessary to have integration. The system works at maximum power.

$$Q'_{gn,out,i,month} = \emptyset_{max,gn,i,out} \times h_{month} \quad [kWh] \qquad (9)$$

2.4 In both cases a) and b) it follows the calculation of:

- Electricity produced in case of CHP unit.
- Generation losses.
- Auxiliaries electricity needs.
- Recoverable losses.
- Primary energy required to the generation system.
- Integration useful thermal energy demand.

This procedure is repeated for each generation system until the thermal energy demand is satisfied.

2.5 CHP Systems in UNI/TS 11300-4

The regulation considers systems of micro cogeneration and small cogeneration those with a maximum electrical power respectively of 50 kW and 1 MW.

The rule imposes a constraint on the microCHP systems: they must be regulated depending on the thermal load and the heat produced cannot be dissipated. The electricity produced is a useful side effect, but it does not affect the machine regulation anyhow. It is considered only in the global calculation of primary energy, according to the method shown by Chapter 2.6 UNI/TS 11300-5.

The electricity produced can be used inside the building to cover its electrical demand, for example due to auxiliaries, Heat Pumps, lighting and transportation. It is possible to export this energy only toward the grid with the on-site compensation.

UNI/TS 11300-4 [18] provides several classifications of CHP systems:

1) Type of engine:
   - Internal combustion engine (Diesel or Otto cycle);
   - Gas turbine with heat recovery from the exhaust stream;
   - Other types like Stirling cycle engine and **Fuel Cell**.
2) Operating way:
   - Without modulation;
   - Thermal Load following.
3) Type of hydraulic circuit for heat recovery:
   - Constant recovery;
   - With the possibility of bypass of the gas exhaust.
4) Storage:

– Without storage;
– With external storage with respect to the CHP system;
– With storage included in the CHP system.

All these are possible combinations of a CHP plant, which can vary a lot between two different utilities. The type of engine depends mostly on the cost of the technology and influences the operation. For example, in case of a SOFC used as CHP, the system should preferably work without modulation because of the characteristics of the technology (high operating temperature).
It is better to avoid heat dissipation to maintain a high global efficiency and to fulfil the constraints of the regulation. The presence of the storage is strictly connected to the energy profile of the user, so it is difficult to discuss a priori.

The norm provides two methods of calculation, depending on the operating way:

1) **Fractional contribution method** (*"Metodo del contributo frazionale"*)
   The CHP unit is sized to work at nominal power for the major part of the year, so the working logic is of the type on/off, without modulation. If the thermal load is higher or equal than the maximum thermal power of the CHP, the CHP produces this thermal power and the corresponding electrical power as a side effect.
   The steps are very simple in this case:
   1.1 Calculation of useful CHP thermal power $Q_{CHP,ter,out}$ from the building energy demand on a month basis.
   1.2 The primary energy entering the CHP is found with the nominal thermal efficiency of the system:

$$Q_{CHP,p,in} = \frac{Q_{CHP,ter,out}}{\eta_{ter,chp}} \quad [kWh] \qquad (10)$$

   1.3 Calculation of net electricity production passing through the nominal electrical efficiency.

2) **Monthly load profile method** (*"Metodo del profilo di carico mensile"*)
   The thermal power of the CHP is bigger than the thermal base load, so the machine will operate in partial load conditions.
   This procedure is longer and is based on a timestep of 1 hour:
   2.1 Evaluation of the building total thermal energy demand for the standard day of each month. So, 12 different values are evaluated.

2.2 Hourly load profile determination for each service and for each standard day. The daily thermal demand is divided between the 24 timesteps with a logic that depends on the type of utility.
2.3 Calculation of the hourly primary energy demand of the CHP, based on the performance curves. In this point it is calculated how much thermal energy is needed from the CHP, to find its point of operation at partial load. Then, using the efficiency corresponding to that point of operation, the primary energy needed to obtain the thermal energy is calculated.
2.4 Hourly electricity production calculation, depending on the electrical efficiency of the point of operation.
2.5 Hourly auxiliary electricity need calculation. This quantity is evaluated from the the specifications of each component of the generation plant.
2.6 Hourly thermal energy need calculation for integration.
2.7 Hourly primary energy need calculation for integration.
2.8 Calculation of the energy need for each month, starting from the corresponding standard day value.

2.6 UNI/TS 11300-5

This section of the UNI/TS 11300 can be considered the "final" part: it contains the formulas to calculate the global primary energy need of the building and the renewable energy share, starting from all the results obtained from the previous parts and UNI/TS 11300-6.

The main sections of UNI/TS 11300-5 [19] are:

1. **Building energy performance definition**

   The energy performance of a building is expressed by two factors, EP_{tot} and EP_{nren}. These numbers are expressed as the ratio between the primary energy need and the conditioned useful surface. They are two outputs of the building model constructed using the regulation, see CHAPTER 5; EPtot is referred to the global energy consumption of the building, both renewable and non-renewable, whilst EP_{nren} is referred only to the non-renewable energy consumption. This is also the value that decides the Energy Label of the building, defined in Chapter 2.7 Energy Label Definition.

$$EP_{tot} = \frac{E_{P,gl,tot}}{A} \quad \left[\frac{kWh}{m^2}\right] \tag{11}$$

$$EP_{nren} = \frac{E_{P,gl,nren}}{A} \quad \left[\frac{kWh}{m^2}\right] \tag{12}$$

Where:
$E_{P,gl,tot}$ is the total yearly primary energy need of the building, in [kWh].
$E_{P,gl,nren}$ is the non-renewable yearly primary energy need of the building, in [kWh].

Similar factors can be also calculated for the single service, in order to define the performance of each stage of the energy conversion inside the building.
The primary energy of a service is always divided in renewable, non-renewable and global. The sum of these quantities for each service gives the primary energy needs of the building, with the same arrangement.
The total primary energy is always found with the sum between the renewable and the non-renewable primary energy.

2. **Yearly primary energy need calculation for each service.**
   A simple energy balance between the energy delivered to the building ($E_{del,k,i}$), considered as a black box system, and the energy exported from the building ($E_{exp,k,i}$), is performed.
   The letter "k" indicates the single service considered (Heating, Sanitary hot water, Ventilation, Cooling, Lighting or Transportation) and the letter "i" indicates the single energy vector.

$$E_{p,k,ren,m} = \sum_i \left(E_{del,k,i} \times f_{P,ren,del,i}\right) - \sum_i \left(E_{exp,k,i} \times f_{P,ren,exp,i}\right) \quad (13)$$

$$E_{p,k,nren,m} = \sum_i \left(E_{del,k,i} \times f_{P,nren,del,i}\right) - \sum_i \left(E_{exp,k,i} \times f_{P,nren,exp,i}\right) \quad (14)$$

$$E_{p,k,tot,m} = \sum_i \left(E_{del,k,i} \times f_{P,tot,del,i}\right) - \sum_i \left(E_{exp,k,i} \times f_{P,tot,exp,i}\right) \quad (15)$$

All f_P are the conversion factors for the single energy vector.

For the delivered vectors, the conversion factors are defined by national regulation, listed in Chapter 3.1, page 34.
For the exported vectors, it is necessary to define them depending on the type of energy source.
For electricity produced with renewable sources, $f_{P,exp}$ is equal to $f_{P,del}$.

For electricity produced with CHP systems, the conversion factors depend on the allocation factor of the electricity a_w and on the energy production:

$$f_{P,exp} = \frac{E \times f_{P,del} \times a_w}{W} \quad \left[\frac{kWh_p}{kWh_e}\right] \tag{16}$$

Where:
E is the delivered energy to the CHP in one year.
a_w is the allocation factor for electricity, defined by the national regulation, see Chapter 3.1, page 34, and Chapter 4.3, page 46.
W is the electricity produced by the CHP in one year.

3. **Renewable energy share calculation**
   The portion of renewable energy is simply defined as the ratio between the renewable primary energy need and the total primary energy need of the building.
   This factor has some constraints, imposed by the national regulation and listed in Chapter 3.2, page 39.

2.7 Energy Label Definition

The Energy Label definition is not treated inside UNI/TS 11300 but is reported here to complete the frame of the energy performance evaluation. The definition is given by the Inter-ministerial Decree 26 June 2015 [20].
There are ten categories, identified by a colour from red to green and two boundaries for the $EP_{gl,nren,rif,standard}$ parameter. This value is calculated for the reference standard building, for which the characteristics are given by the Minimum Requirements Decree [20].
The classes are identified by a letter from G, the worst, to A4, the best, and by a colour, from red to green, as shown in Figure 3. A distinct label is the Nearly Zero Energy Building (NZEB), for which it is necessary to respect some specific characteristics provided by the regulation, not reported in the thesis because they do not concern the purpose of this study.
From UNI/TS 11300, it is calculated the $EP_{gl,nren}$ of the building; then it is possible to calculate the Energy Label depending on the comparison with the reference building.
Using a software like TerMus® of ACCA company, the one chosen for this work (see from Chapter 5.3, page 66), it is possible to calculate the Energy Label of the building and all the control parameters, starting from the characteristics of the building.

FIGURE 3: ENERGY LABELS SUBDIVISION

	A4	$\leq 0{,}40\ EP_{gl,nren.}$
$0{,}40\ EP_{gl,nren} <$	A3	$\leq 0{,}60\ EP_{gl,nren.}$
$0{,}60\ EP_{gl,nren} <$	A2	$\leq 0{,}80\ EP_{gl,nren.}$
$0{,}80\ EP_{gl,nren} <$	A1	$\leq 1{,}00\ EP_{gl,nren}$
$1{,}00\ EP_{gl,nren} <$	B	$\leq 1{,}20\ EP_{gl,nren}$
$1{,}20\ EP_{gl,nren} <$	C	$\leq 1{,}50\ EP_{gl,nren}$
$1{,}50\ EP_{gl,nren} <$	D	$\leq 2{,}00\ EP_{gl,nren}$
$2{,}00\ EP_{gl,nren} <$	E	$\leq 2{,}60\ EP_{gl,nren}$
$2{,}60\ EP_{gl,nren} <$	F	$\leq 3{,}50\ EP_{gl,nren.}$
	G	$> 3{,}50\ EP_{gl,nren}$

CHAPTER 3

Italian Requirements for the Energy Performance of Buildings

UNI/TS 11300 provides essentially the method for the calculation of the building energy consumption. All the results, obtained from the application of the technical regulation, must be compared with the limits imposed by several Ministerial Decrees, in order to respect the objectives of Italy in terms of buildings efficiency and renewable energy share.
In this chapter, the most relevant constraints are listed and analysed, with a focus on those limits that affect the generation plant of a building and, for this reason, can have an impact on the utilization of a SOFC microCHP system.

3.1 Ministerial Decree 26 June 2015

According to the article 4, subsection 1, letter a), of Legislative Decree 19 August 2005, n. 192 [21], the Ministerial Decree 26 June 2015 (*DM 26/06/2015*) [20] gives the general framework for the calculation of buildings energy performance and the classification of the type of intervention. All quantities evaluated following the regulation UNI/TS 11300 must be compared with the limit values, depending on the building and on the type of renovation done.

The *DM 26/06/2015* is composed of five parts:

1) "Political" part: it contains the references to all Italian laws and UE directives and the articles of the Ministerial Order;
2) Attachment 1: it contains all general information for the calculation of the energy performance of buildings [22];
3) Attachment 2: it contains all references to the technical regulations to be used [23];
4) Appendix A: it contains the parameters of the reference building [24];
5) Appendix B: it contains the specific requirements for buildings subjected to energy redevelopment [25].

The Ministerial Decree contains a lot of information not related to the analysed work; for this reason, only the limits related to the energy generation will be analysed in detail in this chapter.

3.1.1 Attachment 1 of *DM 26/06/2015*

The Attachment 1 of *DM 26/06/2015* [22] is divided in 6 chapters: the first one gives the general framework for the energy performance, whilst the others provide the building requirements depending on the type of renovation.

Regarding the energy produced by renewable sources and cogeneration:

- It is considered only as contribution to the demand of the same type of energy. In case of electricity, the energy surplus can be exported toward the grid.
- It enters directly in the energy performance of the building until it covers the entire demand. The energy surplus, if can be exported, is considered as a negative contribution according to UNI/TS 11300. This contribution is converted though the proper conversion factor (Table 4) and subtracted to the primary energy need of the building, see Chapter 4.4, page 49, for further details.
- For the CHP systems, the entering primary energy is assigned to the electricity production or to the heat production depending on the respective allocation factors a_w and a_q.

$$a_w = \frac{\frac{\eta_{el}}{\eta_{el,ref}}}{\frac{\eta_{el}}{\eta_{el,ref}} + \frac{\eta_{th}}{\eta_{th,ref}}} \qquad a_q = \frac{\frac{\eta_{th}}{\eta_{th,ref}}}{\frac{\eta_{el}}{\eta_{el,ref}} + \frac{\eta_{th}}{\eta_{th,ref}}} \tag{17}$$

Where:
η_{el} and η_{th} are the CHP electrical and thermal efficiencies.
$\eta_{el,ref}$ is the national electrical system efficiency, equal to 0.413.
$\eta_{th,ref}$ is the standard thermal efficiency, equal to 0.9.
The values of national electrical system efficiency and standard thermal efficiency are provided by *DM 26/06/2015*.

- The energy produced by renewable sources and CHP can be counted to cover the building electricity demand due to auxiliaries for heating and ventilation, heat pumps, lighting and people transportation.

In Attachment 1 the value of all conversion factors in primary energy (f_p) for each energy vector is also provided, as shown in Table 4. The subscript "*nren*" indicates a non-renewable energy source and "*ren*" a renewable one, whilst "*tot*" indicates the total factor, found as the sum between $f_{p,nren}$ and $f_{p,ren}$.

For a SOFC microCHP system fed with Natural Gas, particularly interesting are the non-renewable conversion factors of Natural Gas and Grid Electricity; the conversion factor for CHPs electricity production is analysed in more detail in Chapter 4.3, page 46.

TABLE 4: PRIMARY ENERGY CONVERSION FACTORS, *DM 26/06/2015*

Energy vector	$f_{p,nren}$	$f_{p,ren}$	$f_{p,tot}$
Natural gas	**1.05**	**0**	**1.05**
Liquefied Petroleum Gas	1.05	0	1.05
Diesel Fuel	1.07	0	1.07
Coal	1.10	0	1.10
Solid Biomass	0.2	0.8	1.00
Liquid and Gaseous Biomass	0.4	0.6	1.00
Grid Electricity	**1.95**	**0.47**	**2.42**
District Heating	1.5	0	1.5
Solid Urban Waste	0.2	0.2	0.4
District cooling	0.5	0	0.5
Thermal energy from solar collectors	0	1.00	1.00
Electricity from PV, micro-wind turbine and micro-hydraulic turbine	0	1.00	1.00
Free cooling	0	1.00	1.00
Heat pump – External thermal energy	0	1.00	1.00
Electricity exported from CHP	UNI/TS 11300-5	UNI/TS 11300-5	UNI/TS 11300-5

For district heating, the conversion factor should be calculated for each single grid and provided to the Italian regulation.
From Chapter 2 of *DM 26/06/2015*, different possibilities are considered to provide the necessary constraints to the calculation of the energy performance.
Table 5 and Table 6 show respectively the constraints related to the energy generation for each chapter of *DM 26/06/2015* and an overview of the possible intervention and the chapter of reference inside *DM 26/06/2015*. The limits related to the building components, like the transmittance, are not taken into account, because they are not related to the purpose of this study.

TABLE 5: GENERATION CONSTRAINTS BY CHAPTER, *DM 26/06/2015*

DM 26/06/2015	Description	Requirements
Chapter 2	MicroCHP plants	Primary Energy Saving > 0%
	Biomass heat generators	Minimum efficiency
Chapter 3	Technical and economical convenience of district heating and cooling	Mandatory connection to the district heating and cooling
	Primary energy factor of heating ($EP_{H,nd}$), cooling ($EP_{C,nd}$) and global performance ($EP_{gl,tot}$)	$EP_{H,nd} < EP_{H,nd,limit}$ $EP_{C,nd} < EP_{C,nd,limit}$ $EP_{gl,tot} < EP_{gl,tot,limit}$
	Efficiencies for heating (η_H), hot water production (η_W) and cooling (η_C)	$\eta_H > \eta_{H,limit}$ $\eta_W > \eta_{W,limit}$ $\eta_C > \eta_{C,limit}$ Limit values from Appendix A of *DM 26/06/2015* (see Table 8)
	Renewable energy share	Minimum value from DL n.28/2011 (see Chapter 3.2, page 39)
Chapter 4	-	-
Chapter 5	Efficiency of the new system, depending on the type of service	$\eta_{new} > \eta_{service,limit}$ Limit values from Appendix A of *DM 26/06/2015*
	Boiler efficiency	Limit values from Appendix B of *DM 26/06/2015*
	Heat Pump COP	Limit values from Appendix B of *DM 26/06/2015*

TABLE 6: GENERATION CONSTRAINTS BY TYPE OF INTERVENTION, *DM 26/06/2015*

Type of Intervention	**Intervention Level Description**	**Chapters of *DM 26/06/2015***
New Buildings	Construction of new buildings	2 and 3
Extension of buildings	Extension connected with the same technical plant.	2 and 3.2
	Extension connected with a new technical plant.	2 and 3
Important renovation of first level	Intervention affecting more than 50% of the building dispersant gross surface and requiring a new plant for heating and/or cooling	2 and 3, only for the services considered

Important renovation of second level	Intervention affecting more than 25% of the building dispersant gross surface and eventually requiring a new plant for heating and/or cooling	2, 4 and 5
Energy redevelopment	Intervention regarding building horizontal or vertical components, opaque or transparent	2 and 5
	Renovation of the entire heating and/or cooling plants or substitution of machineries	2 and 5

3.1.2 Appendix A of *DM 26/06/2015*

This appendix [24] contains the numerical values of the parameters to be used for the reference building. Indeed, the Energy Performance factors (*EP)* of the real building are compared with those of the reference building to assign the Energy Label.

First, the transmittance values for vertical, horizontal and transparent components are provided. Table 7 below shows an example with the values of the vertical opaque components toward the external environment.

TABLE 7: TRANSMITTANCE LIMITS, *DM 26/06/2015*

Climatic Zone	U [W/m²K]	
	2015	2019/2021
A and B	0.45	0.43
C	0.38	0.34
D	0.34	0.29
E	0.30	0.26
F	0.28	0.24

More important for the aim of this study is the paragraph related to the technical plants, and so also to the generation subsystem. The values of the seasonal average efficiencies are provided in Table 8; the same values are also the limits to be considered in the Attachment 1 of *DM 26/06/2015*.

It is important to underline that these numbers are not the values to be respected for each machine, but for the entire plant. In case a CHP unit is installed, the minimum thermal efficiency is 0.55, to be respected by the combination of the CHP and the thermal integration.

TABLE 8: SEASONAL GENERATION EFFICIENCY LIMITS, *DM 26/06/2015*

Generation Subsystem	**Thermal Energy Production**			**In situ electricity production**
	H	C	W	
Liquid Fuel	0.82	-	0.8	-
Gaseous Fuel	0.95	-	0.85	-
Solid Fuel	0.72	-	0.7	-
Solid Biomass	0.72	-	0.65	-
Liquid Biomass	0.82	-	0.75	-
Steam compression HP with electric motor	3.00	-	2.50	-
Refrigerating machine with electric motor	-	2.50	-	-
Absorption HP	1.20	-	1.10	-
Indirect flame refrigerating machine	-	0.6 x η_{gn}	-	-
Direct flame refrigerating machine	-	0.6	-	-
Steam compression HP with endothermic engine	1.15	1.00	1.05	-
CHP	**0.55**	**-**	**0.55**	**0.25**
Electric resistance	1.00	-	-	-
District heating/cooling	0.97	0.97	-	-
Solar Thermal	0.3	-	0.3	-
PV	-	-	-	0.1

3.2 Legislative Decree 3 March 2011, n.28

For new building construction, extension of buildings and important renovation of first level, *DM 26/06/2015* imposes that a certain amount of primary energy must come from renewable sources. The prescribed percentage is provided by Legislative Decree 3 March 2011, n.28 (*DL 03/03/2011* [26]), that represents the actuation of the EU Directive 2009/28/CE [27].
The aim is to reach the 20-20-20 objectives about renewable energy share in buildings, a weak point in Italy, where a lot of buildings are historical or old with low chance of efficient energy redevelopments.
The Italian regulation says that each region can impose stricter values on the renewable energy share but, in this study, only the national limits are taken into account.
In the Attachment 3 of *DL 03/03/2011*, n. 28 [26], are provided the obligations for new buildings and important renovations:

1) The renewable share of thermal energy for sanitary hot water production must be equal to 50%. For the sum of hot water production, heating and cooling, the values are the following:

a) 20% if the building title request is submitted between the 31st of May 2012 and the 31st of December 2013;
b) 35% if the building title request is submitted between the 1st of January 2013 and the 31st of December 2016;
c) 50% if the building title request is submitted after the 1st of January 2017.

2) These limits cannot be respected using only electrical renewable sources, whose energy is transformed in thermal energy with an electric resistance.
3) The electrical renewable power that must be installed is:

$$P = \frac{1}{K} \times S \quad [kWe] \tag{18}$$

Where:
S is the building surface, in [m^2].
K is a coefficient, expressed in [m^2/kW], whose value is:
a) 80 if the building title request is submitted between the 31st of May 2012 and the 31st of December 2013;
b) 65 if the building title request is submitted between the 1st of January 2013 and the 31st of December 2016;
c) 50 if the building title request is submitted after the 1st of January 2017.

4) In case of PV or Solar Collectors, they must be roof integrated.
5) The renewable share constraints are not considered if the building is connected to a district heating grid that covers the entire thermal energy demand for heating and hot water production.
6) For public building the renewable share limits are increased by 10%.
7) If it is technically impossible to respect, totally or partially, the renewable share limits, the project designer must highlight it in the technical relation, analysing all possible technological options in a detailed way. The relation must follow the Republic President Decree 2 April 2009, n.59 [28].
8) In case of point 7), the global energy index for the building must respect the following inequality:

$$I \leq I_{192} \times \left(\frac{1}{2} + \frac{\frac{\%_{effective}}{\%_{limit}} + \frac{P_{effective}}{P_{limit}}}{4} \right) \quad \left[\frac{kWh}{m^2 y}\right] \tag{19}$$

Where:

I_{192} is the maximum global energy index given by the current regulation, explained in the next paragraph, Chapter 3.3, page 41.
$\%_{effective}$ is the renewable energy share actually obtained in the project.
$\%_{limit}$ is the limit given by point 1).
$P_{effective}$ is the renewable power effectively obtained in the project.
P_{limit} is the limit given by point 3).

3.3 Legislative Decree 19 August 2005, n.192

The *DL 19/08/2005*, n.192 [21], updated by *DL 29/12/2006*, n.311 [11], provides the value for the parameter I_{192} in the Attachment C. The index is expressed in [kWh/m^3] and depends on:

– The ratio between surface and volume of the building;
– The climatic zone;
– The Degree Days (DD).

An example of table is shown below, with the values for all buildings, except those in class E1. All missing data can be found by linear interpolation.

TABLE 9: LIMIT VALUES FOR THE PARAMETER I_{192} DEPENDING ON THE CLIMATIC ZONE

Shape ratio S/V	**Climatic zone** A	B		C		D		E		F
	Until 600 DD	Until 601 DD	Until 900 DD	Until 901 DD	Until 1400 DD	Until 1401 DD	Until 2100 DD	Until 2101 DD	Until 3000 DD	Over 3000 DD
≤ 0.2	2.5	2.5	4.5	4.5	7.5	7.5	12	12	16	16
≥ 0.9	11	11	17	17	23	23	30	30	41	41

CHAPTER 4

SOFC microCHP and Regulation

In this chapter several parts of the Italian regulation framework are analysed to show positive and negative aspects about SOFC micro and mini CHP, considering the real operating conditions of the machine. The reference for the analysis is BLUEgen®, the main product of SolidPower company.

Figure 5: BLUEgen® technical specifications, taken from the English brochure of the product [29], gives the technical specifications of BLUEgen®.

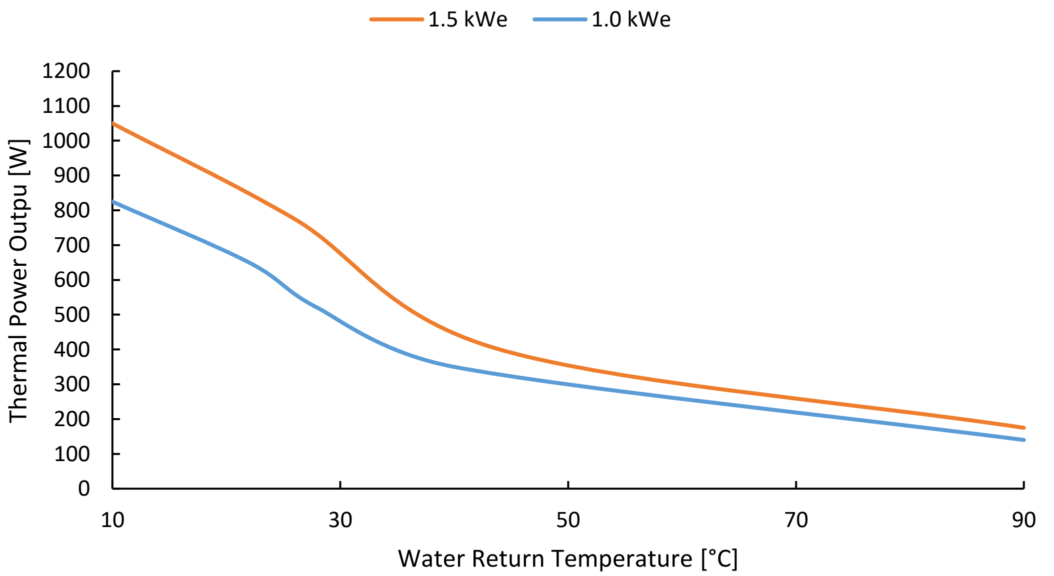
FIGURE 4: BLUEGEN® PICTURE FROM THE PRODUCT BROCHURE [29]

FIGURE 5: BLUEGEN® TECHNICAL SPECIFICATIONS [29]

Operation mode	Power-led, continuous (approx. 8,700 h per year)
Fuel type	Natural gas, bio-methane
Fuel cell technology	SOFC (Solid Oxide Fuel Cell)
Fuel consumption 1)	2.51 kW
Electrical efficiency 1) (output)	Up to 60 % (1.5 kW)
Thermal efficiency 1) (output)	Up to 25 % (0.6 kW)
Overall efficiency 1)	Up to 85 %
Electrical energy generated per year 1)	~ 13,000 kWh_{el}
Thermal energy generated per year 1)	~ 5,220 kWh_{th}
Control	Remote monitoring and control via Internet
Weight, Dimensions (H x W x D)	195 kg, 1,010 x 600 x 660 mm
Noise level	< 47 db (A)
Service interval 2)	12 months
Full maintenance service	Yes (120 months)
Subsidies	Subsidy programmes differ by country. Please contact your local distributor to find out more.

The output power of BLUEgen® depends on the return temperature of the water. Figure 6 shows the behaviour of the Thermal Output Power in two different conditions of electrical output, 1.5 kWe and 1.0 kWe.

FIGURE 6: BLUEGEN® THERMAL POWER OUTPUT FUNCTION OF THE WATER RETURN TEMPERATURE



The nominal condition, characterized by electrical power of 1.5 kW and maximum electrical efficiency (60%), has a thermal output of 0.6 kW when the returning water temperature is 35°C. This temperature is the regulation reference for the power outputs in microCHP applications, so it is used as reference also for BLUEgen®.

4.1 Priority and Operating Condition

A SOFC is a machine with an operating temperature higher than 700 °C. For this reason, it cannot operate with a load following logic bit it must work at constant load. The ideal utilities for the its use are those with an almost constant thermal and electrical load during the year, for example a big pool. Otherwise, for "standard" users it is necessary to implement a thermal energy storage to uncouple the heat production with respect to the electricity production.

The priority order given by UNI/TS 11300-4 [18] (Chapter 2.4, page 26) represents an advantage for this system, that is very good for base load application. Obviously, this order is related to the fact that, when a CHP is installed, it is necessary to make it work the highest possible number of hours. A SOFC microCHP has very few mechanical moving parts like the air blower; for this reason, it requires much less maintenance than an ICE microCHP and can reach very high availabilities, also up to 99%.

Because of its non-flexible operating condition, the yearly energy calculation of a SOFC microCHP system must follow the "Fractional Contribution Method" of UNI/TS 11300-4, see Chapter 2.5, page 28. This method has the advantage of being very simple, but it must be validated by a detailed study of the electrical and thermal load fluctuations of the utility, in order to avoid frequent stops of the machine.

So, for one BLUEgen® unit, working constantly during the year with water at 35 °C, the primary energy needed is:

$$Q_{SOFC,p,in} = \frac{Q_{SOFC,th,out}}{\eta_{th,chp}} = \frac{\phi_{SOFC,th} \times h_{year}}{\eta_{th,chp}} = \\ = \frac{0.6 \times 8{,}760}{0.25} = 21{,}024 \quad [kWh_p] \qquad (20)$$

The thermal energy and the gross electricity production are:

$$Q_{SOFC,th,out} = \phi_{SOFC,th} \times h_{year} = 0.6 \times 8{,}760 = 5{,}256 \quad [kWh_t] \qquad (21)$$

$$Q_{SOFC,el,out} = Q_{SOFC,p,in} \times \eta_{el} = 21{,}024 \times 0.6 = 12{,}614 \quad [kWh_e] \qquad (22)$$

In a program based on UNI/TS 11300, like TerMus®, the calculation is performed on a month basis and can bring to slight differences. Already from this numbers and from the technical specifications of BLUEgen®, it is clear the production unbalance of the machine between heat and electricity. Indeed, the ratio between the electrical production and the thermal production is around 2.4: for this reason, the thermal production is considered a secondary product of the machine. If the machine works without modulation, this number is also the ratio between the electrical and thermal efficiency. These considerations are fundamental for the next section, where the "definition issue" of the Italian regulation is described.

4.2 Sizing Depending on Thermal Power

For a conventional microCHP, for example an ICE, it is right to size the machine with the thermal load, because of the high heat rate with respect to the electricity generation. For this reason, UNI/TS 11300 imposes two constraints to CHPs: they must be regulated following the thermal load and no heat should be dissipated, as shown in Chapter 2.5, 28.

Table 10 shows an example of an ICE microCHP (TOTEM® from Asja Group® company [30]) and the electricity/heat ratio obtained, with the same hypothesis of continuous functioning during the entire year.

TABLE 10: EXAMPLE OF AN ICE MICROCHP ELECTRICITY/HEAT RATIO

TOTEM® microCHP		
Thermal Power	[kWt]	21.6
Electrical Power	[kWe]	10.0
Thermal Efficiency	[%]	64.0%
Electrical Efficiency	[%]	29.6%
Working hour	[h]	8760
Thermal Energy produced	[kWht]	189,216
Electricity produced	[kWhe]	87,600
Ratio Electricity/Heat	[-]	**0.4625**

It is evident that, even with a high electrical efficiency, the heat produced by an ICE microCHP is predominant with respect to the electricity produced.

Instead, a SOFC has a low production of heat to favour the electricity production. The point is that a SOFC is essentially an electric machine while the regulation considers it as thermal. This "definition issue" can have positive or negative effects depending on the type of utility.
The positive effect is that, having less heat produced, it is simpler to have a thermal base load condition for the machine, especially if the system is equipped with a thermal storage. This, coupled with the high electricity production, has certainly a beneficial effect on the energy performance of the building.
The negative effect is related to the electrical consumption, which is treated quite approximatively in the regulation. The electricity demand is attributed to:

- Auxiliaries, for example pumps or air blowers;
- Lighting (in case of non-residential buildings);
- Ventilations;
- People transportation.

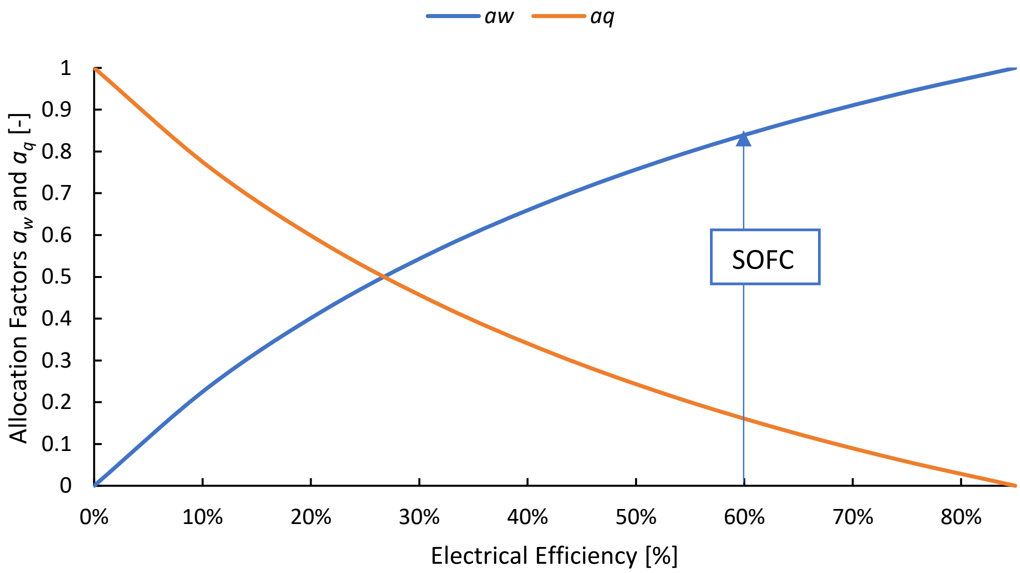
The electrical consumption of the TerMus® model is not so realistic because it is considered in a very simplified way, so there is the possibility that the calculation of self-consumed electricity is far from reality; this can impact significantly on the calculation of the primary energy needs. Unfortunately, the regulation about the electricity demand was not available for this study, but a clear example of this situation is given in CHAPTER 5, with the analysis of the TerMus® model.
Another problem is that can be possible to "trick" the regulation to obtain a better Energy Label without improving so much the energy performance of the building. This is possible oversizing the SOFC to obtain a lot of electricity exported but, at the same time, keeping the thermal power under the limit calculated by the regulation. The point is that the regulation does not impose a constraint on the electrical oversizing; at the contrary, if the thermal power of the CHP is too big for the building thermal demand, the regulation does not allow its installation.
If the SOFC microCHP is oversized, the electricity exported will be converted in primary energy and subtracted to the primary energy demand of the building; the result is that the building seems more efficient, but the model is not a good picture of the real situation. It would be better if an active control of the regulation is prescribed to avoid both electrical and thermal oversizing.

4.3 Allocation and Conversion Factors

The electricity and heat allocation factors a_w and a_q divide the input primary energy of a CHP, assigning it to the electricity production or to the heat production. They depend on

electrical and thermal efficiency of the machine and on reference efficiencies, as explained in Attachment 1 of MD 26/06/2015 [20] (Chapter 3.1, page 34).
To show how these parameters change with the electrical efficiency, a global efficiency equal to 85% is considered, in order to have a direct confrontation with BLUEgen®, which has the same global efficiency. Then, increasing the electrical efficiency, the allocation factors are calculated; the sum of the two must be equal to 1.
The figure below shows the shape of allocation factors' curves.

FIGURE 7: ALLOCATION FACTORS FUNCTION OF ELECTRICAL EFFICIENCY



Analysing the a_w curve, it is evident that the electricity production is favoured. Indeed, to have a_w equal to 0.5 (and so half of the primary energy assigned to electricity production) is only necessary an efficiency of 27%.
A system with a SOFC microCHP unit like BLUEgen® has a 60% electrical efficiency. The corresponding allocation factors are 0.84 for electricity and 0.16 for heat. So, 84% of input primary energy is assigned to the electricity production; this is another evidence of the "definition issue" previously mentioned. It is a big contradiction that a CHP with these technical specifications has to work following the thermal load.

The electricity conversion factor depends linearly on the electricity allocation factor. The formula given by UNI/TS 11300-5 [19] can be simplified, in case of a CHP working always at nominal conditions, by substituting to the ratio between primary energy E and produced electricity W the inverse of the electrical efficiency.

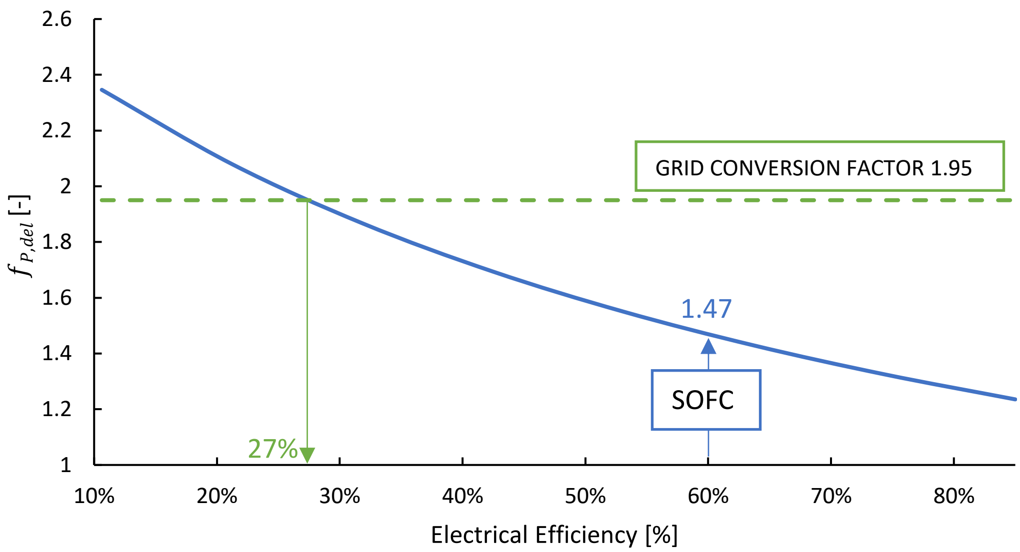
$$f_{P,exp} = \frac{E \times f_{P,del} \times a_w}{W} = \frac{f_{P,del} \times a_w}{\eta_{el}} \quad \left[\frac{kWh_p}{kWh_e}\right] \tag{23}$$

a_w increases faster with respect to η_{el}, so the ratio between them is higher than 1 and decreases if η_{el} increases.

$f_{P,del}$ is the conversion factor of the primary energy in input: normally it is natural gas with a conversion factor equal to 1.05, see Table 4.

Increasing η_{el} from 10% to 85% the following curve is obtained.

FIGURE 8: ELECTRICITY CONVERSION FACTOR CURVE



To simplify the comparison, Figure 8 also shows the grid conversion factor. Its value is 1.95 because only the non-renewable part must be considered with a SOFC fed with natural gas (and in general for all CHP fed with fossil fuels).

To obtain the same conversion factor of the grid, 27% of electrical efficiency is necessary. In case of a BLUEgen® unit, it is more convenient to self-consume the electricity with respect to export it, also from the regulation point of view. Indeed, the conversion factor is 1.47 for the exported energy, lower than that of the grid. This factor counterbalances the higher electrical production achieved, reducing the risk of SOFC oversizing to obtain a higher electricity export, because it makes less convenient from the point of view of the energy performance to sell electricity to the grid.

The low conversion factor brings also to a reduction of the CO_2 production, that is calculated by computer programs based on UNI/TS 11300 (TerMus® in this case) using pollution factor dependent on the type of fuel.
It could seem that it is more convenient, with the same electricity production, to have a lower electrical efficiency, to have a higher primary energy subtracted to the demand. This is not true because, with a lower efficiency, the input primary energy would be higher reducing the performance of the building.

4.4 Primary Energy Calculation

The primary energy need for the SOFC system is evaluated from the energy balance of the system; starting from the useful thermal energy to the distribution, the efficiencies give the information of how much input energy is needed.
The thermal energy, as said in the previous section, must be self-consumed without dissipation.
The electricity can be self-consumed or exported to the national grid. The regulation considers in two diverse ways these contributions:

- Self-consumption: this term is directly subtracted to the electricity need of the building for auxiliaries, heat pumps, lighting or transportation. The interpretation of the regulation is that each unit of electricity self-consumed is a saving of primary energy from the grid. So, it has the same conversion factor of the electricity from the grid. Anyway, this term does not appear in the results because it is subtracted directly without conversion.
- Export: this term is very important for a SOFC installation in a computer program, because it can be far from reality. As already mentioned in Chapter 4.2, page 45, the electric part of the regulation is not so accurate, therefore the real self-consumption and exportation can be very different.
  The electricity in output is considered with a conversion factor that decreases with the electrical efficiency, as shown in Figure 8. For a SOFC microCHP, that has always high efficiencies, the exported electricity saves less primary energy with respect to the self-consumed electricity.

To give a clearer idea of this type of error, a small example, always based on a BLUEgen® unit, is proposed. Table 11 shows the initial guess data.

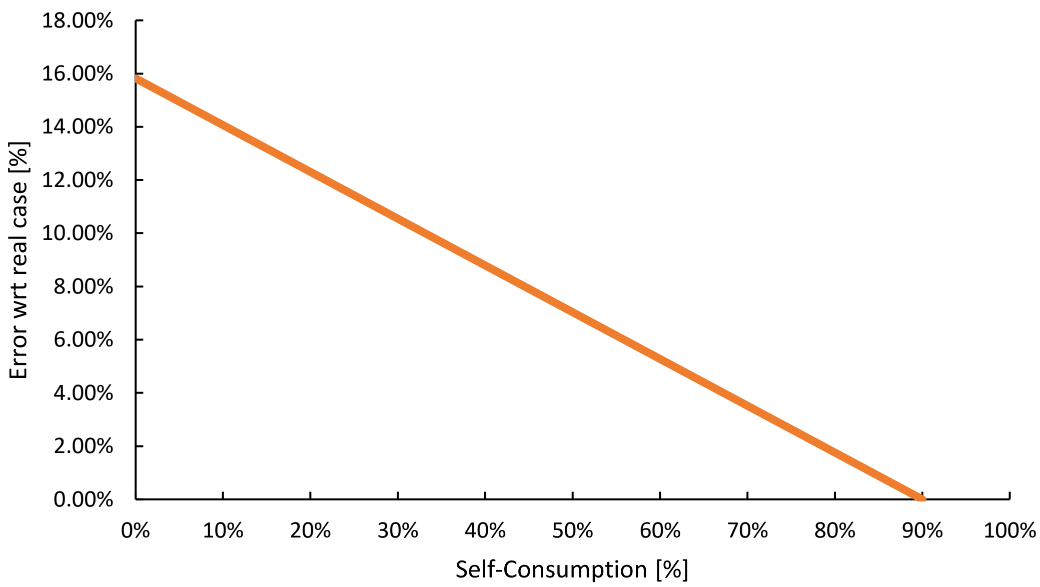
TABLE 11: GUESS DATA FOR BLUEGEN® EXAMPLE

BLUEgen® example	
Electric Power	1.5 kW_e
Thermal Power	0.6 kW_t
Electrical Efficiency	60%
Thermal Efficiency	25%
Operation Hours	8760 h/y
$f_{P,nren,SOFC}$	1.469
$f_{P,nren,GRID}$	1.95
Electricity Demand	30000 kWh_e
SOFC Electricity Production	12614 kWh_e
Real Self-Consumption	90%
Primary Energy Need without SOFC	58500 kWh_p
Primary Energy Need with SOFC	34509 kWh_p

Starting from the resulting primary energy need, self-consumptions smaller than the real one (90%) are computed in an Excel® file. For each self-consumption value, it is calculated the new Primary Energy Need with SOFC, higher than the initial one because there is a difference between the conversion factor of the exported electricity and the grid one (Figure 8). This primary energy difference brings to an error, that increases if the self-consumption of the model decreases.

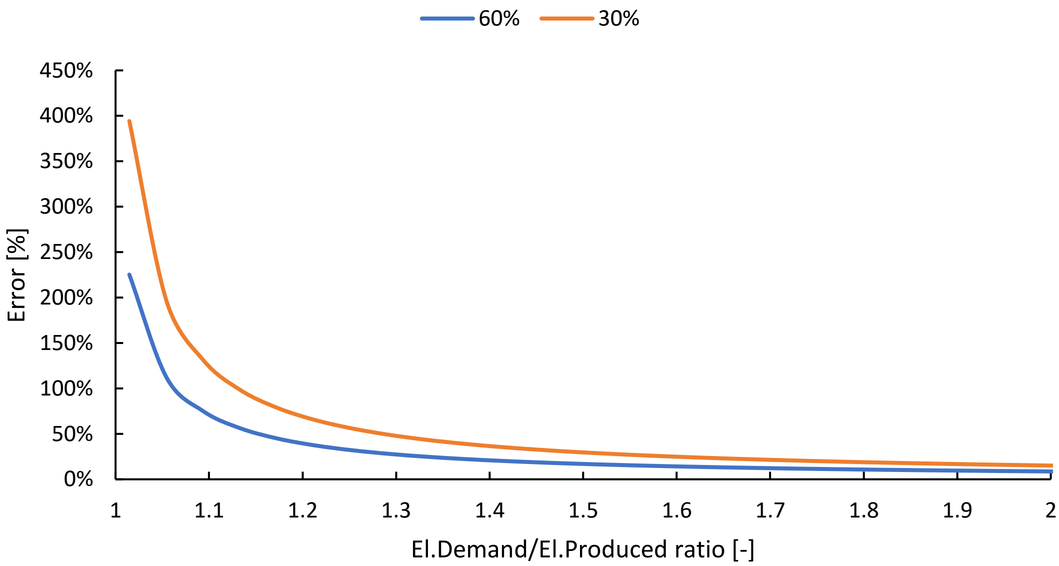
The point is to show, in Figure 9, the error that a program following the regulation, like TerMus®, can commit considering a smaller self-consumption than the real one, evaluated with other means.

FIGURE 9: ERROR ON PRIMARY ENERGY NEED CALCULATION DEPENDING ON SELF-CONSUMPTION



The curve is linear and has a maximum if the self-consumption considered by the program following the regulation is zero. The error is not too big, but it can make the difference in the final building Energy Label.
The error represents how much primary energy surplus is calculated with respect to the real and right case. This difference comes from the definition of the conversion factor for the electricity exported: the fact that it is different from that of the grid is conceptually right, but at the same moment it requires to have a precise electrical model, as similar as possible to the reality.
If the self-consumption is 90%, obviously the error goes to zero. It is also possible that the software overestimates the self-consumption, but it is less probable because a lot of possible electrical load are not considered.
Figure 10 below shows how the error changes with respect to ratio between electricity demand and electricity production. The curves are referred to constant values of "wrong" self-consumption (30% and 60%) and a real self-consumption of 90%.

FIGURE 10: ERROR CURVE DEPENDING ON THE RATIO EL.DEMAND/EL. PRODUCTION



If the ratio between electricity demand and electricity production increases, the error increases a lot, also up to 100%. So, it is particularly important to realize an electrical model more accurate than the regulation, in order to estimate the possible error done by the software simulation based on the regulation.

The error on primary energy calculation gives a clear idea about the fact that the regulation considers in a very simplified way the electrical consumption of a building.

Indeed, the only electrical devices that can be inserted in the software are those related to the auxiliaries, to lighting and transportation.
In a lot of commercial and industrial applications, there is machinery with a high electrical consumption that is not considered at all for the Energy Label evaluation. Possible examples are the cold rooms, used by hospitals and other sanitary and research facilities, or data centres facilities. All these utilities are characterized by a constant electrical consumption during the year, that is ideal for SOFC CHP applications.
Anyway, further analyses on the utility should be done to understand if this error is an important quantity. In this simple example, it is not considered a thermal energy demand, that reduces significantly the weight of the electrical demand in several cases of commercial building. Indeed, the purpose of the example was to focus the attention on the approximations in the regulation about the electrical model of the building.

4.5 Primary Energy Saving (PES)

Regarding the Primary Energy Saving, the Italian minimal requirements decree gives a limit value for microCHP applications, equal to zero (Table 5). So, a CHP unit must guarantee the use of less primary energy with respect to the reference efficiencies.
The expression of PES is given by *DL 08/02/2007*, attachment 3 [31]:

$$PES = \left(\frac{1}{\frac{CHPH\eta}{Ref\ H\eta} + \frac{CHPE\eta}{Ref\ E\eta}} \right) \times 100 \quad [\%] \tag{24}$$

Where:
$CHPH\eta$ is the CHP thermal efficiency.
$Ref\ H\eta$ is the reference thermal efficiency.
$CHPE\eta$ is the CHP electrical efficiency.
$Ref\ E\eta$ is the reference electrical efficiency.

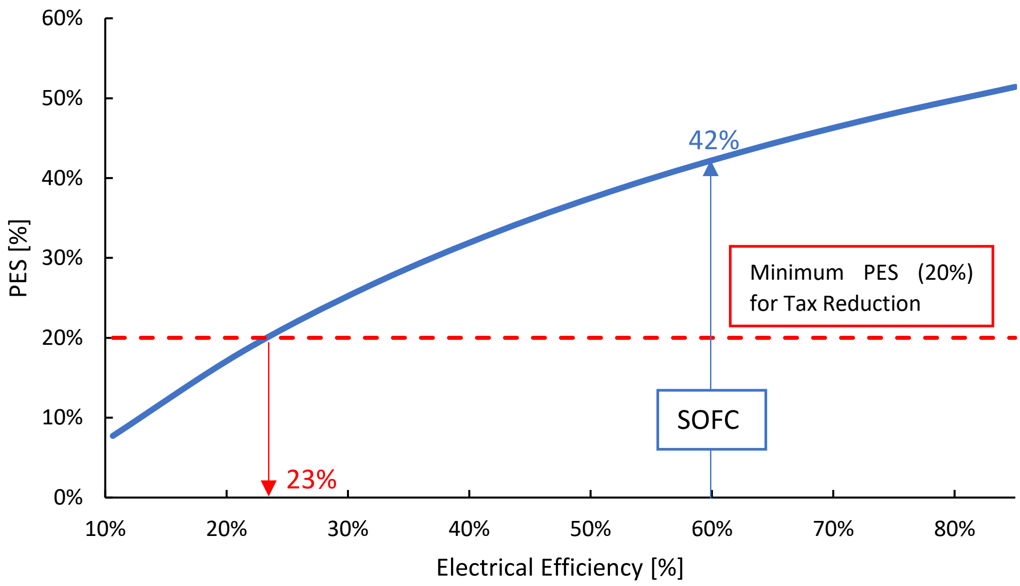
ENEA (http://www.agenziaefficienzaenergetica.it/), the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, published on April 10th, 2018, the update of the requirements to be respected to obtain the tax reduction for energy redevelopment, following the Budget Law 27 December 2017, n.205 [6].
This document sets for microCHP systems two constraints:

1) PES > 20%;

2) All useful heat must be exploited for heating and/or sanitary hot water production.

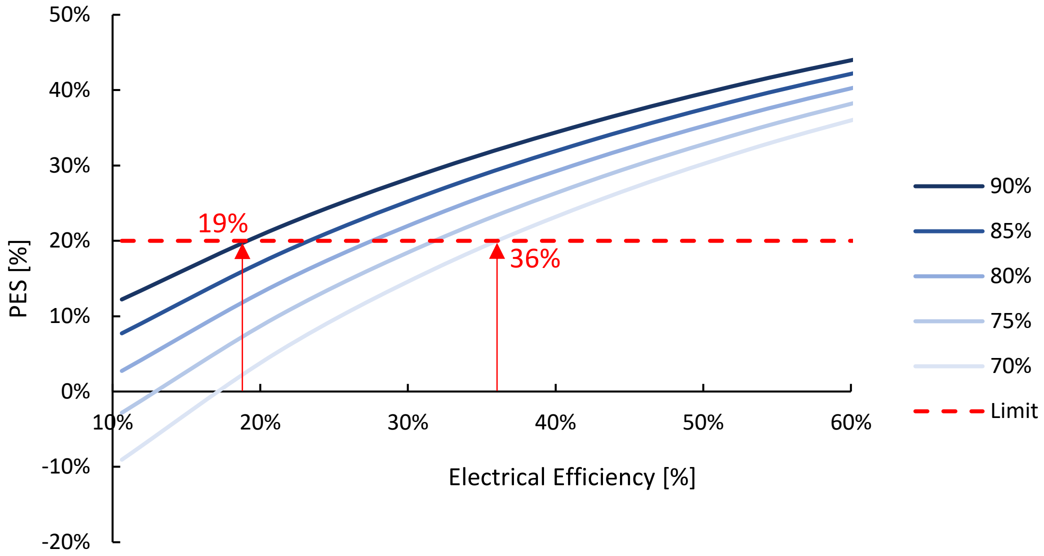
The second constraint is already imposed by UNI/TS 11300 as technical specification. The first one, instead, imposes a far stricter value on PES, that is not so easy to achieve with common technology.
Figure 11 shows the PES function of the electrical efficiency. As the previous analysis, a global efficiency of 85% is considered, the same of a BLUEgen® unit.

FIGURE 11: PES FUNCTION OF ELECTRICAL EFFICIENCY



With 85% of global efficiency, it is very difficult to have a PES lower than zero; it would be necessary to have 4% of electrical efficiency. This is the reason of the higher limit imposed by ENEA: 20% is a value that guarantees a good improvement of building efficiency. But, reaching it with a conventional CHP unit is not trivial. The minimum electrical efficiency required, indeed, is 23% that, for a microCHP with internal combustion engine, is quite difficult and expensive to reach, see Figure 1.
Instead, for a SOFC module like BLUEgen®, a PES equal to 42% can be reached.
Figure 12 shows also the variation of PES with global efficiency. This quantity increases for the curves with darker blue. With lower global efficiency, it is almost impossible for conventional CHPs to respect the tax deduction limit.

FIGURE 12: PES FUNCTION OF ELECTRICAL EFFICIENCY, FOR DIFFERENT GLOBAL EFFICIENCIES



4.6 Seasonal Efficiency

The Ministerial Decree 26 June 2015, Appendix A [24], gives the limits for the mean seasonal efficiency of the plant, as seen in Chapter 3.1, page 34. These values must be respected every time a substitution of the system producing energy is performed.

For heating and hot water production, the generation limits for CHPs are 0.55 for thermal production and 0.25 for electricity production. Clearly, these values are referred to a common internal combustion engine CHP.

When a SOFC microCHP is installed, the electrical efficiency is not an issue at all. At the contrary, the thermal efficiency limit seems to exclude the Fuel Cell based CHP units, whose efficiency is usually around half of the limit. But this is only an impression: indeed, the minimal requirements are referred to the mean seasonal efficiency of the entire plant. If the SOFC is integrated with a simple boiler (whose efficiency respects the values given by the *DM 26/06/2015* for boilers), the value prescribed of mean seasonal efficiency is easily respected. In addition, the small thermal contribution of the SOFC does not weight so much in the final calculation of mean seasonal efficiency.

It is also important to underline that, in the TerMus® model, no evidence of an active control on the limit of 0.25 on the seasonal electrical efficiency has been found.

4.7 Minimum Renewable Energy Share for New Buildings and Important Renovations

Legislative Decree 3 March 2011, n.28 [26], imposes certain limits to the renewable energy share and to the electrical renewable power installed, as shown in Chapter 3.2, page 39; these constraints are valid for new buildings and for important renovation, as defined in Chapter 3.1, page 34. The minimum renewable energy share for new building and important renovations is 50%, increased to 60% for public buildings.

A SOFC microCHP, and in general all common CHPs, works with Natural Gas as fuel. So, electricity and heat produced by the system are not considered renewable at all. Excluding the cases in which is possible to intervene on the fuel to increase the renewable percentage, for example biogas from organic digesters, the entire plant layout can become very complicated in order to respect the limits of renewable energy share.

Qualitatively, to respect the limit on the sanitary hot water, on the total thermal energy and on the electrical renewable power installed, it would be necessary for example to install a Heat Pump and a Photovoltaic plant. Considering also a SOFC installation, the risk is to increase too much the complexity of the system and the related initial investment, also because the Heat Pumps are not still a mature technology from the economical point of view.

For this reason, the minimum renewable energy share is a big obstacle for the diffusion of SOFC microCHP in case of new buildings and important renovations, however remaining an effective way to improve a faster integration of renewable energy sources within the building sector, thanks to the possibility of operating in smart grid conditions.

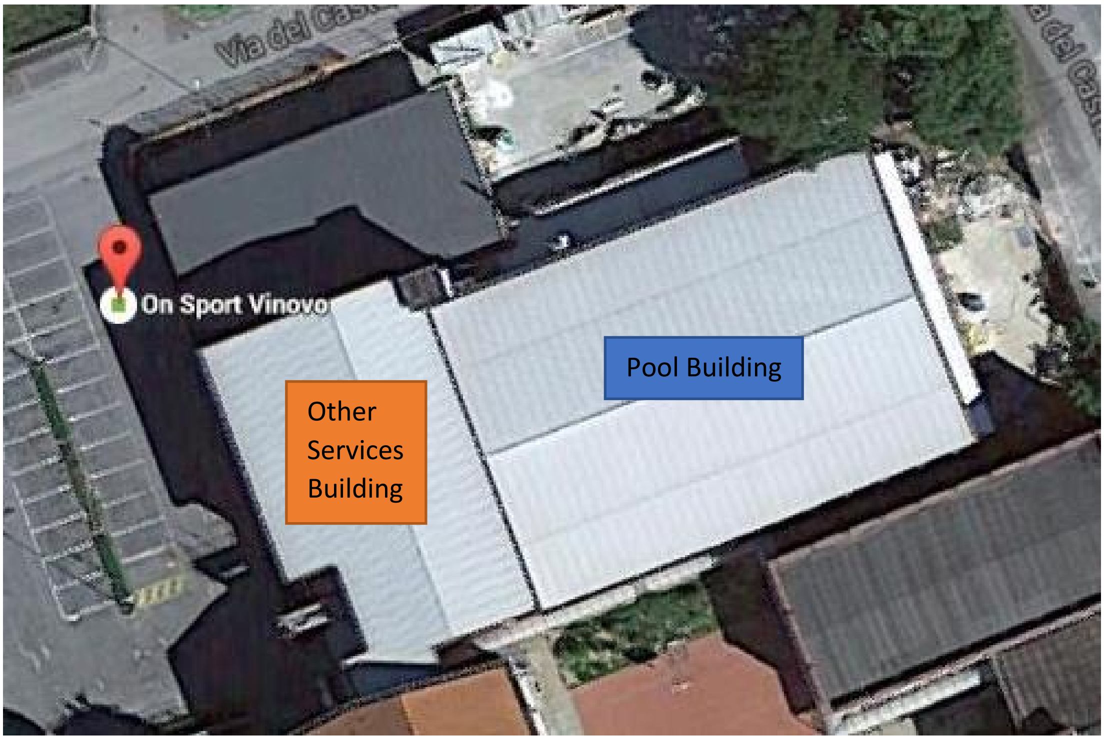
The only possible exception to this constraint consists in the point 7) and 8) of *DL 03/03/2011*, n. 28 (see Chapter 3.2, page 39). If it is technically impossible to respect the renewable energy constraints, it is necessary to demonstrate it considering all possible technological options. Furthermore, it must be guaranteed a certain global energy index. If no renewable energy is used and no electrical renewable power is installed (limit case), the global energy index is a half of I_{192}. This limit is very low and difficult to obtain, so a SOFC installation in new buildings is very unlikely now, with the current regulation.

CHAPTER 5

Case Study – Vinovo's Pool

The case study is the public pool of Vinovo, a small town in the province of Turin. It is currently managed by the On Sport society, which administrates two other sport facilities in Northern Italy. The pool counts fifty employees and never performed an energy analysis of any kind. The first intervention has been done by Coesa Srl® company starting from the 15th of February 2016, after performing an Energy Audit [32].
Figure 13 shows an aerial view from Google Maps of the pool.

FIGURE 13: VINOVO'S POOL BUILDING AERIAL VIEW [32]



The building is composed by two adjacent parts, very different one from the other.
The pool building is a single big room at ground floor and contains the swimming pool and the children pool. The technical rooms are partially underground, located in the northern side.

The other part hosts all support services necessary for the activity: locker rooms, showers, bathrooms, offices, a gym, a kitchen with a canteen and some bedrooms. This building has three floors and one basement.
All data related to the building and to the energy consumption have been provided by Coesa Srl®, which performed an Energy Audit on this facility. For this reason, the same baseline period is considered: from September 2014 to August 2015.
In the next sections, all real energy consumptions are described. To give an idea of the total energy need, Table 12 shows the annual natural gas and electricity demands and the primary energy in Tonnes of Oil Equivalent (TOE).

TABLE 12: VINOVO'S POOL ANNUAL NG AND ELECTRICITY DEMANDS

Energy need		**2014/2015**
Natural Gas	Sm^3	101,478.5
	TOE	83.72
Electricity	kWh_{el}	178,336.0
	TOE	33.35
Total Primary Energy	TOE	117.07

Furthermore, all data about the building are provided. The aim is to realize a simulation model whose consumption is similar to the consumption of the real building. The software used is TerMus®, by ACCA Software company, based on the Italian regulation.

5.1 Real Building Energy Demands

5.1.1 Natural Gas Consumption

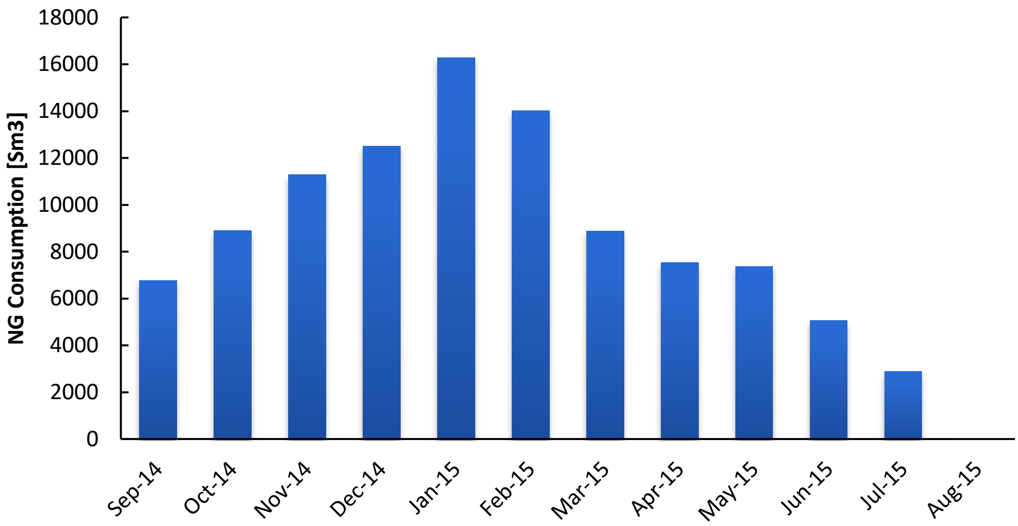
Table 13 and Figure 14 show the natural gas demand during the year considered. The consumption depends strongly on the Degree Days, so it is seasonal, with the highest values in winter. There is also an important use of hot water for showers; in August, the pool is closed and the demand is zero.

TABLE 13: VINOVO'S POOL MONTHLY NG CONSUMPTION

	NG Consumption [Sm^3]
Sep-14	6,763
Oct-14	8,898
Nov-14	11,286
Dec-14	12,510
Jan-15	16,281

Feb-15	14,017
Mar-15	8,871
Apr-15	7,529
May-15	7,371
Jun-15	5,071
Jul-15	2,882
Aug-15	-

FIGURE 14: VINOVO'S POOL MONTHLY NG CONSUMPTION



5.1.2 Heating and Hot Water Demands

The entire thermal energy need is satisfied by a centralized plant with the following characteristics.

The generation unit is an old boiler with a useful thermal power of 465.2 kW and a nominal efficiency of 92.5%. The hot water is used to heat up new water for the pools, for the showers in the locker rooms and inside the Heating Battery of the HVAC system. The heating system is an all-air system served by three Air Treatment Units (*UTA*), with the following specifications:

TABLE 14: AIR TREATMENT UNITS TECHNICAL SPECIFICATIONS

		UTA 1	UTA 2	UTA 3
Extraction Air Flowrate	m^3/h	24,000	8,650	7810
Expulsion Air Flowrate	m^3/h	24,000	8,650	7810
Heating Battery Power	kW	150	150	135
Heat Recovery	-	Yes	Yes	Yes

UTA 1 is responsible for the heating and ventilation of the pool building. It has a high nominal flow rate because frequent and continuous air exchanges must be done to avoid an uncomfortable vapour concentration in the pools room. The regulation imposes that the entire volume of the room must be renewed nine times every hour. Even if this value is not constant during the year, it represents certainly a high energy consumption.
UTA 2 and *UTA 3* are used for the other building, that requires less ventilation but more heating power.
Starting from the hot water consumption related to the pool water exchange and to the showers, it was possible for Coesa Srl® company to evaluate the percentage of thermal energy related to each service. The hypotheses are that the water has to be heated up to 28°C for the swimming pool and up to 33°C for the smallest pool. The evaporation losses are included.
Figure 16 and Figure 15 show respectively the monthly natural gas consumption for each service and the share for each service.

FIGURE 15: VINOVO'S POOL TOTAL NG CONSUMPTION BY SERVICE

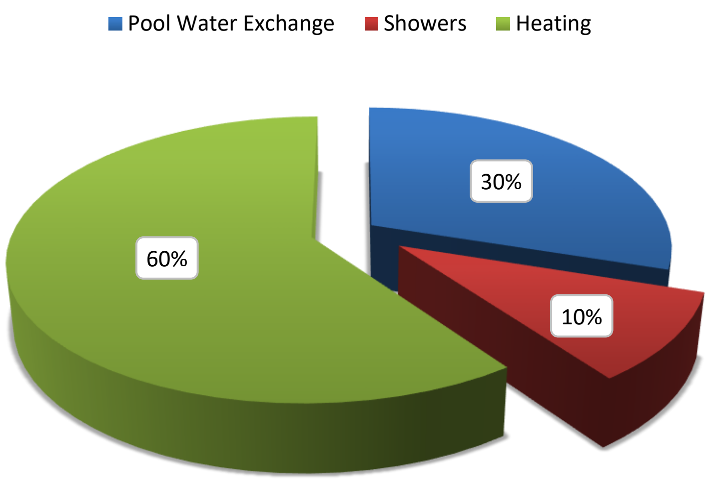
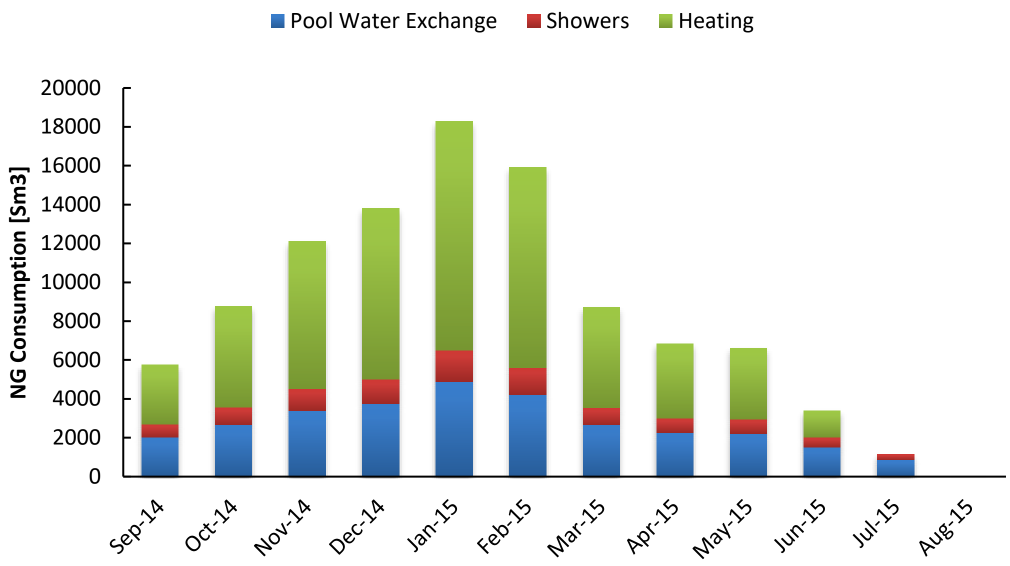


FIGURE 16: VINOVO'S POOL MONTHLY NG CONSUMPTION BY SERVICE



The NG consumption attributed to heating is around 60,000 Sm^3, to pool water exchange is around 30,000 Sm^3 and to showers is around 10,000 Sm^3. It is evident that a lot of energy is used for hot water production: this feature makes the Vinovo's pool particularly attractive for CHP applications.

In the TerMus® model, heating and hot water demands obtained have to be similar to the real consumption. For heating, it is considered the difference of Degree Days between the regulation model and the real climatic data; this will bring to a higher NG consumption in the model. For sanitary hot water, it is implemented the same consumption.

5.1.3 Electricity Consumption

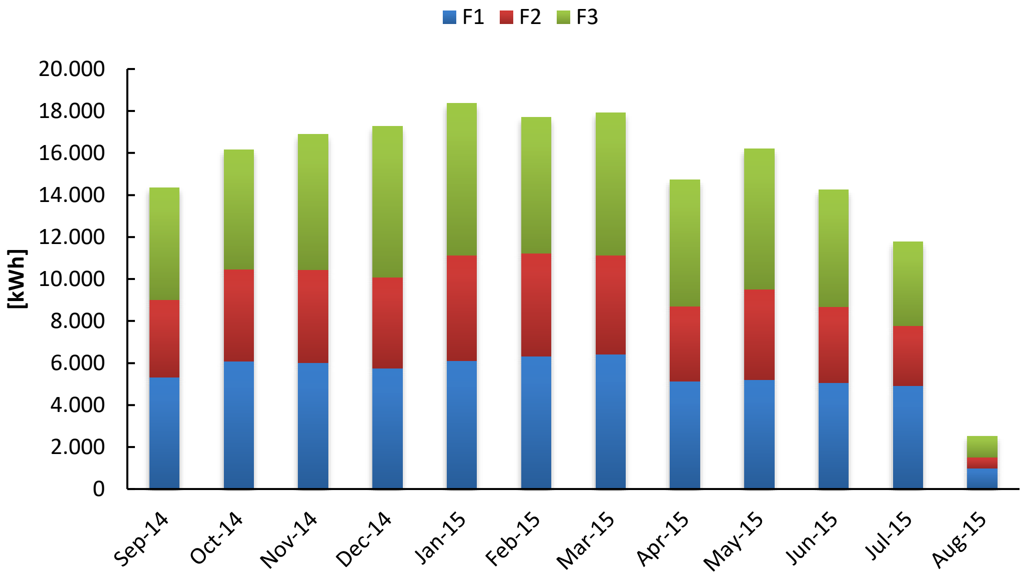
Table 15 and Figure 17 show the electricity demand during the year considered. The detail of the consumption for each time slot is very important for the aim of the study; indeed, an almost constant consumption during the entire day is a favourable condition for a SOFC microCHP application.

TABLE 15: VINOVO'S POOL MONTHLY ELECTRICITY CONSUMPTION FOR EACH TIME SLOT

2014/2015	Electricity Consumption						
Month	F1		F2		F3		TOTAL
	kWh		kWh		kWh		kWh
Sep-14	5,313	37%	3,699	26%	5,346	37%	14,358
Oct-14	6,091	38%	4,382	27%	5,692	35%	16,165

Nov-14	6,015	36%	4,424	26%	6,451	38%	16,890
Dec-14	5,760	33%	4,327	25%	7,193	42%	17,280
Jan-15	6,120	33%	5,004	27%	7,253	39%	18,377
Feb-15	6,326	36%	4,909	28%	6,468	37%	17,702
Mar-15	6,418	36%	4,721	26%	6,783	38%	17,922
Apr-15	5,144	35%	3,555	24%	6,019	41%	14,717
May-15	5,199	32%	4,308	27%	6,705	41%	16,211
Jun-15	5,063	36%	3,618	25%	5,573	39%	14,254
Jul-15	4,930	42%	2,841	24%	4,004	34%	11,775
Aug-15	998	40%	526	21%	995	40%	2,519

FIGURE 17: VINOVO'S POOL MONTHLY ELECTRICITY CONSUMPTION FOR EACH TIME SLOT



As previously said, the pool is closed during August, so the electricity consumption is smaller by far with respect to the other months. The electric model made by Coesa considers all auxiliaries, electric motors for the HVAC system and the lighting.
The table below shows the electrical powers of all auxiliaries and of the lighting.

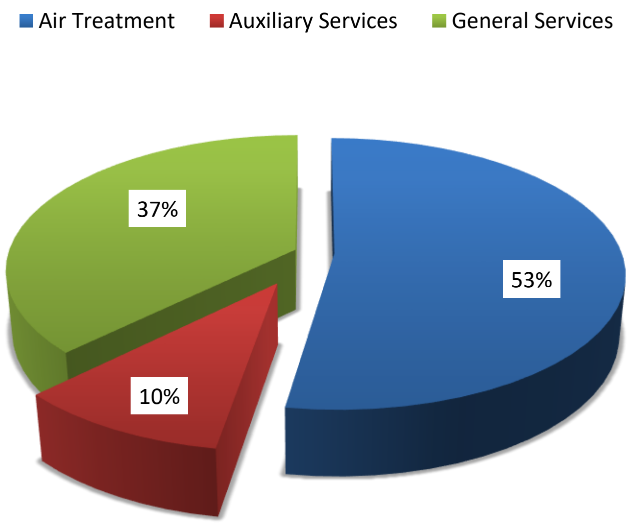
TABLE 16: AUXILIARIES AND LIGHTING ELECTRICAL POWERS

AUXILIARIES	**Quantity**	**Total Electrical Power [kW]**
UTA Electric Motor	3	35
Pump	8	5.6
Summer Air Conditioner	2	3.0
LIGHTING		

Pool Spotlight	11	2.42
Pool Fluorescent Lamp	15	1.74
Gym Fluorescent Lamp	9	2.25
Fluorescent Lamp 72 W	25	1.8
Fluorescent Lamp 36 W	41	1.476
Fluorescent Lamp 116 W	17	1.972

Starting from the electric model, it is evaluated the percentage of electricity consumed for each service (Figure 18): Air Treatment (*UTA*'s electric motors), General Services (Lighting and other consumptions) and Auxiliary Services (Pumps).

FIGURE 18: VINOVO'S POOL TOTAL ELECTRICITY CONSUMPTION BY SERVICE



In the TerMus® model, the same electricity consumption is obtained, to avoid errors in the energy performance calculation.

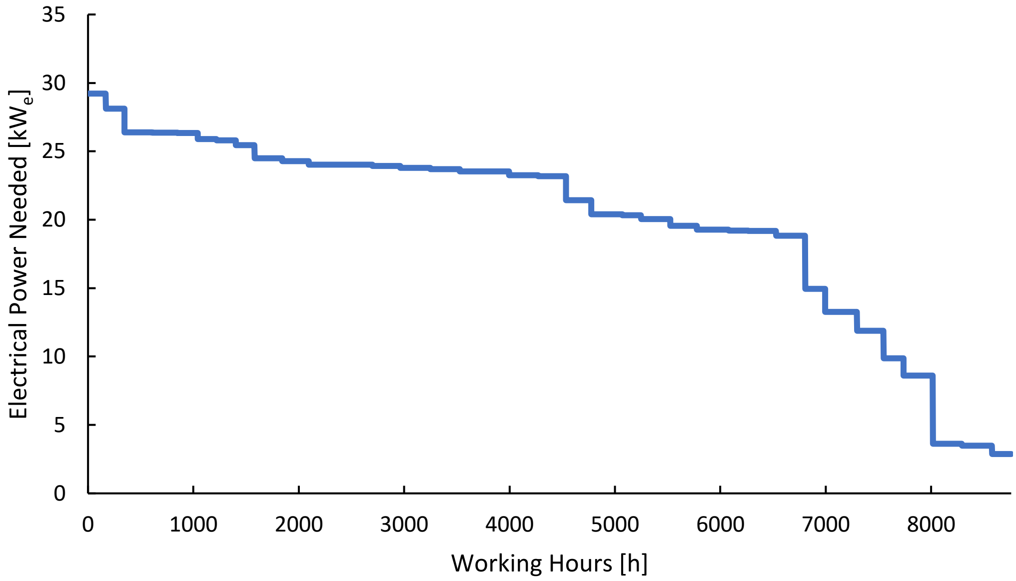
5.2 SOFC microCHP Sizing

To improve the energy performance of the building, it is proposed the installation of a SOFC microCHP system, based on the SOLIDPOWER product BLUEgen®. The objective is to understand if the regulation considers in a positive way this type of plant in a real project.

Even if the regulation obliges all CHP systems to regulate following the thermal load, the sizing of a SOFC system cannot be based only on the thermal power. Anyway, it is necessary to be sure that all thermal energy can be recovered.

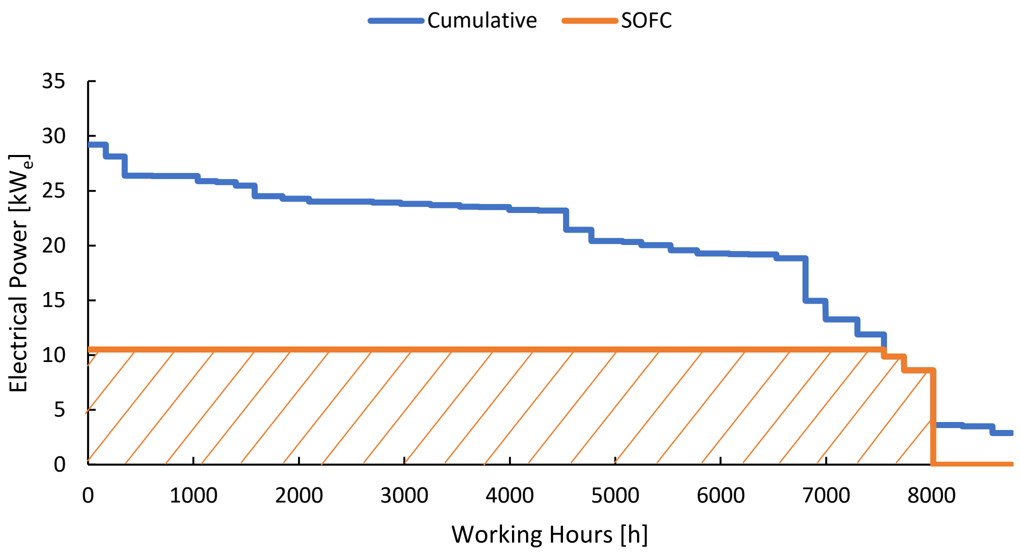
In case of a big swimming pool building, a certain amount of thermal power is always required to maintain the water temperature; so, the pools can be used as a thermal storage. For this reason, in the Vinovo's pool, all the thermal energy is useful for the sanitary hot water production.
Therefore, the sizing of the system can be based on the electrical power. Starting from the electrical consumption, divided in the three different time slots (F1, F2 and F3), it is possible to evaluate the mean hourly electrical power need for each month. Reordering this data, a cumulative curve is found, useful to estimate an appropriate size for the SOFC.

FIGURE 19: VINOVO'S POOL ELECTRICAL POWER CUMULATIVE



The electrical power curve is quite flat for more than 6,000 hours per year, so it is very attractive for a CHP application. A reasonable electrical power for a SOFC system is around 10 kW, because it guarantees a high electricity production, a high self-consumption and a continuous operation during the year. To reach this power, an assembly of 7 BLUEgen® is necessary, with a total electrical power of 10.5 kW.
Figure 20 shows the electrical power cumulative curve of the SOFC system.

FIGURE 20: SOFC ELECTRICAL POWER SIZING



The system works for 8016 hours, the total hours coming out considering that the pool is closed in
August. The electrical power is constant for 94% of the machine working time, and the maximum reduction required is of 2 kW. Even if it would not be possible to achieve this regulation, a small portion of electricity can be exported toward the grid; obviously, this fraction must be extremely small and possibly zero.
If all the electricity is self-consumed, the SOFC would produce 48% of the needed energy, whilst the rest would be covered by the national grid. The main quantities related to the SOFC microCHP installation are shown in Table 17.

TABLE 17: 10.5 KW SOFC MICROCHP PRODUCTION CALCULATIONS

	Constant Load	With Regulation
Working Hours [h]	8,016	
Nominal Hours wrt to total [%]	100%	94.2%
Utilization Factor [%]	92.0%	
Electricity Production [kWh]	84,168	83,525
Exported Electricity [%]	0.8%	0.0%
Maximum El. Production [kWh]	91,980	
Ratio El.Prod./Max El.Prod. [%]	91.5%	90.8%
Electrical Demand Covered [%]	48%	

It is evident that the difference between the two cases is very small, because the electrical power of the utility is quite constant during the year. The ratio between the working hours and the total hours of a year is high (92%), but not the maximum that this type of system could have. Indeed, the ratio between the electricity production and the maximum possible electricity production underlines that around the 10% of production is lost because of the pool's closing period.

The zone with electrical power lower than 5 kW is related entirely to the August closing period of the pool; the choice is to turn off the system during this month, but, being a modular system, it can also be possible to run two or three BLUEgen® for the entire year. Starting from the cumulative, the choice of the electrical power can be very wide. Eventually, with this shape, a power up to 19.5 kW is possible, increasing a lot the self-consumption but increasing also the probability of system oversize, the electricity export and the necessity of power regulation. So, it is preferred a more prudent electrical power for this study.

Table 18 shows the results for a 19.5 kW machine, to show the differences with respect to a smaller electrical power.

TABLE 18: 19.5 KW SOFC MICROCHP PRODUCTION CALCULATIONS

	Constant Load	**With Regulation**
Working Hours [h]	8,016	
Nominal Hours wrt to total [%]	100%	72.1%
Utilization Factor [%]	92.0%	
Electricity Production [kWh]	156,312	146,397
Exported Electricity [%]	6.3%	0.0%
Maximum El. Production [kWh]	170,820	
Ratio El.Prod./Max El.Prod. [%]	91.5%	85.7%
Electrical Demand Covered [%]	84%	

If the system is run at constant load, the 6.3% of the production is exported toward the national grid. Instead, if the choice is to regulate the machine, for approximately 30% of the time the SOFC would work at partial load. This is negative because this machine cannot follow the power load instant by instant. In conclusion, it is possible to install a greater power than the one considered, but for the aim of the study only the case with 7 BLUEgen® is considered.

5.3 TerMus® Model: Structural Components

5.3.1 Opaque components

The opaque components of the building have been taken from the TerMus® structural archive. Seen the purpose of the study, the structural part is considered in a more simplified way with respect to the technical part.

All structural components layers are described in terms of:

- Layer thickness (*s*), in [mm];
- Layer thermal conductivity (*λ*), in [W/mK];
- Thermal conductance (*C*), in [W/m²K];
- Superficial mass (*MS*), in [kg/m²];
- Vapour permeability (*P*), in [kg/msPa];
- Specific heat (*CS*), in [J/kgK];
- Thermal resistance (*R*), in [m²K/W];

The most important components are:

- External walls: they are of the type perforated bricks masonry with empty case (*Muratura a cassa vuota in laterizio forato*) with the following characteristics.

FIGURE 21: EXTERNAL WALLS STRATIGRAPHY, ON THE LEFT THE STRUCTURE LAYERS, ON THE RIGHT THE PRESSURE DIAGRAM

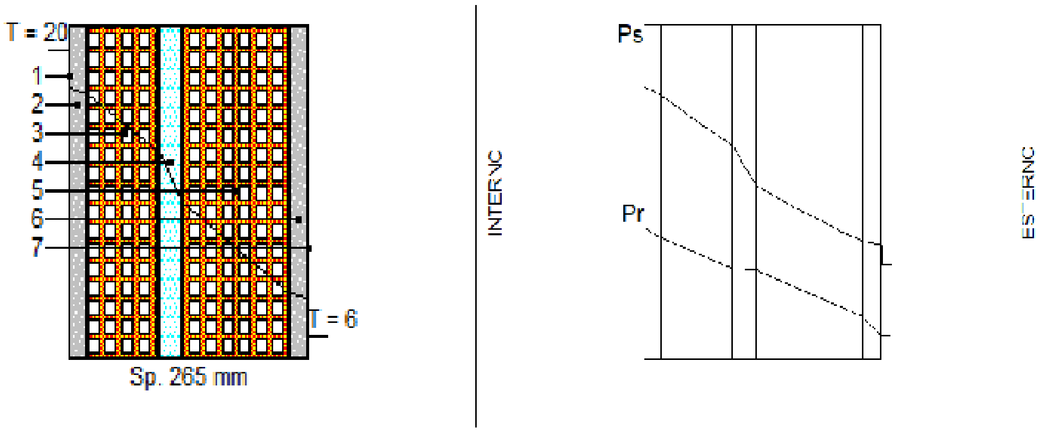


TABLE 19: EXTERNAL WALLS LAYERS SPECIFICATIONS

N.	Layer Description	s [mm]	λ [W/mK]	C [W/m²K]	MS [kg/m²]	P<50*10¹² [kg/msPa]	CS [J/kgK]	R [m²K/W]
1	Internal Resistance	0	-	7.7	-	-	0	0.13
2	Internal Plaster	20	0.7	35	28	18	1000	0.029

3	Perforated Bricks	80	-	5	64	20.57	1000	0.2
4	Air Gap	25	0.14	5.6	0.03	193	1008	0.179
5	Perforated Bricks	120	-	3.226	96	20.57	1000	0.31
6	External Plaster	20	0.9	45	36	8.5	1000	0.022
7	External Resistance	0	-	7.7	-	-	0	0.13

TABLE 20: EXTERNAL WALLS PROPERTIES

Total Thickness	[mm]	265
Total Resistance	[m^2K/W]	0.999
Transmittance	[W/m^2K]	1.001
Thermal Capacity per unit of surface	[kJ/m^2K]	56.636
Superficial Mass	[kg/m^2]	160
Periodic Thermal Transmittance	[W/m^2K]	0.43
Attenuation Factor	-	0.43
Phase Displacement	[h]	8.32

– Internal walls: they are important because the model takes into account different temperatures depending on the type of room, so there can be exchanges between internal rooms. They are of the type concrete block lightened by a hole (*Blocco in calcestruzzo alleggerito da un foro*).

FIGURE 22: INTERNAL WALLS STRATIGRAPHY, ON THE LEFT THE STRUCTURE LAYERS, ON THE RIGHT THE PRESSURE DIAGRAM

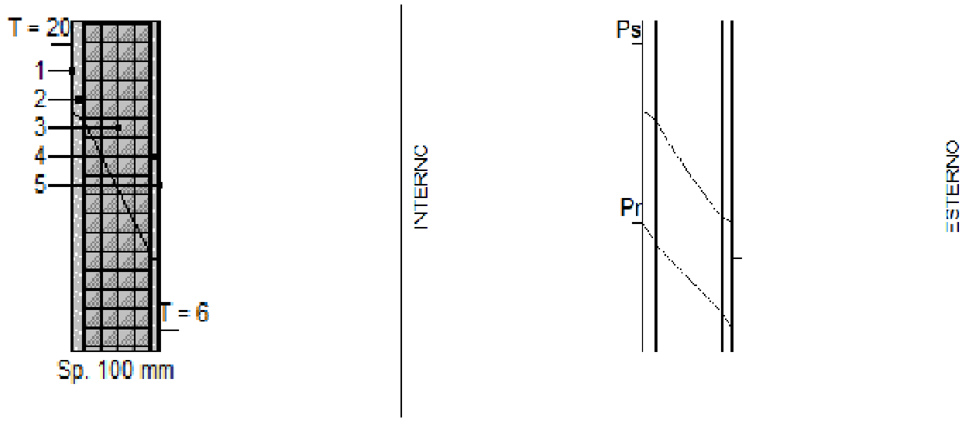


TABLE 21: INTERNAL WALLS LAYERS SPECIFICATIONS

N.	Layer Description	s [mm]	λ [W/mK]	C [W/m^2K]	MS [kg/m^2]	P<50*10^{12} [kg/msPa]	CS [J/kgK]	R [m^2K/W]
1	Internal Resistance	0	-	7.7	-	-	0	0.13
2	Plaster	15	0.7	46.667	21	18	1000	0.021
3	Lightened Concrete Block	75	-	3.846	48	28.8	1000	0.26
4	Plaster	10	0.7	70	14	18	1000	0.014
5	External Resistance	0	-	7.7	-	-	0	0.13

TABLE 22: INTERNAL WALLS PROPERTIES

Total Thickness	[mm]	100
Total Resistance	[m^2K/W]	0.555
Transmittance	[W/m^2K]	1.8
Thermal Capacity per unit of surface	[kJ/m^2K]	38.638
Superficial Mass	[kg/m^2]	48
Periodic Thermal Transmittance	[W/m^2K]	1.61
Attenuation Factor	-	0.89
Phase Displacement	[h]	2.6

– Roof and floor covering: it is of the type collaborating blocks masonry (*Laterocemento-blocchi collaboranti*).

FIGURE 23: ROOF COVERING STRATIGRAPHY, ON THE LEFT THE STRUCTURE LAYERS, ON THE RIGHT THE PRESSURE DIAGRAM

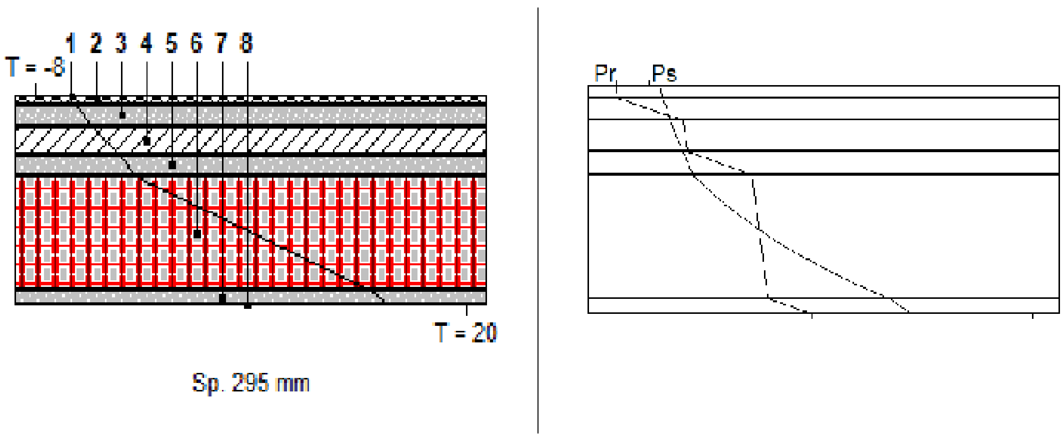


TABLE 23: ROOF COVERING SPECIFICATIONS

N.	Layer Description	s [mm]	λ [W/mK]	C [W/m²K]	MS [kg/m²]	P<50*10¹² [kg/msPa]	CS [J/kgK]	R [m²K/W]
1	Internal Resistance	0	-	25	-	-	0	0.04
2	Internal Floor	15	1.47	98	25.5	193	1000	0.01
3	Cement Mortar	30	1.4	46.667	60	8.5	1000	0.021
4	Lightened Concrete Screed	40	1.16	29	16	193	1000	0.034
5	Cement Mortar	30	1.4	46.667	60	8.5	1000	0.021
6	Brick Block	160	-	3.311	144	193	1000	0.302
7	External Plaster	20	0.9	45	36	8.5	1000	0.022
8	External Resistance	0	-	10	-	-	0	0.1

TABLE 24: ROOF COVERING PROPERTIES

Total Thickness	[mm]	295
Total Resistance	[m²K/W]	0.552
Transmittance	[W/m²K]	1.812
Thermal Capacity per unit of surface	[kJ/m²K]	74.003
Superficial Mass	[kg/m²]	306
Periodic Thermal Transmittance	[W/m²K]	0.96
Attenuation Factor	-	0.53
Phase Displacement	[h]	7.18

5.3.2 Transparent Components

All windows toward the external environments are classified, in order to obtain a heat dispersion as similar as possible to the reality. Inside the building there are thirty-eight different types of windows; for every window, the right parapet and above-window box heights are defined to obtain the same height of the wall.

The following table shows all windows' geometrical data.

TABLE 25: WINDOWS DESCRIPTION

	Width [cm]	Height [cm]	Window Leaves Number	Parapet Height [cm]	Above-window Box Height [cm]	Windows Number	Area [m^2]
1	150	210	2	0	43	5	15.8
2	95	253	1	0	0	1	2.4
3	240	253	3	0	0	1	6.1
4	250	253	3	0	0	2	12.7
5	226	253	3	0	0	1	5.7
6	480	253	6	0	0	1	12.1
7	250	50	4	170	50	2	2.5
8	259	215	4	0	55	1	5.6
9	120	210	2	0	60	1	2.5
10	194	120	2	90	60	4	9.3
11	120	250	2	0	20	1	3.0
12	212	165	2	90	15	8	28.0
13	205	210	2	0	60	1	4.3
14	250	120	4	90	60	14	42.0
15	126	210	2	0	60	1	2.6
16	124	120	1	90	60	1	1.5
17	100	120	1	90	60	3	3.6
18	150	253	2	0	17	1	3.8
19	90	210	1	0	60	3	5.7
20	180	120	3	90	60	1	2.2
21	200	120	3	90	60	1	2.4
22	123	210	1	0	60	1	2.6
23	370	167	4	110	23	4	24.7
24	560	278	6	22	0	6	93.4
25	250	136	4	90	44	3	10.2
26	280	140	4	90	40	1	3.9
27	220	110	4	90	70	2	4.8
28	150	228	2	0	42	1	3.4
29	132	214	2	0	56	1	2.8
30	245	120	4	90	30	1	2.9
31	260	120	4	90	30	2	6.2
32	280	120	4	90	30	1	3.4
33	120	140	2	90	10	1	1.7
34	100	140	2	90	10	2	2.8
35	225	200	4	0	40	2	9.0
36	212	80	4	194	0	3	5.1

37	200	80	4	194	0	1	1.6
38	194	80	4	194	0	3	4.7

The total window area is 357 m^2. Because of the high number of windows, to simplify the model, the dispersion parameters are following, the same for each window.
The glass is double with an air gap of 8 mm and metal spacers. The transmittance is calculated automatically by TerMus® following the Italian regulation.
The frame is made of metal with thermal cut, with a transmittance of 2.8 W/m^{2}K.
The parapet and the above-window box are made with the same materials of the external walls.

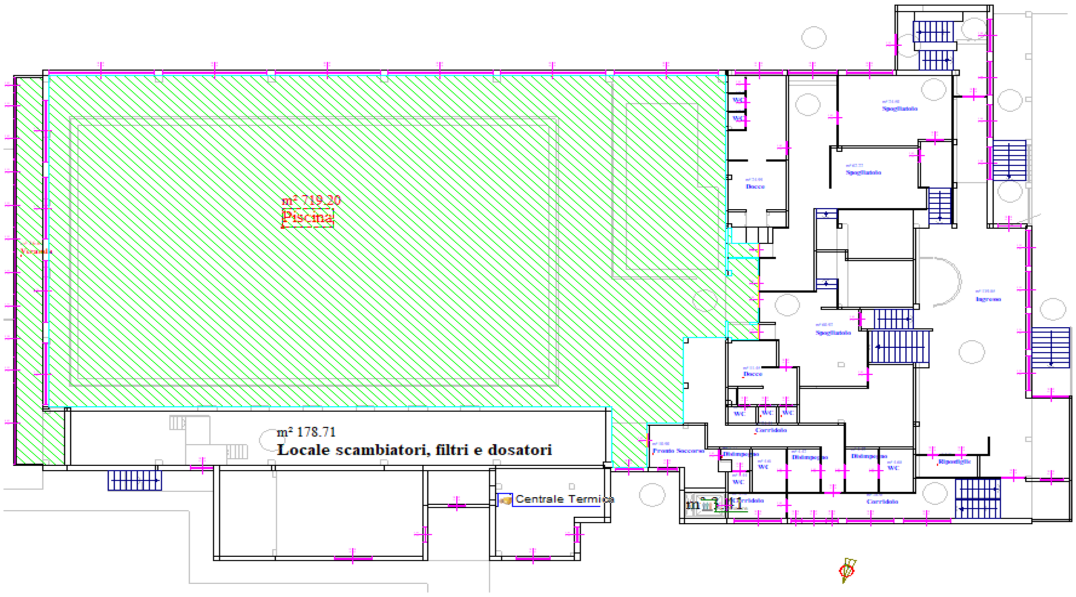
5.4 TerMus® Model: Zones

The regulation considers a zone as a room or a set of rooms with the same thermo-hygrometric characteristics. For this reason, the swimming pool room is certainly separated from the rest of the building; furthermore, the bathrooms must be considered as a separated zone, as well as the locker rooms with showers. All other rooms, instead, are counted as a single zone.
To identify the zones, it is used the plan of the building: from the Autocad file, the drawing is recreated on TerMus®, adding all building components and assigning each closed space to a zone.
The model counts five zones:

z1) Swimming Pool

The pools room has a surface of 756 m^2 and occupies a big part of the building. The room has a height of 6.64 meters, with a total of 10 big windows on North and West sides. On the West side, there is a small veranda with a limited height.
Figure 24 below shows the TerMus® view of the swimming pool zone. A larger figure is reported in APPENDIX A.

FIGURE 24: VINOVO'S POOL GROUND FLOOR, SWIMMING POOL ZONE



This zone has the following characteristics, all implemented inside the software for the calculations:

1.1 The intended use of the zone belongs to class E6(1), "Swimming pools, saunas and similar", of Italian regulation.

1.2 The internal project temperature is 28°C during the entire year.

1.3 The ventilation service is given by UTA 1, with the specifications given by Table 26:

TABLE 26: SWIMMING POOL ZONE VENTILATION SPECIFICATIONS

Ventilation	
Air Exchanges [Vol/h]	9
Correction factor	0.34
Correction factor for mixed plants	1
Ventilation efficiency	0.8

1.4 The hot water demand of this zone causes a big energy consumption. This is related to the fact that the exchanged water must be heated up from the aqueduct temperature to the pool temperature, that is 28 °C. The second energy loss is related to the evaporation from the pools.

With all these contributions it is possible to evaluate the amount of hot water (at 28°C) necessary for this zone, starting from the water exchanges and the evaporation, as shown in Table 27.

TABLE 27: SWIMMING POOL ZONE HOT WATER DEMANDS

Hot Water	Volume [m^3]	Water exchange [m^3/d]	Water exchange [l/d]	Total daily hot water demand [l/d]
Swimming Pool	525	36.9	36,900	38,925
Small Pool	12	0.9	900	
Evaporation	-	1.1	1,125	

The assumption is that this value remains constant during the year, excluding the closing days of Vinovo's Pool. Obviously, it is an approximation of the real consumption, but it is the only way to implement the hot water demand on TerMus®.

1.5 The lighting power installed in this zone is 4.16 kW, from the electric model described in the previous section.
1.6 All other parameters are automatically obtained by the software from the regulation or evaluated starting from the project.

z2) Other zone

The total surface of all rooms belonging to this category is 1242 m^2. The rooms considered are the entrance, locker rooms without showers, corridors, closets, warehouses, the canteen, the kitchen, bedrooms and the gym. Even if they are very different, all these rooms share the air-conditioning system and have the same heating and ventilation specifications.

The mean height of the zone is 2.61 m. Figure 25, Figure 26 and Figure 27 show the entire building and the rooms under this zone. It is immediately clear that, excluding the pool, most of the building is considered under this category. Larger figures are reported in APPENDIX A.

FIGURE 25: VINOVO'S POOL GROUND FLOOR, OTHER ZONE

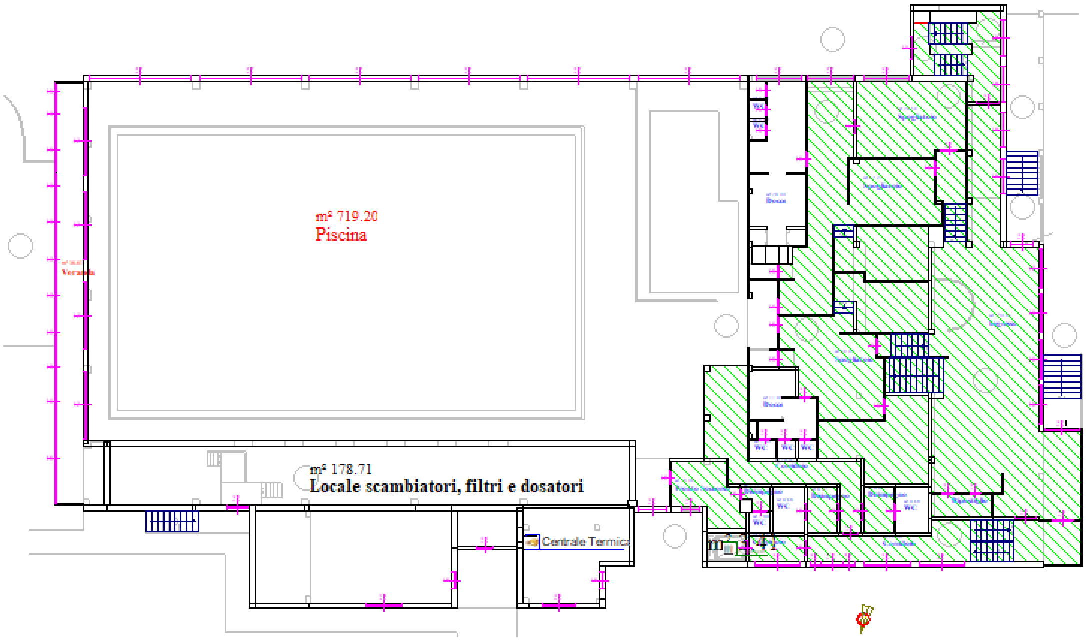


FIGURE 26: VINOVO'S POOL FIRST FLOOR, OTHER ZONE

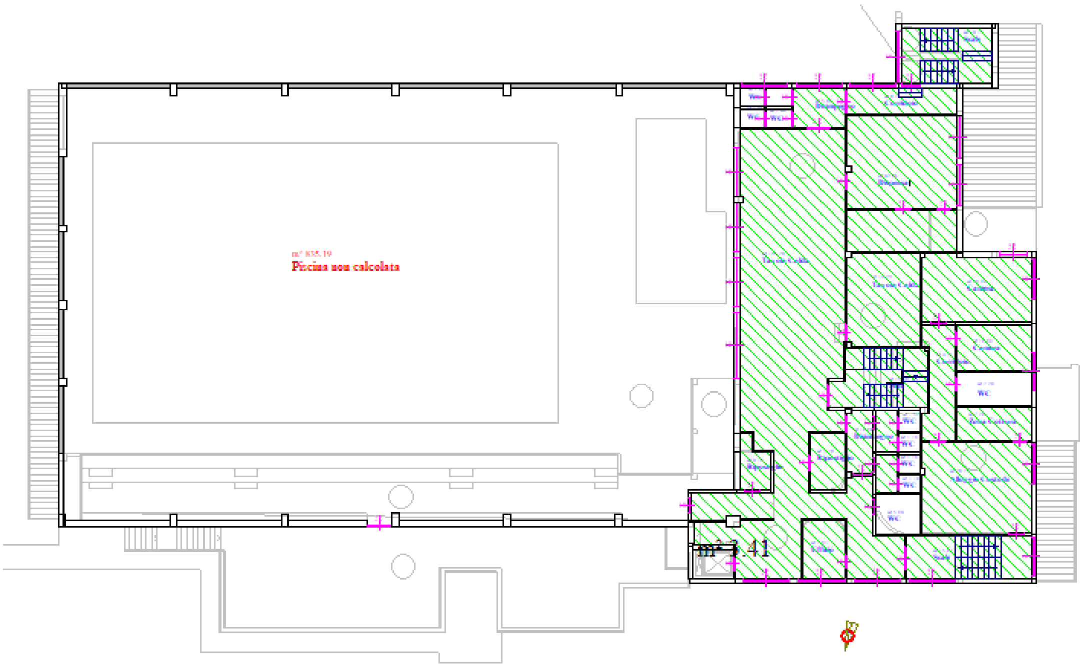
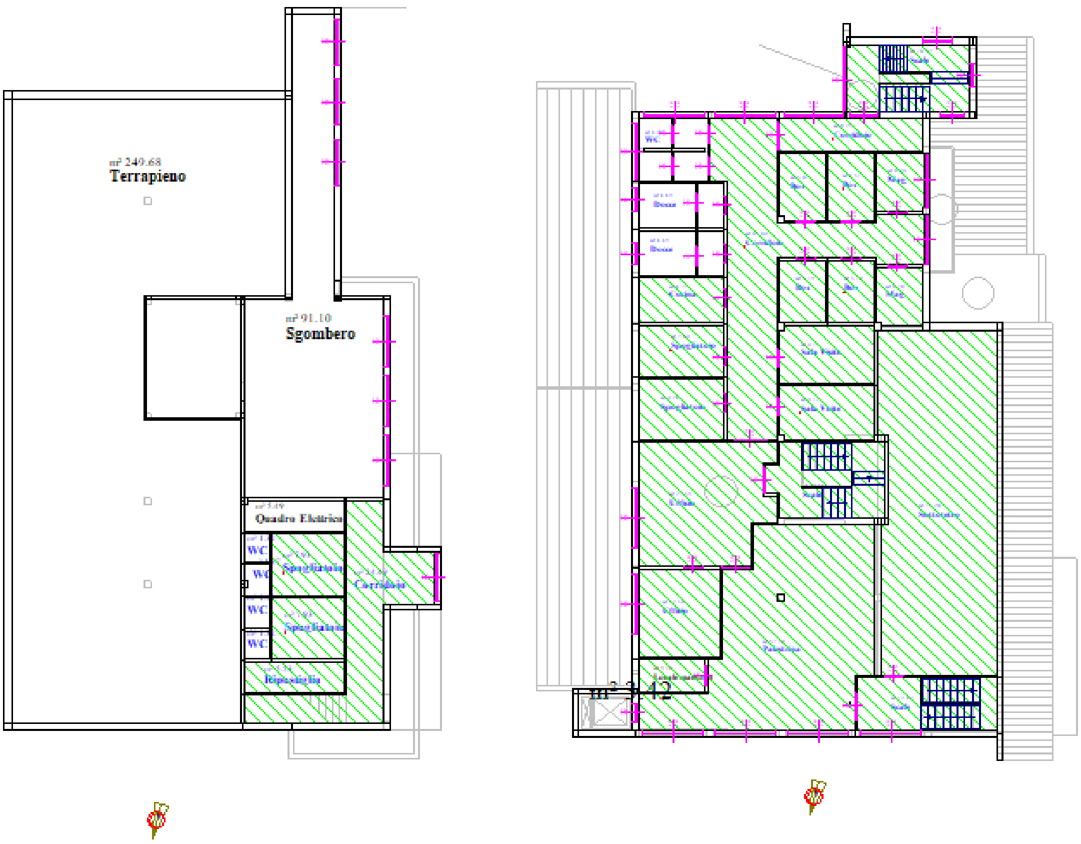


FIGURE 27: VINOVO'S POOL BASEMENT (ON THE LEFT) AND SECOND FLOOR (ON THE RIGHT), OTHER ZONE



This zone has the following characteristics, all implemented inside the software for the calculations:

2.1 The intended use of the zone belongs to class E6(3), "Support services to sport activities", of Italian regulation.

2.2 The internal project temperature is 20°C in winter and 26°C in summer.

2.3 The ventilation service is given by UTA 2 and UTA 3, with the specifications given by Table 28:

TABLE 28: OTHER ZONE VENTILATION SPECIFICATIONS

Ventilation	
Air Exchanges [Vol/h]	0.5
Correction factor	0.6
Correction factor for mixed plants	1
Ventilation efficiency	0.8

2.4 This zone is not considered for the sanitary hot water demand. The entire consumption is divided between the pool and the showers.

2.5 The lighting power installed in this zone is 7.498 kW, from the electric model described in the previous section. Excluding the pool, all lighting is assigned to this zone, to simplify the results display.

2.6 All other parameters are automatically obtained by the software from the regulation or evaluated starting from the project.

z3) Toilets

The total surface of this zone is 51 m^2. It has exactly the same features of the previous zone and shares the same air-conditioning plant. The only difference is related to the ventilation required by the regulation, whose specifications are given by Table 29.

TABLE 29: TOILETS ZONE VENTILATION SPECIFICATIONS

Ventilation	
Air Exchanges [Vol/h]	8
Correction factor	1
Correction factor for mixed plants	1
Ventilation efficiency	0.8

Even if the air exchanges must be very high, the volume is small so the consumption from this zone is almost negligible.

The hot water consumption of the bathrooms zone is considered negligible, compared to that of the showers.

z4) Showers

The total surface of this zone is 50 m^2, because only four locker rooms in the entire building are equipped with showers. The mean height is 2.62 m.

This zone has the same features of "Other zone", except for the ventilation and hot water demand.

4.1 The ventilation service specifications are shown in Table 30.

TABLE 30: SHOWER ZONE VENTILATION SPECIFICATIONS

Ventilation	
Air Exchanges [Vol/h]	8
Correction factor	0.43
Correction factor for mixed plants	1
Ventilation efficiency	0.8

4.2 Regarding the hot water demand for showers, it has been evaluated, in the energy audit by Coesa Srl® company, a daily consumption of 7.5 m^3 per day, equal to 7500 litres per day.

z5) Not calculated zone

The rooms not considered in the calculations are those that are not conditioned by the plant:

4.1 At ground floor, the rooms for heat exchangers, filters and dispensers and the technical rooms for the thermal plant;

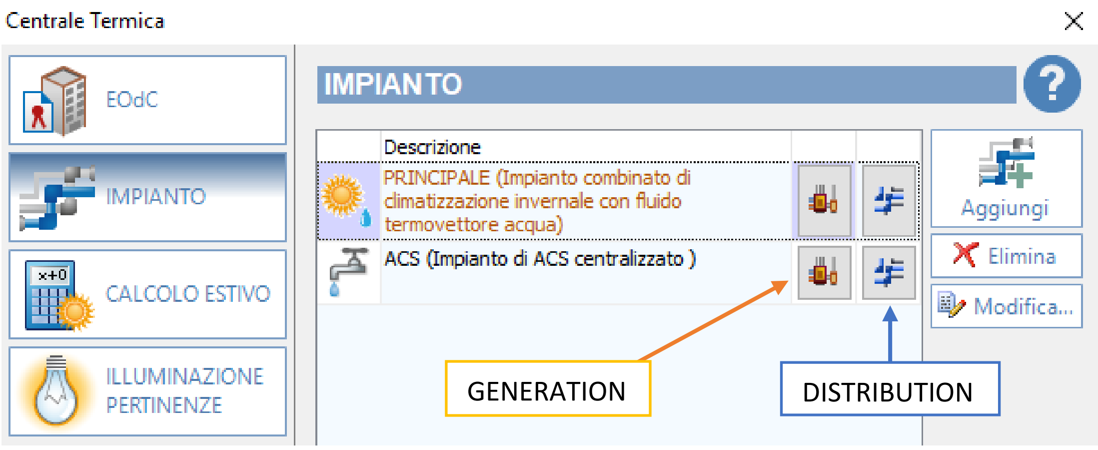
4.2 At underground floor, the electrical cabinet room and the embankment room;

4.3 At second floor, the machinery room.

5.5 TerMus® Model: Thermal Plant

The thermal plant model is divided in two systems: the first one is a combined plant for heating with water as heat transfer fluid (called "*PRINCIPALE*" in Figure 28), whilst the second is a centralized sanitary hot water production plant (called "*ACS*" in Figure 28). Figure 28 shows the TerMus® page of plant initialization.

FIGURE 28: TERMUS PAGE FOR THERMAL PLANT INITIALIZATION



Each system is composed by the generation and the distribution systems.

5.5.1 Generation

For both systems, a 465.2 kW boiler without condensation is considered, fed with natural gas.

Obviously, in the real plant there is only one boiler, but in the model it's necessary to consider two identical boilers. Knowing only the thermal power and the nominal efficiency, it is used by TerMus® a standard method to calculate all specifications of the boiler, following UNI/TS 11300-2, appendix B. Boiler's data are provided in Table 31.

TABLE 31: VINOVO'S POOL EXISTING BOILER SPECIFICATIONS

Nominal Power	[kW]	465.2
Partial Load Power	[kW]	150
Auxiliaries Electricity Consumption at Nominal Condition	[W]	858
Auxiliaries Electricity Consumption at Partial Load Condition	[W]	286
Auxiliaries Electricity Consumption at No Load Condition	[W]	15
Nominal Condition (TEST)		
Efficiency	[%]	89.2
Mean Temperature	[°C]	70
Efficiency Correction factor	[-]	0.04
Partial Load Condition (TEST)		
Efficiency	[%]	87.81
Mean Temperature	[°C]	50
Efficiency Correction factor	[-]	0.05

5.5.2 Heating distribution

The heating distribution starts from the water distribution, whose efficiency is calculated by TerMus® following UNI/TS 11300-2, equal to 0.985. The hot water exchanges heat with the air inside the UTAs, then enters the HVAC system distribution and goes in all zones of the building.

Figure 31 shows the entire system, whilst Table 32 shows the specifications of each system.

FIGURE 29: HEATING DISTRIBUTION BLOCK DIAGRAM

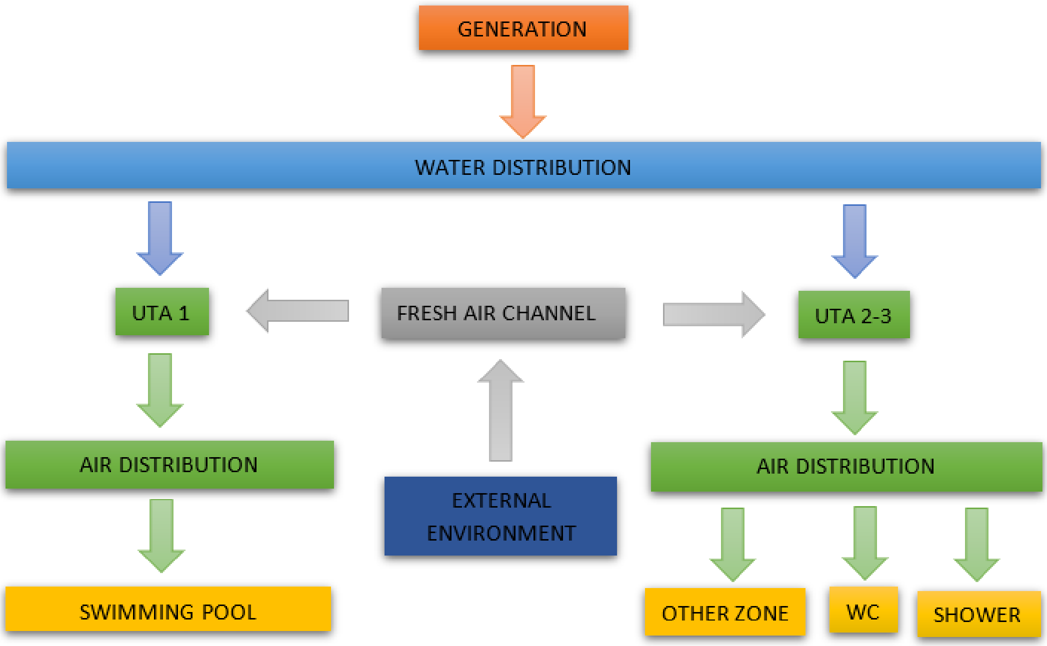


TABLE 32: HEATING DISTRIBUTION SPECIFICATIONS

Water Distribution	
Efficiency (from UNI/TS 11300-2)	0.985
UTA	
Air Extracted wrt Air Entered	100 %
Output Air Temperature	32 °C
Type of Heat Recovery System	Centralized
Heat Recovery Efficiency	0.75
Air Distribution	
Efficiency (from UNI/TS 11300-2)	Calculated
Position	Zone
Swimming Pool	
Ventilation	Mechanical
Air Flow Rate	20,000 m^3/h
Regulation Efficiency	0.6
Other Zone	
Ventilation	Mechanical

Air Flow Rate	13,000 m^3/h
Regulation Efficiency	0.6
TOILETS	
Ventilation	Mechanical
Air Flow Rate	1173 m^3/h
Regulation Efficiency	0.6
Shower	
Ventilation	Mechanical
Air Flow Rate	1129 m^3/h
Regulation Efficiency	0.6

5.5.3 Hot water distribution

This system is very simple to implement on TerMus®, because the software automatically calculates the efficiency depending on the regulation and takes the hot water demands from the hot water consumptions provided in the zone specifications.
The efficiency evaluated is 0.9259.

5.7 TerMus® Model: SOFC microCHP Installation

Fuel Cells are not considered as a real installation possibility by Italian directive, so there is not a model in TerMus® to add all the specification of this machine. With a PEMFC, it would be necessary to insert all data about the regulation of the machine, because this type of Fuel Cells is suitable to regulate. Instead, with a SOFC, the model of the machine can be very simple, at least for the evaluation of the energy performance.
Thanks to its constant functioning, the SOFC belongs to the category "Fractional Contribution Method", from UNI/TS 11300-4, Chapter 2.5, page 28.
The functioning logic is:

- ON STATE when the thermal power required to the SOFC is greater than or equal to its nominal thermal power. It's the same to say that the Load Factor is greater than or equal to one.
- OFF STATE when the thermal power need is smaller than the nominal thermal power of the SOFC.

To adopt this simplified method, it's necessary to control some parameter to see if the Fuel Cell works in good conditions:

1) The thermal power of the SOFC system depend on the temperature of the return water from the distribution system. An essential requirement, added on the TerMus® model, is a constant return temperature, equal to 35 °C.

2) It must be controlled the electricity production of the SOFC, in the results of the model, to be sure that the CHP unit works the entire year without stops. Indeed, with an ON/OFF regulation logic, the risk is that the simulation forces the SOFC to turn on and off often. This is impossible in the reality, so the model would lose validity in this case.

With these precautions, the SOFC microCHP can be modelled with three parameters, shown in Table 33.

TABLE 33: SOFC MICROCHP SPECIFICATIONS FOR TERMUS® MODEL

SOFC microCHP Specifications

Installation Site	Thermal Plant Room	
Type of Fuel	Methane	
Nominal Thermal Power	[kW]	4.2
Nominal Electrical Efficiency	[%]	60
Nominal Thermal Efficiency	[%]	25

TerMus® automatically calculates the electrical power starting from the thermal and electrical efficiency; it is evident the "definition issue" explained in Chapter 4.2, page 45, indeed the electrical power is only considered a secondary product of the thermal power, the only important quantity in the current regulation. With this definition, the electrical power of the SOFC is equal to 10.1 kW instead of 10.5 kW, because of the approximation made in the technical specifications. It has been maintained this power on the TerMus® model because it is the way the regulation sees this machine; it starts from the nominal thermal power and find the electrical power passing through the efficiencies.

The CHP is added to the plant in series with the boiler, only on the sanitary hot water side. All the distribution and emission parts remain the same as the base case.

CHAPTER 6

TerMus® Results

In this Chapter, the results related to the TerMus® models are presented, starting from the Base Case. This model is compared with the real Vinovo's Pool consumptions, to show the differences and the common points. Then, the SOFC Case is described, compared with the Base Case to quantify the convenience of a SOFC microCHP installation.
A further analysis is carried on: different microCHPs with decreasing electrical efficiency are compared from the point of view of the Energy Label of Vinovo's Pool. In the last paragraph, the results related to an Improved Building case are shown, considering the Vinovo's Pool as a new building.

6.1 Base Case Results

After the implementation of all data regarding the building and the thermal plant, it is possible to run the simulation to see how much the model is accurate with respect to the reality. The climatic data of the building are automatically given by the software.

TABLE 34: VINOVO'S WINTER PROJECT DATA

Winter Project Data	
Climatic Zone	E
External Relative Humidity	44.4%
Degree Days	2573
Wind Speed	3.892 m/s

The first results from TerMus® are given in the technical relation of the building. Table 35 shows the final results. Then, a comparison with the real case is performed.

TABLE 35: GENERAL TERMUS® RESULTS

Building		
Gross Volume	m^3	9445.19
Gross Dispersing Surface	m^2	3533.6
Shape Ratio S/V	1/m	0.37
Net Volume	m^3	8041.72
Net Walking Surface	m^2	1970.22
Average Net Height	m	4.08

Total Thermal Capacity	kJ/K	381,760
Heating Season	-	From 15/10 To 15/04
Heating		
Useful Thermal Energy Demand	kWh	353,337
Primary Energy Demand	kWh	853,373
Auxiliary Electricity Demand	kWh	53,900
Sanitary Hot Water		
Thermal Energy Demand	kWh	302,578
Primary Energy Demand	kWh	435,607
Auxiliary Electricity Demand	kWh	21,325
Energy Performance		
Useful Thermal Energy Performance Index	kWh/m^2	170.8
Heating Energy Performance Index	kWh/m^2	433.1
Hot Water Energy Performance Index	kWh/m^2	221.1
Energy Label	-	C

The Energy Label of the building comes out to be C. This is not related to the fact that the building has good thermal performances, but it's due to the presence of lighting and ventilation. These two services, in the Vinovo's Pool, consume a lot of electricity increasing a lot the global primary energy demand. The presence of a big electrical consumption determines an enlargement of the distance between the Energy Labels, because their definition does not distinguish between heat and electricity (see Chapter 2.7 Energy Label Definition). This has an impact on the reference building consumption, on which the Energy Label evaluation is based; the consequence is that all energy classes are flattened.

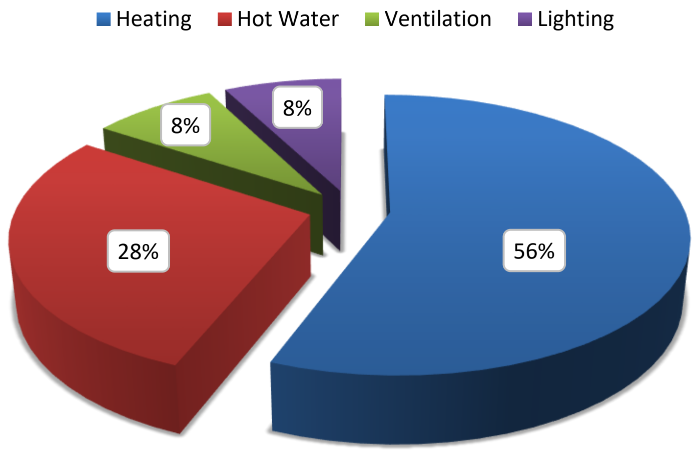
Indeed, the energy performance of the building, both from the structural and technical point of view, is very bad.

Table 36 and Figure 30 show how the total primary energy is divided between the single services.

TABLE 36: PRIMARY ENERGY CONSUMPTION BY SERVICE, TERMUS® MODEL

Service	Primary Energy [kWh]
Heating	878,618
Hot Water	445,630
Ventilation	126,847
Lighting	119,265
TOTAL	1,570,360

FIGURE 30: PRIMARY ENERGY CONSUMPTION SHARE BY SERVICE, TERMUS MODEL



It is important to underline that the primary energy consumption is the result of the conversion of both natural gas and electricity consumptions.
The NG consumption resulting from the simulation is:

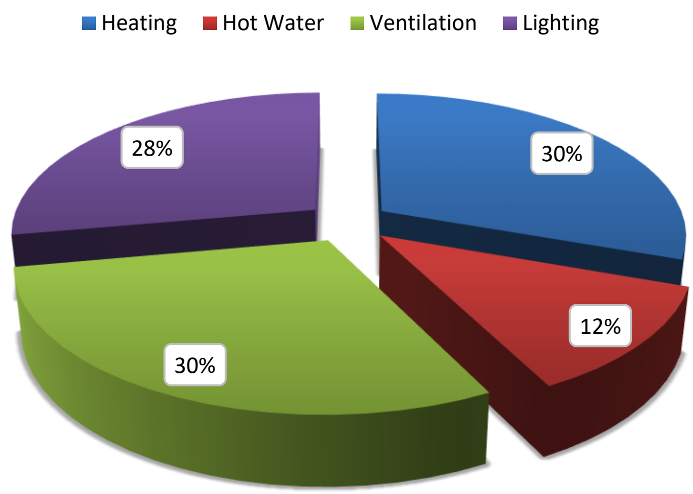
- 75,403 Sm^3 for heating. This value is larger of 7.6% with respect to the real one because the regulation considers standard degree days and does not take into account the pool closing days. A more detailed analysis is performed in this Chapter.
- 39,710 Sm^3 for sanitary hot water production. The choice for the simulation is to have this consumption as similar as possible to reality in order to have good conditions for the CHP installation.

The electricity consumption shares are shown by the following table and cake diagram.

TABLE 37: ELECTRICITY CONSUMPTION BY SERVICE, TERMUS® MODEL

Service	Electricity [kWh]
Heating	53,900
Hot Water	21,326
Ventilation	52,416
Lighting	49,283
TOTAL	176,925

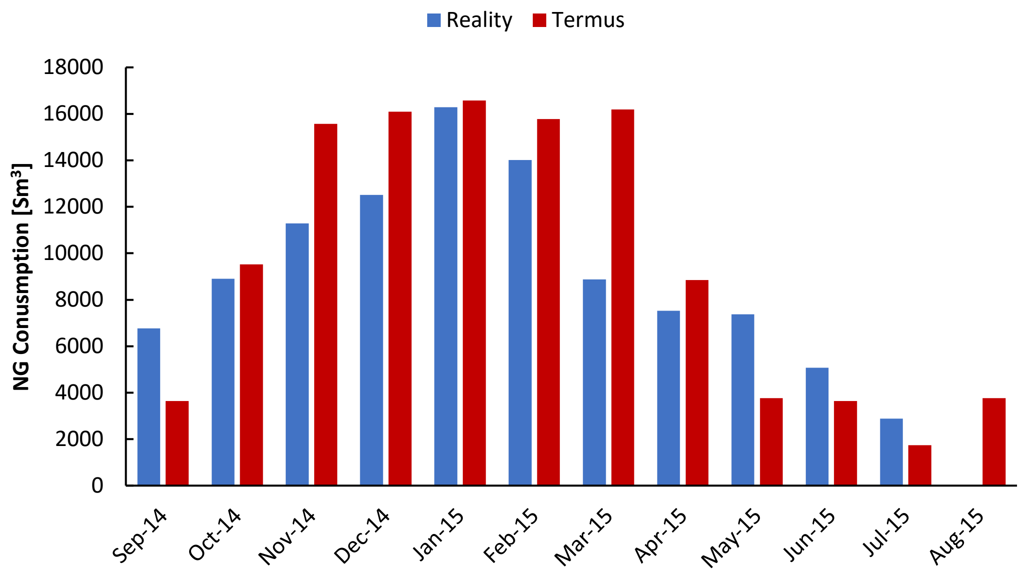
FIGURE 31: ELECTRICITY CONSUMPTION SHARE BY SERVICE, TERMUS MODEL



The total electricity consumption is very similar to the real value (only 0.7% less), even if the electrical power used in the building model is lower with respect to the real power. The approximation of the electrical part is evident: only four types of load are considered, and it's very complicated to understand how the final value is calculated.
The consumptions calculated by TerMus® are much more constant during the year, so a smaller power gives the same value of total consumption; for example, the TerMus® model does not take into account differences between working days and holidays, because it is not possible to insert such differences in the software.

To compare in a more accurate way the natural gas consumption, the monthly values from the simulation results can be used, as shown in Figure 32.

FIGURE 32: MONTHLY NG CONSUMPTION COMPARISON BETWEEN REALITY AND TERMUS MODEL



In general, it is possible to say that the model is a good approximation of the reality. The most important differences are:

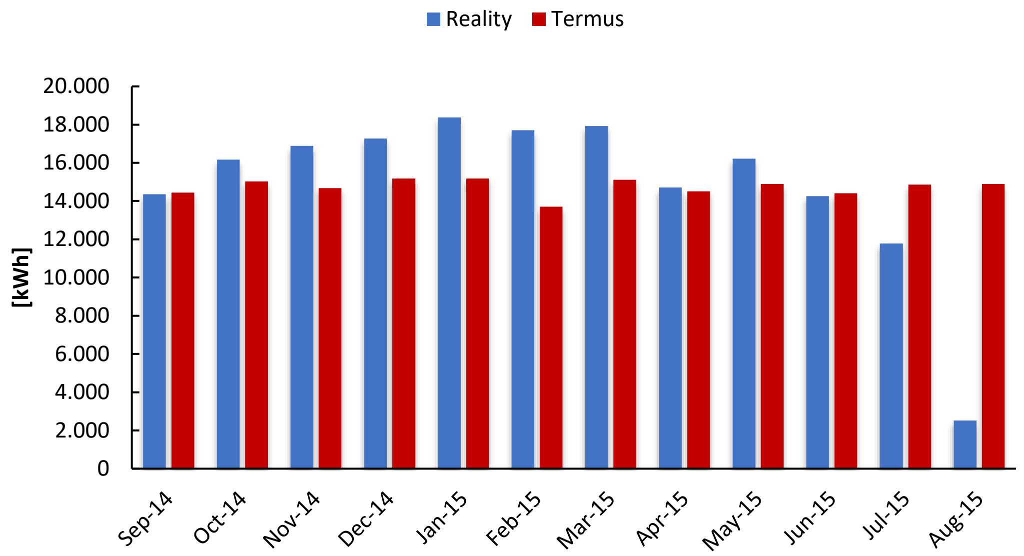
- In winter, the model consumption for heating is quite higher, especially in November and March. This is caused by the difference between the standard Degree Days and the real ones.
- The model total consumption during the months not considered in the heating season is a bit lower with respect to reality. Indeed, being in the E climatic zone, it is also possible to have cold weeks during September and May, that causes an increase of the real values for pre-heating of air and hot water consumption.
- The model considers a hot water demand in August, whilst the real consumption is negligible.
- Considering also the Degree Days, it is possible to show how much the model is far from reality (Table 38: NG consumption comparison considering the degree days).

TABLE 38: NG CONSUMPTION COMPARISON CONSIDERING THE DEGREE DAYS

	TerMus® Model	**Real Case**
NG [Sm^3]	115110	101479
Degree Days [DD]	2573	2440
Specific Consumption [Sm^3/DD]	44.7	41.6
Difference [%]	7.6	

Also for electricity, it's shown a monthly comparison in Figure 33.

FIGURE 33: MONTHLY ELECTRICITY CONSUMPTION COMPARISON BETWEEN REALITY AND TERMUS MODEL

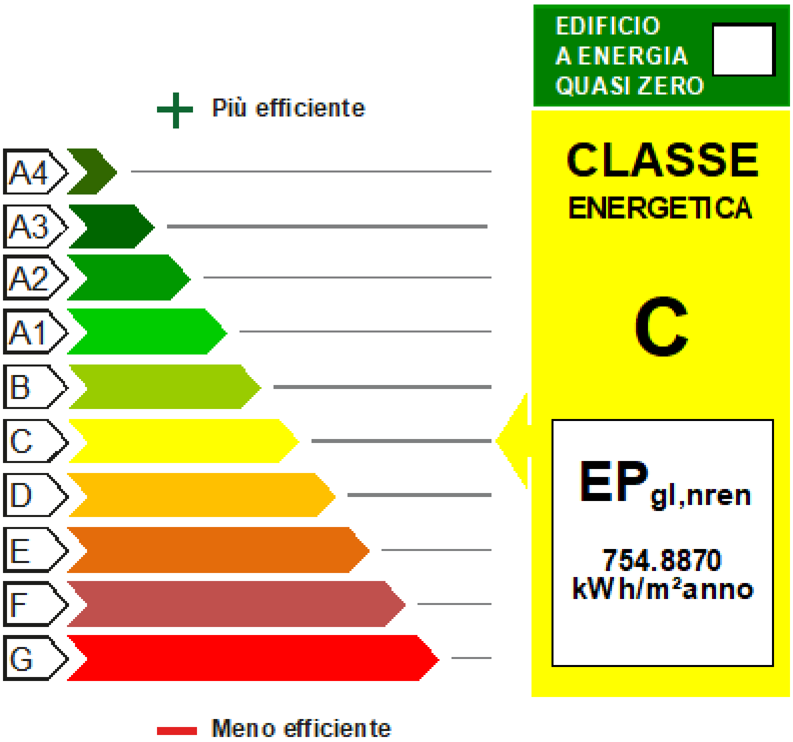


The model gives a good approximation of the electricity consumption almost for the entire year. The general shape of the model is more constant during the year with respect to reality. The most important differences are:

- In winter, the electrical consumption of the model is lower than the real one. This is negative because the model does not follow the same shape of the real electrical demand, that has a slight increase in winter.
- In summer, the software considers a higher consumption with respect to the reality. This is caused by the ventilation contribution, that is maximum in the warmest months.
- In August, the software does not take into account the pool closing period.

The final Energy Label of the model is C, with a value of $EP_{gl,nren}$ of 754.887 kWh/m^2 per year.

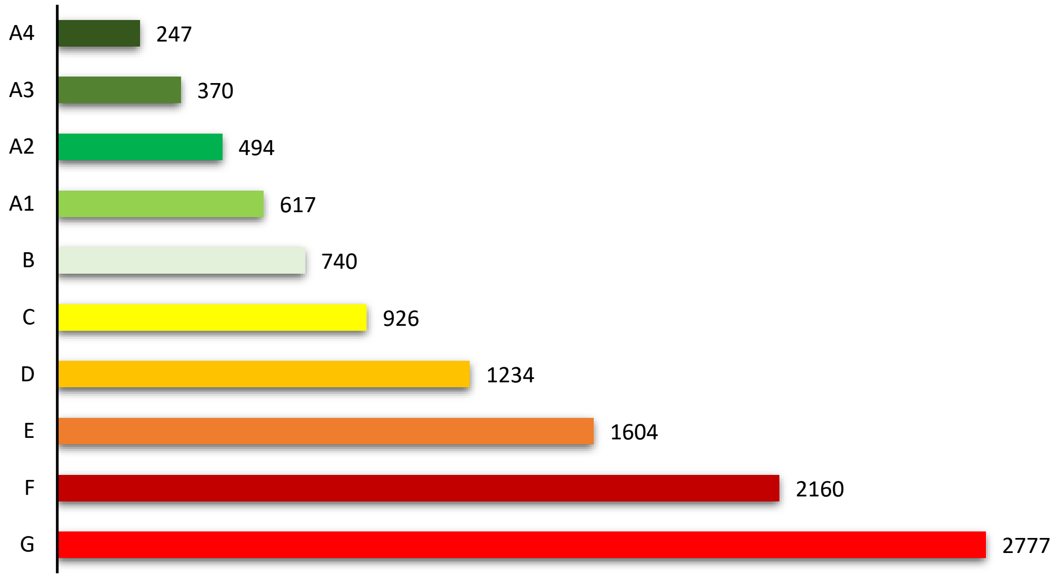
FIGURE 34: VINOVO'S POOL ENERGY LABEL



The specific consumption value is very high, even if the energy class is not so low as it could be expected. This is related to the class calculation method, that does not distinguish the electrical and thermal part, bringing to enlarge the classes when the lighting and the auxiliaries are added because of the highest value of primary energy consumption. The reference building, whose specific consumption determines the Energy Label classification, is good from the thermal point of view but presents some problem on the electrical part. For example, it does not distinguish between different types of lightnings, bringing to flattening a lot the energy classes when all the electrical consumptions are considered in the real building.

Figure 35 shows the ranges of each energy class, starting from the standard building's $EP_{gl,nren}$, equal to 617.04 kWh/m^2 per year. The numbers on the right side of the bars represent the lower boundary of the corresponding energy class; indeed, the Energy Label of the Base Case is C, because its value of $EP_{gl,nren}$ is between 926 kWh/m^2 and 740 kWh/m^2.

FIGURE 35: ENERGY CLASSES SUBDIVISION



To reach a low energy class, like E or F, it would be necessary to have a huge consumption, surely unsustainable for the utility. This is an example of energy class enlarging because of the presence of all electrical consumptions.

The global energy performance factor comes from the single factors for each service of the building. Table 39 shows all the Energy Performance factors, renewable, non-renewable and total. Because of the renewable share of the electricity from the national grid, the renewable *EP*s are not zero. The global renewable share is anyway very small, around 5%.

TABLE 39: ENERGY PERFORMANCE FACTORS FOR EACH SERVICE

	Heating	
$EP_{h,ren}$	kWh/m^{2}year	12.9
$EP_{h,nren}$	kWh/m^{2}year	433.1
EP_{h}	kWh/m^{2}year	445.9
	Sanitary Hot Water	
$EP_{w,ren}$	kWh/m^{2}year	5.1

$EP_{w,nren}$	kWh/m²year	221.1
EP_{w}	kWh/m²year	226.2
Ventilation		
$EP_{v,ren}$	kWh/m²year	12.5
$EP_{v,nren}$	kWh/m²year	51.9
EP_{v}	kWh/m²year	64.4
Lighting		
$EP_{l,ren}$	kWh/m²year	11.8
$EP_{l,nren}$	kWh/m²year	48.8
EP_{l}	kWh/m²year	60.5
Global		
$EP_{gl,r}$	kWh/m²year	42.2
$EP_{gl,nr}$	kWh/m²year	754.8
$EP_{gl,tot}$	kWh/m²year	797.0

6.2 SOFC Case Results

To show the changes from the base case to this one, all results are compared with those from the previous Chapter. The outcome expected is that there is an increase on the natural gas need for sanitary hot water production, while all the electricity demands are decreased.

Table 40 shows the general results.

TABLE 40: GENERAL TERMUS® RESULTS WITH SOFC MICROCHP

		Base Case	***SOFC Case***
Heating			
Useful Thermal Energy Demand	kWh	353,337	353,337
Primary Energy Demand (nren)	kWh	853,373	836,837
Auxiliary Electricity Demand	kWh	53,900	53,900
Sanitary Hot Water			
Thermal Energy Demand	kWh	302,578	302,578
Primary Energy Demand (nren)	kWh	435,607	393,803
Auxiliary Electricity Demand	kWh	21,325	21,259
Energy Performance			
Useful Thermal Energy Performance Index	kWh/m²	170.8	170.8
Heating Energy Performance Index	kWh/m²	433.1	424.7

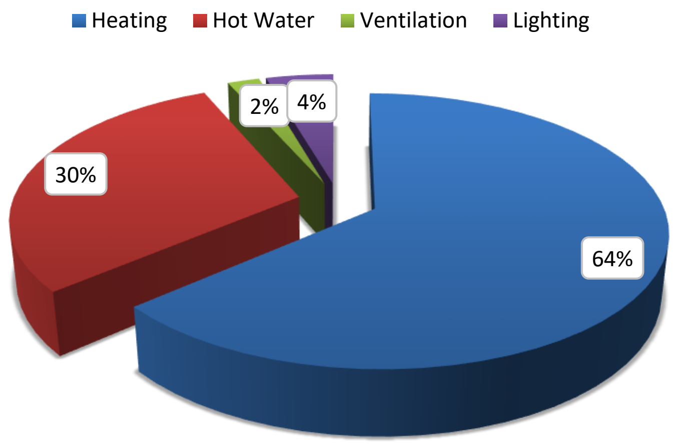
Hot Water Energy Performance Index	kWh/m^2	221.1	199.9
Energy Label	-	C	B

Thanks to the installation of the SOFC microCHP, the energy class is improved from C to B. This is related to the reduction of the primary energy need of the building.

TABLE 41: PRIMARY ENERGY CONSUMPTION COMPARISON, BETWEEN BASE CASE AND SOFC CASE

	Base Case	***SOFC Case***	
Service	Primary Energy [kWh]		Difference
Heating	878,618	848,746	-3.4%
Hot Water	445,630	396,396	-11.0%
Ventilation	126,847	28,157	-77.8%
Lighting	119,265	59,522	-50.1%
TOTAL	1,570,360	1,332,821	-15.1%

FIGURE 36: PRIMARY ENERGY SHARE BY SERVICE, SOFC TERMUS MODEL



With respect to the base case, an important primary energy reduction is obtained (-15.1%). This reduction is particularly great in the electric services, ventilation and lighting, as shown in Table 41. Previously, the share for these two services was 8% each, now it's 2% for ventilation and 4% for lighting (Figure 36).
To give a clear idea of the new consumptions, Table 42 shows the natural gas and electricity demands.

TABLE 42: NG AND ELECTRICITY CONSUMPTIONS COMPARISON, BETWEEN BASE CASE AND SOFC CASE

	Base Case	***SOFC Case***	***Difference***
	NG [Sm3]		
Heating	75,403	75,403	0.0%
Hot Water	39,710	50,446	+27.0%
TOTAL	115,113	125,849	+9.3%
	Electricity [kWh]		
Heating	53,900	42,080	-21.9%
Hot Water	21,326	5,518	-74.1%
Ventilation	52,416	28,157	-46.3%
Lighting	49,283	12,869	-73.9%
TOTAL	176,925	88,624	-49.9%

The total electricity demand from the grid decreases of 50% with respect to the base case. This is mainly related to the electricity production of the SOFC, but a small portion is due to the fact that, for the sanitary hot water production, the auxiliary electricity necessary for the boiler is reduced thanks to the thermal energy of the CHP unit. As expected, the NG consumption has a slight increase due to the SOFC contribution.
The specifications of the electricity produced by the SOFC microCHP are the following:

TABLE 43: SOFC MICROCHP ENERGY PRODUCTION, SOFC TERMUS® MODEL

SOFC production		
Electricity Produced	[kWh]	88,301
Thermal Energy Produced	[kWh]	36,792
Working Hours	[h]	8760
Electricity Export	[kWh]	18,400
Self-Consumption	[%]	79%

Table 43 shows two very important results. The first one is that TerMus® makes the SOFC work for the entire year without stops, confirming that the thermal load of Vinovo's Pool is always greater than the nominal thermal power of the Fuel Cell. The second one is the self-consumption: this is quite different from the self-consumption expected looking at the electrical power cumulative.
This is a case in which an error on the primary energy need calculation is committed, because a greater percentage of electricity is exported with respect to the real case, see Chapter 4.4, page 49. The difference between the conversion factors determines a slight

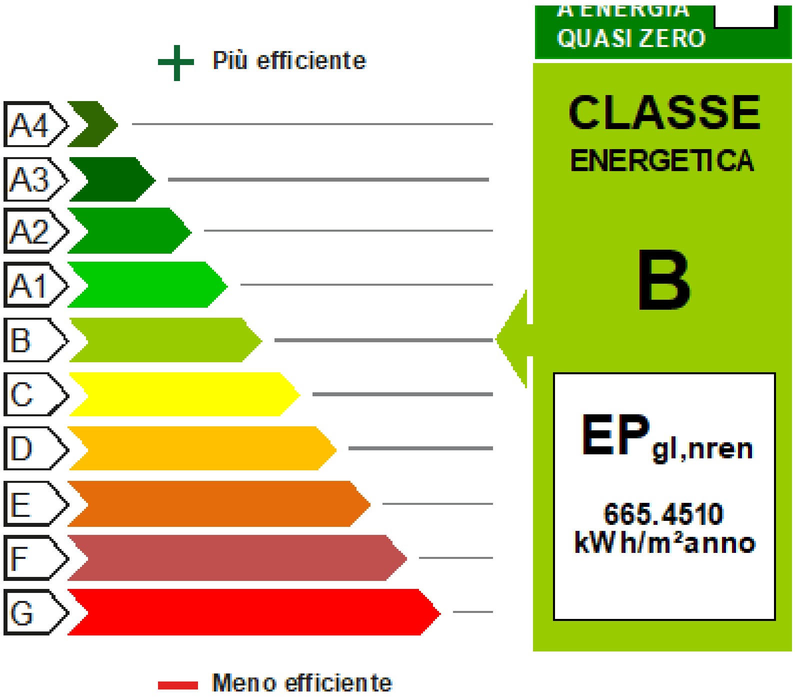
increase of the primary energy, a contribution that would not be present if the self-consumption was 99%, as it is in the real building with this electrical power.
The hypothetical primary energy added to the final value is:

$$\Delta E = \left(f_{P,nren,GRID} - f_{P,nren,SOFC}\right) \times W = \\ = (1.95 - 1.469) \times 18{,}400 = 8{,}850\ [kWh] \qquad (25)$$

Where:
$f_{P,nren,GRID}$ is the non-renewable grid conversion factor of electricity, equal to 1.95 (see Table 4).
$f_{P,nren,SOFC}$ is the non-renewable SOCF microCHP conversion factor of electricity, equal to 1.469, as calculated in Chapter 4.3, page 46.
W is the exported electricity (see Table 43).
Anyway, this error will not be considered in the next analyses, because it is small if compared to the total primary energy consumption of the building.

The energy class of the building is based only on the building structure, so the $EP_{gl,nren}$ value of the standard building is always 617.04 kWh/m² per year.
The final energy class of the model is B, with a value of $EP_{gl,nren}$ of 665.451 kWh/m² per year. The reduction with respect to the base case is of the order of 10%, so it represents a very positive effect of the SOFC installation, considering that the size of the machine is quite small.

FIGURE 37: SOFC MODEL ENERGY CLASS



To show the reduction of each specific consumption, Table 44 is proposed.

TABLE 44: ENERGY PERFORMANCE INDEXES COMPARISON, BETWEEN BASE CASE AND SOFC CASE

	Base Case **[kWh/m²y]**	***SOFC Case*** **[kWh/m²y]**	***Difference*** **[%]**
	Heating		
$EP_{h,ren}$	12.9	6.0446	-53.0%
$\boldsymbol{EP_{h,nren}}$	433.1	424.7429	-1.9%
EP_h	445.9	430.7874	-3.4%
	Sanitary Hot Water		
$EP_{w,ren}$	5.1	1.3162	-74.1%
$\boldsymbol{EP_{w,nren}}$	221.1	199.8776	-9.6%
EP_w	226.2	201.1939	-11.0%
	Ventilation		
$EP_{v,ren}$	12.5	0.6018	-95.2%
$\boldsymbol{EP_{v,nren}}$	51.9	13.6895	-73.6%
EP_v	64.4	14.2914	-77.8%
	Lighting		
$EP_{l,ren}$	11.8	3.0698	-73.9%
$\boldsymbol{EP_{l,nren}}$	48.8	27.1411	-44.4%
EP_l	60.5	30.2109	-50.1%
	Global		
$EP_{gl,r}$	42.2	11.0325	-73.9%
$\boldsymbol{EP_{gl,nr}}$	754.8	665.4511	-11.8%
$EP_{gl,tot}$	797.0	676.4836	-15.1%
REN Share [%]	5.4%	1.6%	-70.4%

The most significant result related to the SOFC installation is the reduction of the non-renewable primary energy need (-11.8%). The CHP contribution is shared by all service and is higher in those that are characterized only by the electricity consumption.
Instead, a negative side effect is the reduction of the renewable energy share (REN Share), from 5.4% to 1.6%, related to a smaller quantity of grid electricity consumed. This percentage is defined as the ratio between $EP_{gl,r}$ and $EP_{gl,tot}$.
As previously specified, even if in this building no renewable energy plants are present, the electricity from the grid determines a small share of renewable energy. If 2.42 primary energy units are withdrawn from the grid, 1.95 are non-renewable and 0.47 are renewable. So, the two contributions cannot be separate in the calculations. This

numbers are not casual, but they are exactly the conversion factors of the electricity grid (see Table 4): global (2.42), non-renewable (1.95) and renewable (0.47).
In conclusion, even if the renewable share is smaller, this side effect is compensated by the great enhance of system's global efficiency.

6.3 Effect of CHP Electrical Efficiency and Size on the Building Performance

To demonstrate practically that the installation of a SOFC brings to greater benefits with respect to other CHP systems, an analysis based on the electrical efficiency is performed. The conditions to have good comparison are:

- All systems must have the same global efficiency, chosen equal to 85%, the same global efficiency of BLUEgen®;
- All systems must have the same input power (16.8 kW);
- All systems must be modelled as working for the entire year without stops.

Six machines are taken into account: the first one is the SOFC, whilst the last one is an ICE with an electrical efficiency of 29.6%, the same as TOTEM® of Asja Group [30]. The electrical efficiencies of the remaining four machines are found by linear interpolation, while the other data are calculated from the input power.

TABLE 45: CHP SPECIFICATIONS FOR A COMPARISON BASED ON THE ELECTRICAL EFFICIENCY

	η_{el} [%]	η_{th} [%]	Φ_{el} [kW_e]	Φ_{th} [kW_t]	Φ_{input} [kW]	$EP_{gl,nren}$ [kWh/m^2y]
SOFC	60.0%	25.0%	10.1	4.2	16.8	665.5
CHP1	53.9%	31.1%	9.1	5.2	16.8	672.5
CHP2	47.8%	37.2%	8.0	6.2	16.8	680.1
CHP3	41.8%	43.2%	7.0	7.3	16.8	689.7
CHP4	35.7%	49.3%	6.0	8.3	16.8	699.3
ICE	29.6%	55.4%	5.0	9.3	16.8	708.9

A simulation on TerMus® is run for each of these CHPs. In Table 45 is also reported the final value of $EP_{gl,nren}$: it is clear that the analysis on the regulation is proved also in this practical case. The electrical efficiency guarantees a smaller primary energy consumption, because it represents a more precious resource. Anyway, it must be underlined that even the ICE microCHP brings an improvement on the energy performance, as shown in Table 46.

TABLE 46: GLOBAL NON-RENEWABLE ENERGY PERFORMANCE FACTOR FOR EACH CHP

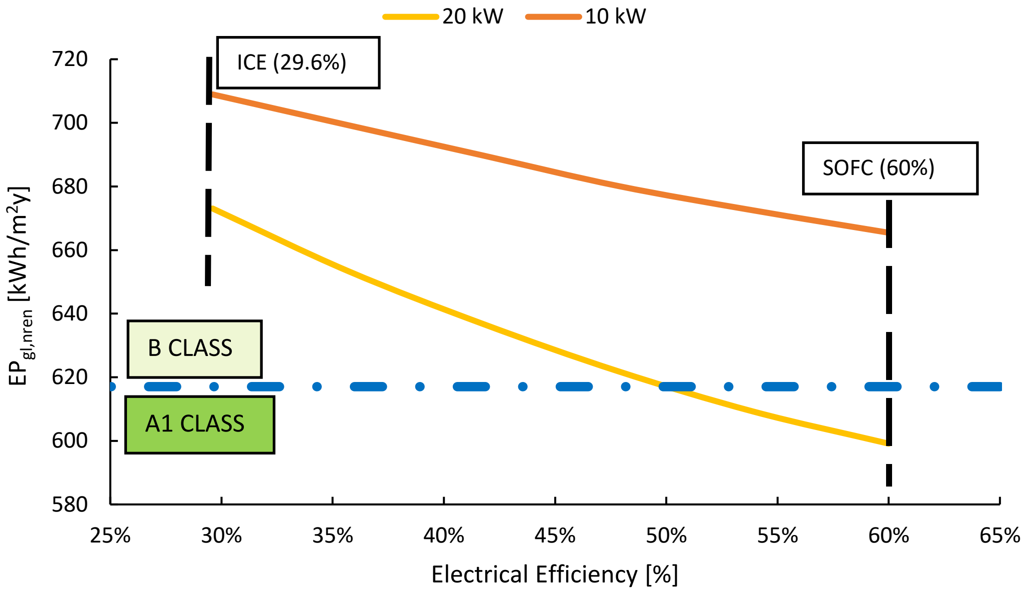
	Base Case [kWh/m²y]	$EP_{gl,nren}$ [kWh/m²y]	Difference	
SOFC	754.8	665.5	-89.3	-11.8%
C1		672.5	-82.3	-10.9%
C2		680.1	-74.7	-9.9%
C3		689.7	-65.1	-8.6%
C4		699.3	-55.5	-7.4%
ICE		708.9	-45.9	-6.1%

The reduction with the SOFC unit is approximately double with respect to the ENGINE unit, so it basically follows the electrical efficiency, not exactly linearly (Figure 38).
If the electrical power increases, a greater reduction of $EP_{gl,nren}$ comes out, but the trend remains very similar.
Figure 38 shows how the energy class changes for two cases:

1) The case related to 7 BLUEgen®, seen in this section, with an electrical power of around 10 kW_e.
2) The case related to a CHP with an electrical power of around 20 kW_e, the maximum power that can be installed based on the electrical power cumulative curve (Chapter 5.2, page 62).

For the 20 kW case, the same methodology as the 10 kW case is followed, using the same electrical efficiencies and the same input power. Then, for each CHP, a TerMus® simulation is run to find the corresponding value of $EP_{gl,nren}$.
The boundaries of the two curves are the ICE (left boundary, 29.6%) and the SOFC (right boundary, 60%), drawn with two dashed black lines.
The dashed blue line represents the boundary between A1 and B classes.

FIGURE 38: GLOBAL NON-RENEWABLE ENERGY PERFORMANCE FACTOR FUNCTION OF ELECTRICAL EFFICIENCY



In the 10 kW case, the energy performance factor decreases with the electrical efficiency, but the building remains in the B class. Instead, in the other case, the energy class is improved from B to A1 with an efficiency higher than 50%.

The orange and yellow lines, with the dashed black lines, create an area of possible CHP cases, each one corresponding to a certain value of $EP_{gl,nren}$. This figure can be read in two directions: fixing the electrical efficiency, it is possible to see the effect of the CHP electrical size on the energy performance; fixing a desired value of $EP_{gl,nren}$, it is possible to find the size and the electrical efficiency necessary to reach that performance.

To reach the A1 class (small area between the dashed blue line, the yellow line and the SOFC black line), the minimum electrical efficiency needed is 50%, with the highest electrical power. Using a SOFC microCHP with 60% electrical efficiency, the necessary power would be around 17 kW_e.

If the size is greater, a higher percentage of the electricity demand of the building will be covered by the CHP. In addition, more electricity will be exported toward the grid. These two contributions have the effect of decreasing $EP_{gl,nren}$, with the consequent improvement of the Energy Label.

A more detailed comparison can be done between the two limit cases, the SOFC and the ICE units, considering a wider range of data. The first parameter considered is the primary energy demand for each service, as shown in Table 47.

TABLE 47: PRIMARY ENERGY CONSUMPTION COMPARISON BETWEEN ENGINE AND SOFC CASES

	ENGINE	*SOFC*
Service	Primary Energy [kWh]	
Heating	869,661	848,746
Hot Water	404,423	396,396
Ventilation	78,461	28,157
Lighting	92,600	59,522
TOTAL	1,445,145	1,332,821

The greatest thermal energy production from the ICE is not as effective as the electrical production on reducing the primary energy consumption; indeed, the demand for hot water production is smaller with a SOFC unit even if the thermal production from this machine is very low. This is the consequence of the fact that the electricity is considered by the regulation a more precious resource with respect to the heat, because more primary energy is needed to produce electricity.

The second comparison is related to the production from the two machines, shown by Table 48.

TABLE 48: ENERGY PRODUCTION COMPARISON BETWEEN ENGINE AND SOFC CASES

		ENGINE	**SOFC**
Electricity Produced	[kWh]	43,575	88,301
Thermal Energy Produced	[kWh]	81,556	36,792
Working Hours	[h]	8760	8760
Electricity Export	[kWh]	0	18,400
Self-Consumption	[%]	100%	79%
Plant Generation Thermal Efficiency	[%]	77%	69%
Plant Seasonal Thermal Efficiency	[%]	75%	76%

The two units work for the same number of hours and all thermal energy is used for the sanitary hot water production. Regarding the electricity production, the export in the ENGINE unit goes to zero, because of its small electrical power. This is an advantage in the simulation, but it means that the electrical power is underestimated, because, as already said, the real electric power of the building is quite different from that of the TerMus® model.
An interesting feature of the regulation is that, comparing the efficiencies, two different results are obtained: the generation thermal efficiency is obviously higher for the system

ENGINE+BOILER, because it is calculated with an energy balance without considering the electricity production.
Instead, the seasonal thermal efficiency becomes higher for the SOFC+BOILER system; this is due to the reduction of the primary energy input from the electricity contribution. It is clear that this formulation of efficiency is quite useless and can lead to make interpretation error.

6.4 Improved Building Case

In the last TerMus® simulation, the building is considered as new. It means that it is necessary to change all structural and technical parameters in order to respect all minimum requirements from the Italian regulation.
First of all, the vertical and horizontal opaque components are improved with insulation layers, to respect the minimum transmittance. The transparent components are also improved with low emittance glasses, with a gap filled with argon. The transmittance limits to be respected are:

TABLE 49: BUILDING COMPONENTS TRANSMITTANCE LIMITS

	Limit [W/m²K]
Vertical Opaque Components	0.28
Roof Horizontal Opaque Components	0.24
Floor Horizontal Opaque Components	0.29
Transparent Components	1.4
Vertical Opaque Components toward Other Zones	0.8

More interesting for the purpose of this study are the limits related to the entire building and to the energy demands. Table 50 shows the limit values and the results from the simulation in two cases: the first without SOFC microCHP and the second with the machine.

TABLE 50: COMPARISON WITH THE REGULATION LIMITS OF THE IMPROVED BUILDING MODEL

		Limit Value	Without SOFC	With SOFC
A'_{sol}	[-]	0.04	0.02	0.02
H'_T	[W/m²K]	0.75	0.32	0.32
$EP_{h,nd}$	[kWh/m²y]	75.77	74.5	74.5
$\eta_{G,h}$	[%]	32.15	32.43	33.59
$\eta_{G,w}$	[%]	56.67	73.73	81.93
$EP_{gl,tot}$	[kWh/m²y]	793.87	519.32	448.42

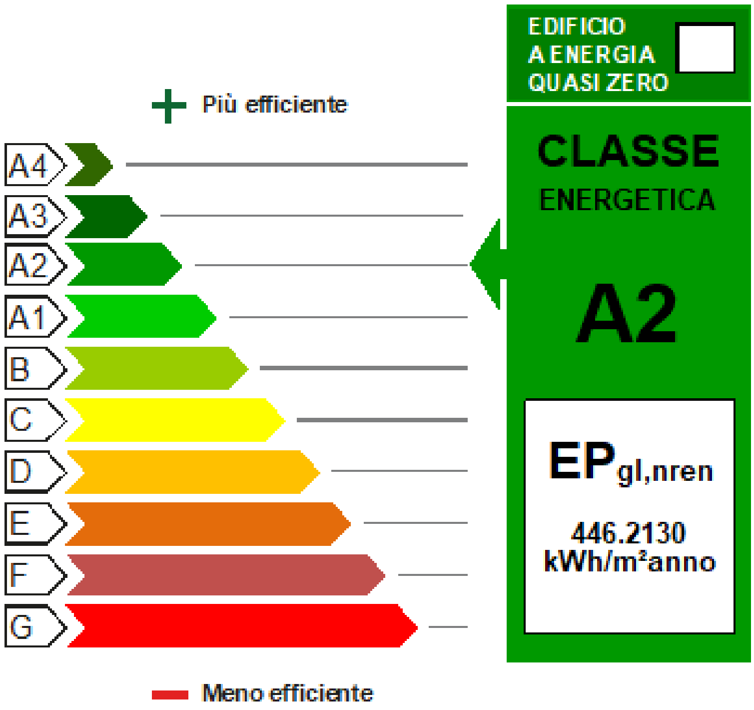
$Q_{w,ren}$	[%]	50.00	2.56	0.24
Q_{ren}	[%]	50.00	2.24	0.29

Where:
A'_{sol} is the solar equivalent surface.
H'_T is the average heat exchange coefficient for transmission.
$EP_{h,nd}$ is the useful energy performance index for heating.
$\eta_{G,h}$ is the heating average seasonal efficiency.
$\eta_{G,w}$ is the hot water production average seasonal efficiency.
$EP_{gl,tot}$ is the global energy performance index of the building.
$Q_{w,ren}$ is the renewable energy share for hot water production.
Q_{ren} is the total renewable energy share.

As previously said, the only requirements not respected in this case are the renewable energy share and the renewable electric power, that is not shown in the table because it is equal to zero in the building. For this reason, if this simulation is a project for a new building, it is impossible considering a SOFC installation, unless an alternative and renewable fuel is used instead of natural gas.
In case of a 100% renewable fuel, used only to feed the SOFC unit, it's reached approximately the 32% of renewable share for hot water production and 17% on the total, still far from the limit of 50%.
The high electricity production reduces also the only renewable contribution represented by the grid. Furthermore, if a PV system is installed, it is probable that a lot of electricity is exported when the electricity production from the sum is high.

The energy performance of the building, considered as new, is much better than the real building. The Energy Label coming out from the simulation is A1, with a value of $EP_{gl,nren}$ equal to 493.59 kWh/m^{2}y. Also in this case, the installation of the SOFC microCHP has a very positive effect: the classes are narrower, so in this case the class passes from A1 to A2, with a final $EP_{gl,nren}$ equal to 446.21 kWh/m^{2}y. Again, the reduction of non-renewable primary energy consumption is in the order of 10%.

FIGURE 39: IMPROVED BUILDING MODEL WITH SOFC ENERGY CLASS



CHAPTER 7

Economic Analysis

In this chapter, the economic analysis of the SOFC microCHP installation in the Vinovo's Pool is performed. The aim is to understand if, from the economical point of view, the machine is convenient, also comparing it with two ICE microCHP.
Being still in a commercialization phase, the initial investment is expected to be high, but with low maintenance costs because of the characteristics of the technology. Because of the cost uncertainties, two cases are studied:

1) PRESENT scenario, where costs as similar as possible to reality are taken into account. In this scenario it is important the presence of the tax deduction.
2) TARGET scenario, where the projections of the costs for the plant are used, without considering the tax deduction. The reason is that the projected costs are those that theoretically permit to the technology the self-sustainment (mature technology).

For both cases, the reference data for the production are those coming out from the sizing of the microCHP based on the electrical power (Chapter 5.2, page 62); the chosen size is 10.5 kW_e, corresponding to the installation of 7 BLUEgen® [29].

TABLE 51: SOFC MICROCHP PRODUCTION DATA FOR ECONOMIC ANALYSIS

SOFC microCHP		
Electrical Power	[kW_e]	10.5
Thermal Power	[kW_t]	4.2
Working Hours	[h]	8,016
Electricity Production	[kWh_e]	84,168
Exported Electricity	[kWh_e]	673
Self-consumption	[%]	99.2%
Thermal Production	[kWh_t]	35,070
Thermal Production	[Sm^3]	3,711
Primary Energy Need	[kWh_p]	140,280
NG consumption	[Sm^3]	14,844
NG consumption net to thermal Production	[Sm^3]	11,133

The choice is to consider the thermal production as a saving on the Natural Gas consumption. To do so, the heat produced is converted in standard cubic meters (Sm^3)

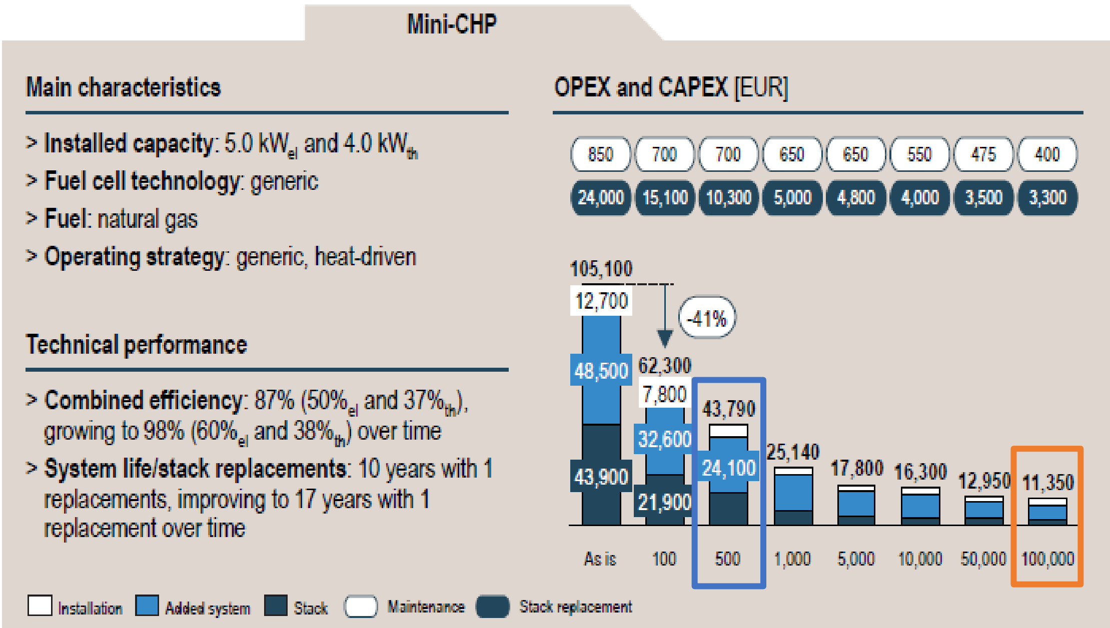
using a NG Lower Heating Value (LHV) equal to 9.45 [kWh/Sm^3]. Then, it is subtracted to the total NG consumption to find the NG consumption of the Fuel Cell only related to the electricity production. All the heat produced is considered self-consumed.

7.1 Input Economical Data

7.1.1 SOFC microCHP costs

For both PRESENT and TARGET cases, the costs for the microCHP system have been taken from the Roland Berger Strategy Consultant study on Fuel Cell systems [4]. Each column is referred to a cumulative production per company of microCHPs.

FIGURE 40: SOFC MICROCHP COST PROJECTION FROM ROLAND BERGER FUEL CELL STUDY [4]



The study has been done in 2015 so, considering that there are already some company producing and selling this type of machines, the hypothesis is that it is possible to use for the PRESENT case the cost related to a cumulative production of 500 units and for the TARGET the cost of the last column (100,000 units).

With these data, the specific costs (Table 52) are obtained dividing for the electrical power (5 kW). Instead, Table 53 shows the total costs used as input in the economic analysis.

Table 52: SOFC microCHP specific costs [€/kW$_e$]

		PRESENT	TARGET
CAPEX			
SOFC cost	[€/kW$_e$]	3,065	795
Added Systems	[€/kW$_e$]	4,820	1,135
Installation	[€/kW$_e$]	873	341
Total Cost	[€/kW$_e$]	8,758	2,270
OPEX			
Stack Replacement	[€/kW$_e$]	2060	660
Stack Duration	[years]	6	10
Maintenance	[€/kW$_e$]	140	80

Table 53: Economic analysis SOFC input costs

	PRESENT	TARGET
CAPEX		
SOFC cost	32,185.65 €	8,342.25 €
Added Systems	50,610.00 €	11,917.50 €
Installation	9,163.35 €	3,575.25 €
Total Cost	91,959.00 €	23,835.00 €
OPEX		
Stack Replacement	21,630.00 €	6,930.00 €
Maintenance	1,470.00 €/y	840.00 €/y

It is evident that a very big cost reduction is expected for this technology, but it is not possible to say when it is going to happen. Indeed, the PRESENT costs are very high, especially the total initial investment (91,959.00 €) and the stack replacement cost (21,630.00 €).

7.1.2 ICE microCHP costs

To show the differences between SOFC and ICE microCHP, two engines are considered, the first one with a size of 10 kW$_e$ and the second one of 5 kW$_e$. The technical specifications of these machines are those of TOTEM® [30]: they have an electrical efficiency equal to 29.6% and a thermal efficiency equal to 64.0%.

Qualitatively, the ICE with the smallest size is expected to have a similar NG consumption as the SOFC, whilst the second engine is expected to have a similar electricity production. The reason of considering two ICEs is to cover more possibilities of competitions.

Table 54 shows the resume of the production data for the SOFC and the two ICEs microCHP.

TABLE 54: SOFC AND ICEs PRODUCTION DATA FOR ECONOMIC ANALYSIS AND COMPARISON

		SOFC	ICE 10 kW	ICE 5 kW
Electrical Power	[kW_e]	10.5	10.0	5.0
Thermal Power	[kW_t]	4.2	21.6	10.8
Electrical Efficiency	[%]	60.0%	29.6%	29.6%
Thermal Efficiency	[%]	25.0%	64.0%	64.0%
PES	[%]	42.2%	30.0%	30.0%
Working Hours	[h]	8,016	8,016	8,016
Electricity Production	[kWh_e]	84,168	80,160	40,080
Exported Electricity	[kWh_e]	673	641	0
Self-consumption	[%]	99.2%	99.2%	100%
Thermal Production	[kWh_t]	35,070	173,319	86,660
Thermal Production	[Sm^3]	3,711	18,341	9,170
Primary Energy Need	[kWh_p]	140,280	270,811	135,405
NG consumption	[Sm^3]	14,844	28,657	14,329
NG consumption net to thermal Production	[Sm^3]	11,133	13,067	5,158
Thermal Self-consumption	[%]	100%	85%	100%

Because of the high thermal power of the 10 kW_e TOTEM®, a thermal self-consumption of 85% is considered.

Unfortunately, Asja Group® does not produce a 5 kW_e CHP, so the economic data are found starting from the 10 kW_e and the 20 kW_e machine, whose data have been asked directly to Asja Group® company. A size coefficient (0.73) is calculated from the system costs of these engines using an exponential law; with the same law, the costs for a hypothetical 5 kW_e machine are evaluated. To do so, it is necessary to work on the specific costs, shown in Table 55. The numbers written in italic font are the calculated ones.

TABLE 55: ICE MICROCHP COSTS, BASED ON TOTEM®

		20 kW_e	10 kW_e	5 kW_e
System Cost	[€/kW_e]	1,600	2,650	*4,389*
Other Costs	[€/kW_e]	650	*1,077*	*1,783*
Total Cost	[€/kW_e]	2,250	3,727	*6,172*

Cost per Working Hour	[€/h]	-	0.56	*0.34*

The specific costs increase when the size decrease, except for the costs per working hour; the hypothesis on this quantity is that decreases following an exponential law with the same exponent of the other costs. Indeed, passing from 10 kW_e to 5 kW_e, the hourly cost (0.28 €/h) is greater than a half of 0.56 €/h. The hourly cost of the 20 kWe machine is not known.

The input total costs for the economic analysis are shown in Table 56. They do not change between PRESENT and TARGET cases, because the ICE is considered a mature technology.

TABLE 56: ECONOMIC ANALYSIS ICE INPUT COSTS

	10 Kw_E	**5 Kw_E**
CAPEX		
System Cost	26,500.00 €	21,945.31 €
Other Costs	10,765.63 €	8,915.28 €
Total Cost	37,265.63 €	30,860.60 €
OPEX		
Maintenance	4,488.96 €/y	2,710.32 €/y

Compared with the SOFC costs of Table 53, the initial investment required for an ICE is smaller, but the greater maintenance cost has to be taken into account carefully, as well as the different electrical production.

7.1.3 Vinovo's Pool input data

The remaining input data are those related to the Vinovo's Pool. The prices of Natural Gas and Bought Electricity have been defined starting from the pool bills; the sold electricity price considered is 0.07 [€/kWh_e].

Table 57 shows the resume of the Vinovo's Pool economic data.

TABLE 57: VINOVO'S POOL ECONOMIC INPUT DATA

	PRESENT TARGET
Natural Gas Price	0.4028 [€/Sm^3]
Bought Electricity Price	0.1952 [€/$kWh_{e]}$
Sold Electricity Price	0.07 [€/kWh_e]
Years of Operation	20

WACC	4.0%	
Fiscal Reduction	65%	-
Years of Fiscal Reduction	10	-

The analysis is extended until the 20th year of operation, enough to understand the behaviour of the cashflow for each case.
Not knowing the financial structure of the On Sport society, a WACC equal to 4.0% is considered for the costs actualization.
The only difference between PRESENT and TARGET cases consists in the fiscal reduction. In the PRESENT scenario it is considered equal to 65% with a maximum of 100,000 € (see Table 1), whilst in TARGET scenario no economical contribution is considered. Obviously, the fiscal reduction is considered both for the SOFC and for the ICEs.

7.2 Present and Target Results

Starting from the input data of Chapter 7.1, page 103, the cash flow for each year of operation can be calculated (Table 58 and Table 59). The year "0" corresponds to the initial investment.
The cash flow is defined as the sum of the costs, fiscal reduction and incomes.
The cumulative cashflow indicates the loss and the gain actualized to year "0" and it is displayed in Figure 41. The gain is highlighted with the bold font.

TABLE 58: SOFC PRESENT CASE CASHFLOW

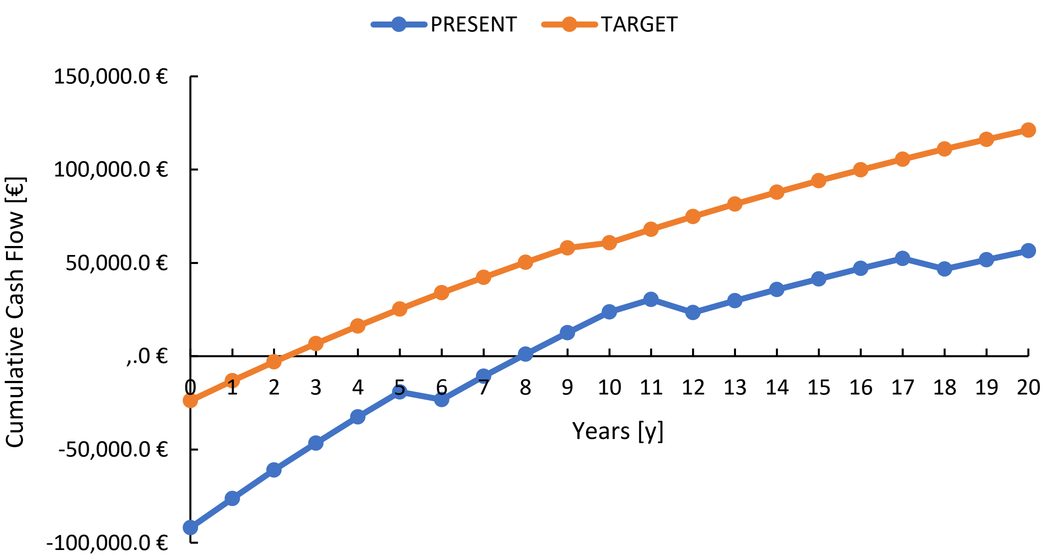
Year	Costs [€/y]	Fiscal Reduction [€/y]	Incomes [€/y]	Cash Flow [€/y]	Present Cashflow [€/y]	Cumulative Cashflow [€/y]
0	-91,959.00 €	- €	- €	-91,959.00 €	-91,959.00 €	-91,959.00 €
1	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	15,736.18 €	-76,222.82 €
2	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	15,130.94 €	-61,091.87 €
3	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	14,548.98 €	-46,542.89 €
4	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	13,989.41 €	-32,553.48 €
5	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	13,451.35 €	-19,102.13 €
6	-27,584.92 €	5,977.34 €	16,343.21 €	-5,264.37 €	-4,160.51 €	-23,262.64 €
7	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	12,436.53 €	-10,826.10 €
8	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	11,958.20 €	**1,132.10 €**
9	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	11,498.27 €	**12,630.37 €**
10	-5,954.92 €	5,977.34 €	16,343.21 €	16,365.63 €	11,056.03 €	**23,686.41 €**
11	-5,954.92 €	- €	16,343.21 €	10,388.29 €	6,748.04 €	**30,434.44 €**
12	-27,584.92 €	- €	16,343.21 €	-11,241.71 €	-7,021.54 €	**23,412.91 €**
13	-5,954.92 €	- €	16,343.21 €	10,388.29 €	6,238.94 €	**29,651.85 €**
14	-5,954.92 €	- €	16,343.21 €	10,388.29 €	5,998.98 €	**35,650.83 €**
15	-5,954.92 €	- €	16,343.21 €	10,388.29 €	5,768.25 €	**41,419.08 €**
16	-5,954.92 €	- €	16,343.21 €	10,388.29 €	5,546.39 €	**46,965.47 €**
17	-5,954.92 €	- €	16,343.21 €	10,388.29 €	5,333.07 €	**52,298.55 €**

18	-27,584.92 €	- €	16,343.21 €	-11,241.71 €	-5,549.22 €	**46,749.32 €**
19	-5,954.92 €	- €	16,343.21 €	10,388.29 €	4,930.72 €	**51,680.05 €**
20	-5,954.92 €	- €	16,343.21 €	10,388.29 €	4,741.08 €	**56,421.13 €**

TABLE 59: SOFC TARGET CASE CASHFLOW

Year	**Costs [€/y]**	**Incomes [€/y]**	**Cash Flow [€/y]**	**Present Cashflow [€/y]**	**Cumulative Cashflow [€/y]**
0	-23,835.00 €	- €	-23,835.00 €	-23,835.00 €	-23,835.00 €
1	-5,324.92 €	16,343.21 €	11,018.29 €	10,594.51 €	-13,240.49 €
2	-5,324.92 €	16,343.21 €	11,018.29 €	10,187.03 €	-3,053.45 €
3	-5,324.92 €	16,343.21 €	11,018.29 €	9,795.22 €	**6,741.77 €**
4	-5,324.92 €	16,343.21 €	11,018.29 €	9,418.48 €	**16,160.25 €**
5	-5,324.92 €	16,343.21 €	11,018.29 €	9,056.23 €	**25,216.49 €**
6	-5,324.92 €	16,343.21 €	11,018.29 €	8,707.92 €	**33,924.40 €**
7	-5,324.92 €	16,343.21 €	11,018.29 €	8,373.00 €	**42,297.40 €**
8	-5,324.92 €	16,343.21 €	11,018.29 €	8,050.96 €	**50,348.36 €**
9	-5,324.92 €	16,343.21 €	11,018.29 €	7,741.31 €	**58,089.67 €**
10	-12,254.92 €	16,343.21 €	4,088.29 €	2,761.90 €	**60,851.57 €**
11	-5,324.92 €	16,343.21 €	11,018.29 €	7,157.27 €	**68,008.85 €**
12	-5,324.92 €	16,343.21 €	11,018.29 €	6,881.99 €	**74,890.84 €**
13	-5,324.92 €	16,343.21 €	11,018.29 €	6,617.30 €	**81,508.14 €**
14	-5,324.92 €	16,343.21 €	11,018.29 €	6,362.79 €	**87,870.93 €**
15	-5,324.92 €	16,343.21 €	11,018.29 €	6,118.07 €	**93,989.00 €**
16	-5,324.92 €	16,343.21 €	11,018.29 €	5,882.76 €	**99,871.76 €**
17	-5,324.92 €	16,343.21 €	11,018.29 €	5,656.50 €	**105,528.25 €**
18	-5,324.92 €	16,343.21 €	11,018.29 €	5,438.94 €	**110,967.19 €**
19	-5,324.92 €	16,343.21 €	11,018.29 €	5,229.75 €	**116,196.94 €**
20	-5,324.92 €	16,343.21 €	11,018.29 €	5,028.61 €	**121,225.55 €**

FIGURE 41: PRESENT AND TARGET CUMULATIVE CASH FLOWS



Regarding the PRESENT case, the most detrimental characteristic from an economical point of view are the very high initial investment and the SOFC stack substitution, that causes a loss in the 6^{th} year, increasing the Payback Time to 7 years and 11 months. Anyway, the incomes related to the electricity production are great and, coupled with the fiscal reduction, permit a relatively fast recovery of the initial investment, considering the commercialization stage of the SOFC microCHPs.
Regarding the TARGET case, the best characteristics is the Payback Time, equal to 2 years and 6 months. If the future costs of this type of technology are going to be similar to those of Table 59, there is a high probability that the Fuel Cells will contribute in a significant way to a distributed electrical grid.
Furthermore, it is possible to evaluate for these two scenarios the following quantities, whose values are shown in Table 60.

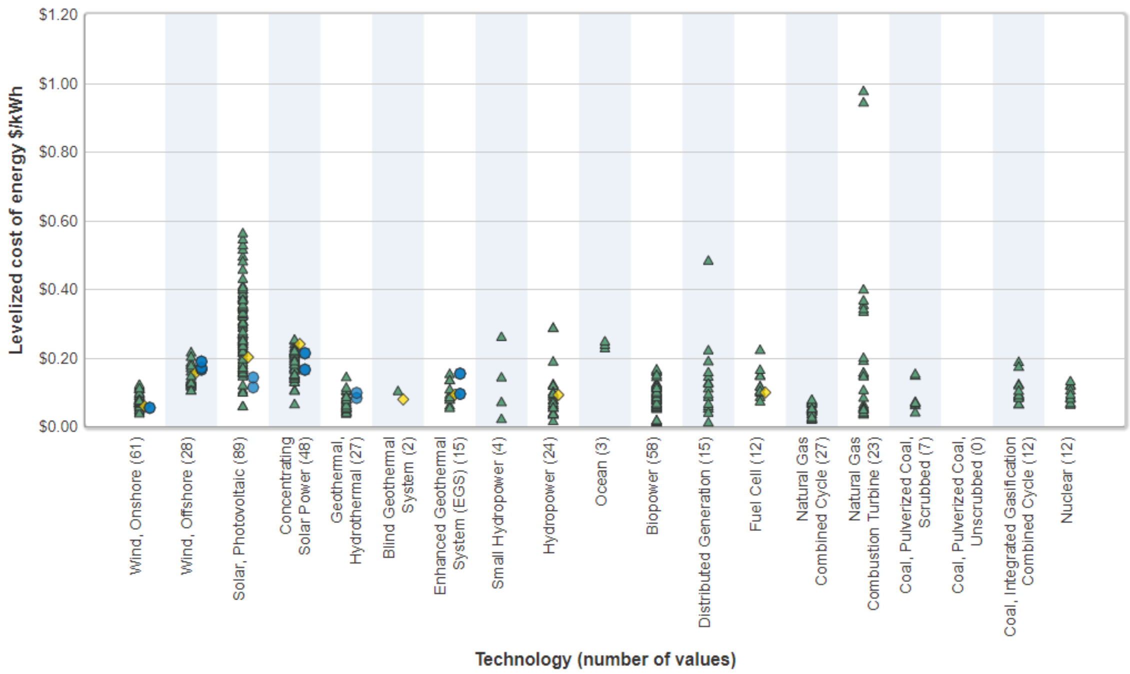
- Levelized Cost of Electricity (LCOE), defined as the ratio between the total costs and the total energy produced during the system lifetime. It gives an idea of the mean cost of electricity of the system during its entire life, including the initial investment.
- Net Present Value (NPV): it corresponds to the last value of the cumulative cash flow and is the final gain of the investment done.
- Internal Rate of Return (IRR), defined as the discount rate for which the NPV goes to zero. It represents the efficiency of the investment as a percentage.
- Return on Investment (ROI), defined as the ratio between the average yearly operative result and the initial investment. It indicates the profitability of the investment.

TABLE 60: LCOE AND FINANCIAL QUANTITIES, VINOVO'S POOL ECONOMIC ANALYSIS

		PRESENT	TARGET
Total Cost	[€]	275,947.36 €	137,263.36 €
Total Production	[kWh_e]	1,683,360	1,683,360
LCOE	[€/kWh]	0.1639	0.0815
	[$/kWh]	0.1906	0.0948
NPV	[€]	56,421.13 €	121,225.55 €
IRR	[%]	7.7%	39.0%
ROI	[%]	8.1%	28.6%

The LCOE reflects the comments done about too high initial investment and stack replacement costs for the PRESENT case; indeed, it is quite high with respect to other technologies, even if it remains lower than the Vinovo's Pool bought electricity price. Figure 42 [33] shows the LCOE value for different technologies, in [$/kWh].

FIGURE 42: LCOE FOR DIFFERENT TECHNOLOGIES [33]



The LCOE referred to the PRESENT case is similar to those in the figure, whilst that of the TARGET case is lower, even competitive with the Natural Gas Combined Cycle technology.

The other three parameters (NPV, IRR and ROI) are more financial and related to the investment done for the system.

The PRESENT case is borderline: it has some advantage, but it does not represent a secure investment. The NPV (56,421.13 €) is approximately half of the initial investment (91,959.00 €) and the IRR (7.7%) is not so high to guarantee a secure gain.

The TARGET case is better by far, even if it is less interesting: it guarantees a very high gain and a very high profitability, with a ROI equal to 28.6%. It means that, in average every year, the gain is 28.6% of the initial investment.

The best way to use these quantities is the comparison with other possible investments: in this case, as shown in Chapter 7.4, page 114, the comparison is done with respect with two ICE microCHPs.

7.3 Sensitivity Analysis, Present Scenario

In this Chapter the sensitivity analysis on PRESENT scenario is performed, to see how much the economic model of Vinovo's Pool is sensitive to a variation of the following quantities:

- Initial Investment;
- OPEX Cost;
- Natural Gas Price;
- Bought Electricity Price;
- WACC.

Each one of these parameters is varied of ± 20% with respect to the initial value. The aim is to understand how the system behaves economically if the initial hypotheses, given in Chapter 7.1, page 103, change.
Table 61 shows the variations of the considered parameters with respect to the original case.
Using a Tornado Diagram for each financial value (NPV, IRR and ROI), it is possible to quantify the sensitivity in terms of gain, efficiency of investment and profitability (Figure 43, Figure 44 and Figure 45).

TABLE 61: PARAMETER VARIATIONS, PRESENT CASE SENSITIVITY ANALYSIS

	Lower Case (-20%)	Base	Upper Case (+20%)
Initial Investment	73,567.20 €	91,959.00 €	110,350.80 €
OPEX	1,176.00 €	1,470.00 €	1,764.00 €
NG Price	0.32 €	0.40 €	0.48 €
Bought Electricity Price	0.16 €	0.20 €	0.23 €
WACC	3.2%	4.0%	4.8%

FIGURE 43: PRESENT CASE SENSITIVITY ANALYSIS, NET PRESENT VALUE

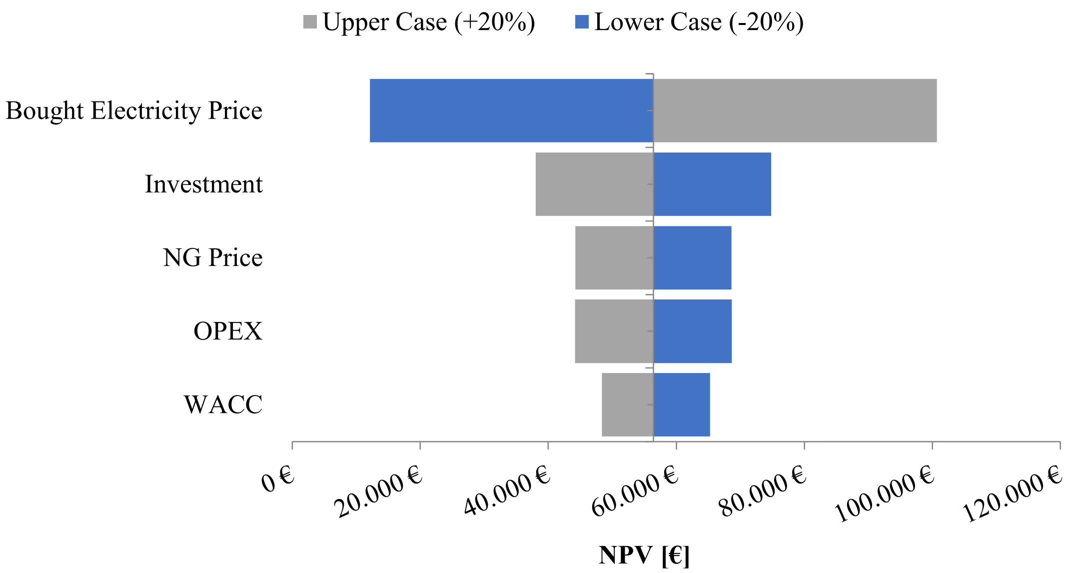


FIGURE 44: PRESENT CASE SENSITIVITY ANALYSIS, INTERNAL RATE OF RETURN

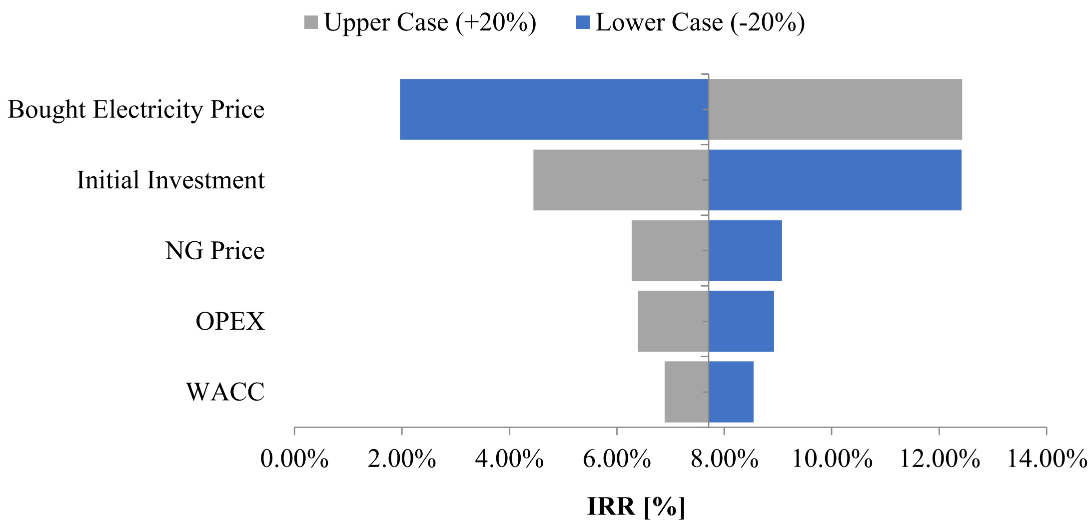
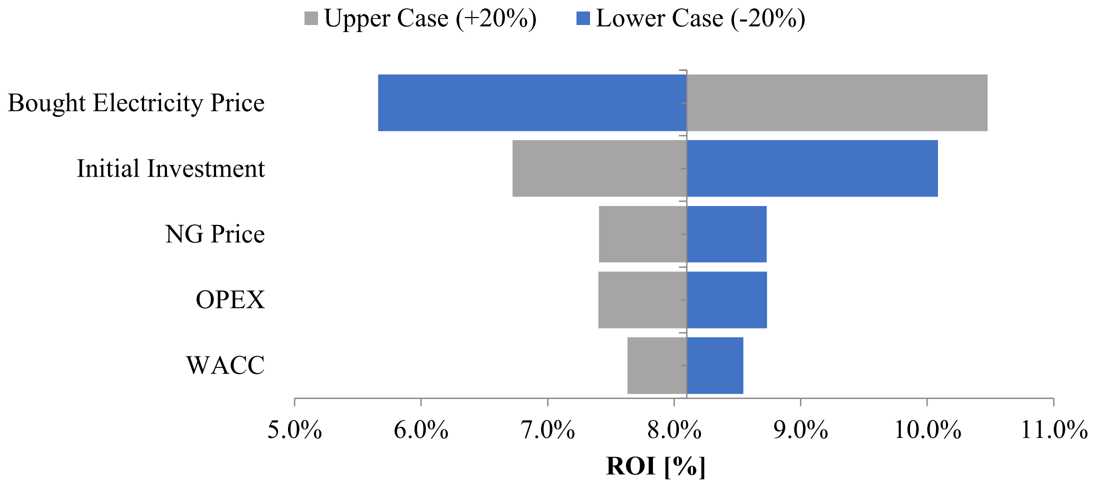


FIGURE 45: PRESENT CASE SENSITIVITY ANALYSIS, RETURN ON INVESTMENT



The convenience of the system depends mainly on two parameters: the price of bought electricity and the initial investment. Indeed, all three financial parameters (NPV, IRR and ROI) have great changes if these values are changed of 20% in positive or in negative. Instead, the system is more resilient to changes of NG price, OPEX and WACC.

It is very interesting to notice that the price of electricity can decide the future of a SOFC microCHP system; an increase of 20% makes the investment very convenient and profitable, whilst a decrease of 20% can erase all positive aspects of the system, that bases its convenience on the self-consumption of electricity produced with high efficiency. It is also necessary to underline that it is improbable that such variations happen during the lifetime of the plant, because normally the energy prices for the utility are well known in the project stage.

The sensitivity related to the initial investment is also important, but it must be considered that for the Fuel Cells a cost reduction is foreseen; for this reason, this type of plant is going to be increasingly convenient, tending to the TARGET case.

The sensitivity analysis for the TARGET case is not shown, because, with the hypothesis done, the system is convenient anyway and, in general, it is less interesting than the PRESENT case, because it has too much unknown variable that can change the entire analysis.

7.4 Comparison with Internal Combustion Engine microCHPs

The last economic analysis is performed comparing the SOFC with two ICEs, respectively with an electrical power of 10 kW_e and 5 kWe.

Table 62 and Table 63 show the cashflows corresponding to their installation in the Vinovo's Pool. Figure 46 shows the comparison between the SOFC PRESENT case and the two ICEs.

TABLE 62: ICE 10 KW_E CASHFLOW

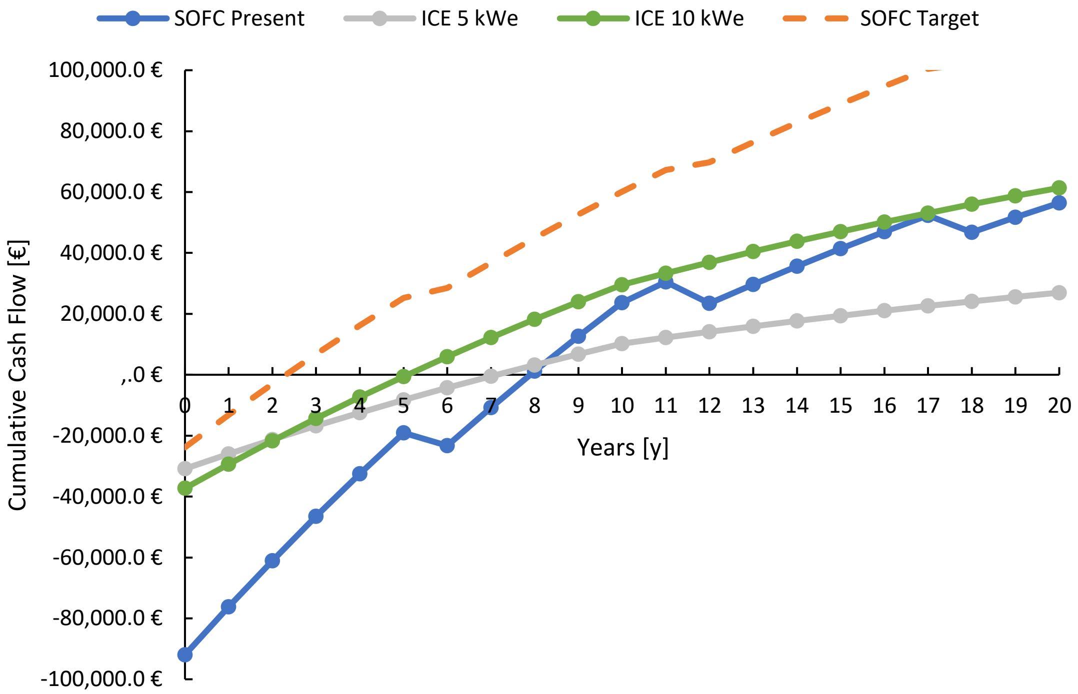
Year	Costs [€/y]	Fiscal Reduction [€/y]	Incomes [€/y]	Cash Flow [€/y]	Present Cashflow [€/y]	Cumulative Cashflow [€/y]
0	-37,265.63 €	- €	- €	-37,265.63 €	-37,265.63 €	-37,265.63 €
1	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	7,917.42 €	-29,348.20 €
2	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	7,612.91 €	-21,735.30 €
3	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	7,320.10 €	-14,415.20 €
4	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	7,038.56 €	-7,376.64 €
5	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	6,767.85 €	-608.79 €
6	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	6,507.54 €	**5,898.75 €**
7	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	6,257.25 €	**12,156.00 €**
8	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	6,016.59 €	**18,172.59 €**
9	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	5,785.18 €	**23,957.78 €**
10	-9,753.11 €	2,422.27 €	15,564.96 €	8,234.12 €	5,562.68 €	**29,520.45 €**
11	-9,753.11 €	- €	15,564.96 €	5,811.85 €	3,775.27 €	**33,295.72 €**
12	-9,753.11 €	- €	15,564.96 €	5,811.85 €	3,630.07 €	**36,925.79 €**
13	-9,753.11 €	- €	15,564.96 €	5,811.85 €	3,490.45 €	**40,416.23 €**
14	-9,753.11 €	- €	15,564.96 €	5,811.85 €	3,356.20 €	**43,772.43 €**
15	-9,753.11 €	- €	15,564.96 €	5,811.85 €	3,227.12 €	**46,999.55 €**
16	-9,753.11 €	- €	15,564.96 €	5,811.85 €	3,103.00 €	**50,102.55 €**
17	-9,753.11 €	- €	15,564.96 €	5,811.85 €	2,983.65 €	**53,086.20 €**
18	-9,753.11 €	- €	15,564.96 €	5,811.85 €	2,868.89 €	**55,955.09 €**
19	-9,753.11 €	- €	15,564.96 €	5,811.85 €	2,758.55 €	**58,713.64 €**
20	-9,753.11 €	- €	15,564.96 €	5,811.85 €	2,652.45 €	**61,366.10 €**

TABLE 63: ICE 5 KW_E CASHFLOW

Year	Costs [€/y]	Fiscal Reduction [€/y]	Incomes [€/y]	Cash Flow [€/y]	Present Cashflow [€/y]	Cumulative Cashflow [€/y]
0	-30,860.60 €	- €	- €	-30,860.60 €	-30,860.60 €	-30,860.60 €
1	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	4,868.01 €	-25,992.58 €
2	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	4,680.78 €	-21,311.80 €
3	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	4,500.75 €	-16,811.05 €
4	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	4,327.64 €	-12,483.41 €
5	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	4,161.20 €	-8,322.21 €
6	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	4,001.15 €	-4,321.06 €
7	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	3,847.26 €	-473.80 €
8	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	3,699.29 €	**3,225.49 €**
9	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	3,557.01 €	**6,782.49 €**
10	-4,788.27 €	2,005.94 €	7,845.06 €	5,062.73 €	3,420.20 €	**10,202.69 €**
11	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,985.63 €	**12,188.33 €**
12	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,909.26 €	**14,097.59 €**
13	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,835.83 €	**15,933.42 €**
14	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,765.22 €	**17,698.64 €**
15	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,697.33 €	**19,395.97 €**

16	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,632.05 €	**21,028.02 €**
17	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,569.28 €	**22,597.30 €**
18	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,508.92 €	**24,106.21 €**
19	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,450.88 €	**25,557.10 €**
20	-4,788.27 €	- €	7,845.06 €	3,056.79 €	1,395.08 €	**26,952.18 €**

FIGURE 46: SOFC AND ICE CUMULATIVE CASH FLOWS



In Figure 46, it is also presented the SOFC TARGET case as added information, even if this curve is not directly comparable with the others because there is no tax reduction in the TARGET scenario. The reason is to show the potential of the Fuel Cell technology if the costs used are going to be reached.

More interesting is the comparison between the other three curves. The SOFC is competitive with the 5 kW ICE because the SOFC has a longer Payback Time but a higher gain. This is again related to the big difference in the initial investment: the SOFC system costs approximately three times the 5 kW_e ICE.

The comparison with the 10 kW_e ICE is more favourable toward the engine: indeed, its curve is always above the SOFC curve with a Payback Time of 5 years against 8 years. Anyway, it seems that it is sufficient a small reduction of the initial SOFC cost, and consequently of the SOFC stack substitution cost, to become competitive with the ICE technology in this case. The reason is that, thanks to the high electrical efficiency, the annual gain is much greater than an ICE.

The last considerations are related to the LCOE and to the financial parameters, listed in Table 64 in order of economic convenience.

TABLE 64: LCOE AND FINANCIAL QUANTITIES, COMPARISON WITH ICE MICROCHPS

		PRESENT	ICE 5 kW_e	ICE 10 kW_e	TARGET
Total Cost	[€]	275,947.36 €	126,625.99 €	232,327.84 €	137,263.36 €
Total Production	[kWh_e]	1,683,360	801,600	1,603,200	1,683,360
LCOE	[€/kWh]	0.1639	0.1580	0.1449	0.0815
	[$/kWh]	0.1906	0.1837	0.1685	0.0948
NPV	[€]	56,421.13 €	26,952.18 €	61,366.10 €	121,225.55 €
IRR	[%]	7.7%	9.5%	16.1%	39.0%
ROI	[%]	8.1%	9.4%	13.2%	28.6%

For the first three cases, there is no big difference regarding the LCOE, while in the TARGET case it is significantly lower.
Even if the NPV of the SOFC microCHP is higher with respect to the 5 kW_e ICE, the engine is still a more convenient investment, with a higher IRR (9.5% against 7.7%) and a higher ROI (9.4% against 8.1%).
The 10 kW_e is far more convenient with respect to PRESENT case because it represents a more secure and profitable investment, but it is much less profitable than the TARGET case.

CONCLUSIONS

The Fuel Cell technology is still in a commercialization stage, but it is ready to become competitive on the market. To permit so, it is necessary some change in the logic of the regulation at a national level, maybe with an effort done at European level.
Analysing the Italian regulation, it is clear that such systems are not still considered a real technical possibility. Indeed, all microCHPs are considered as thermal machine and must work with a logic of thermal load following, regardless their electrical efficiency. This problem has been called “definition issue” in the master thesis.

Being the SOFC a system producing mainly electricity recovering heat as secondary product, the constraint on the thermal production can represent a problem for the sizing and installation. This working logic precludes every possibility of smart grid functioning of the microCHP, because the thermal load of the utility must be followed.
Another aspect of the Italian regulation is that the electrical efficiency is always favoured with respect to the thermal efficiency. The reason is that the electricity is a more precious product than the heat. This makes the SOFC a good way to enhance the primary energy saving, especially when it is sized in order to maximize the self-consumption, that is rewarded by the regulation.
For the sizing of the SOFC microCHP system, it is not possible to base the calculations on the regulation, because it is based only on the thermal load. Therefore, it is necessary to make further analyses on the utility to choose the proper electrical power of the machine.

Regarding the building as a whole, the installation of a SOFC microCHP rises the Energy Label of a building by one or two classes, reducing the primary energy demand more than other CHPs with lower electrical efficiencies. This is positive because the Energy Label, if used in an effective way, can be a very effective mean to improve the energy efficiency of building commercial sector and to increase the value of a building.
An effort should be done to treat in a more detailed way the electrical consumption of a building; indeed, only four services (Auxiliaries, Lighting, Ventilation and People Transportation) are considered by the regulation.

In new buildings or important renovations of first level, a renewable energy share constraint must be respected. The application of a SOFC microCHP fed with Natural Gas, in this case, is unlikely because it would rise the technical complexity of the system and the total initial investment, especially if a Heat Pump has to be installed. A configuration with a SOFC and a Heat Pump could become convenient if both technologies have reached the maturity.
To install a SOFC in a new building, it can also be possible to use a renewable fuel, but anyway it is very difficult to respect the renewable energy constraints only with this configuration.

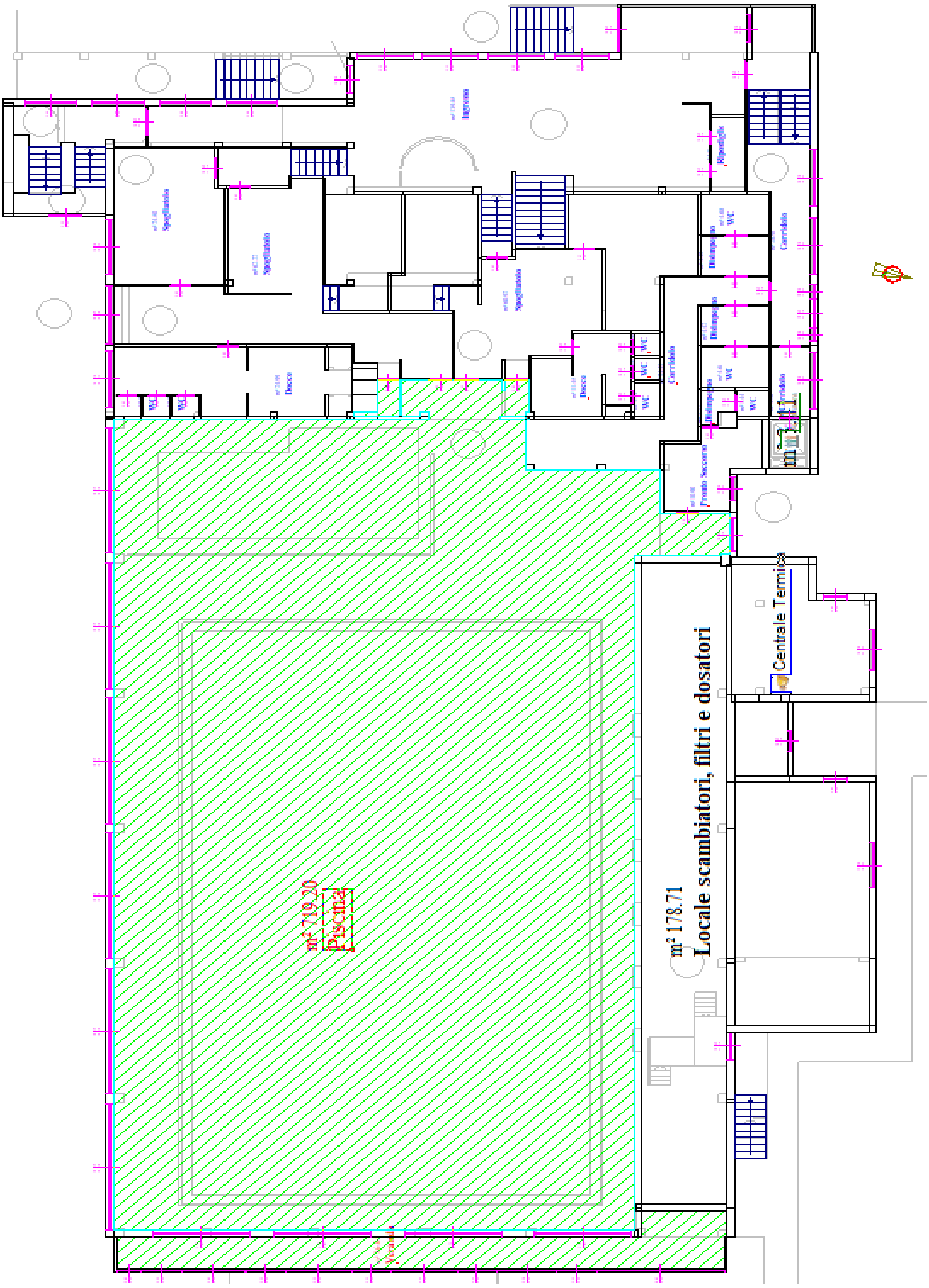
From the economical point of view, a big cost reduction is expected for the SOFC microCHP systems (and for the Fuel Cells in general), that should make this technology far more convenient than the other microCHP technologies.

At present, the very high investment cost and the high cost for the stack substitution of the SOFC microCHP makes it still less convenient than an Internal Combustion Engine. Anyway, this technology it is close to be competitive with the ICEs if some cost reductions are going to be carried on by the Fuel Cell companies and brought to the market.

APPENDIX A

Swimming Pool Zone

FIGURE 47: VINOVO'S POOL GROUND FLOOR, SWIMMING POOL ZONE



Other zone

FIGURE 48: VINOVO'S POOL GROUND FLOOR, OTHER ZONE

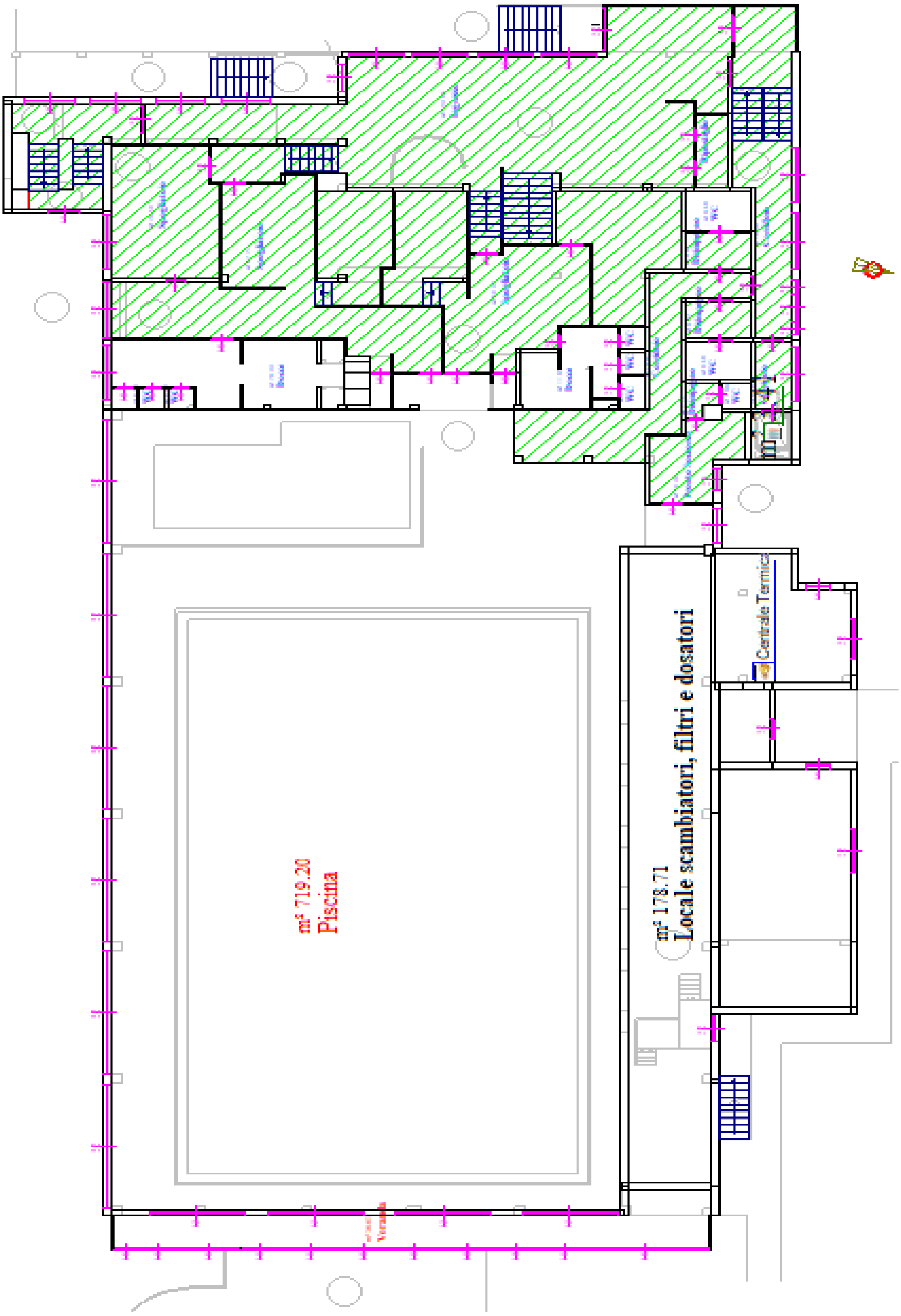


FIGURE 49: VINOVO'S POOL FIRST FLOOR, OTHER ZONE

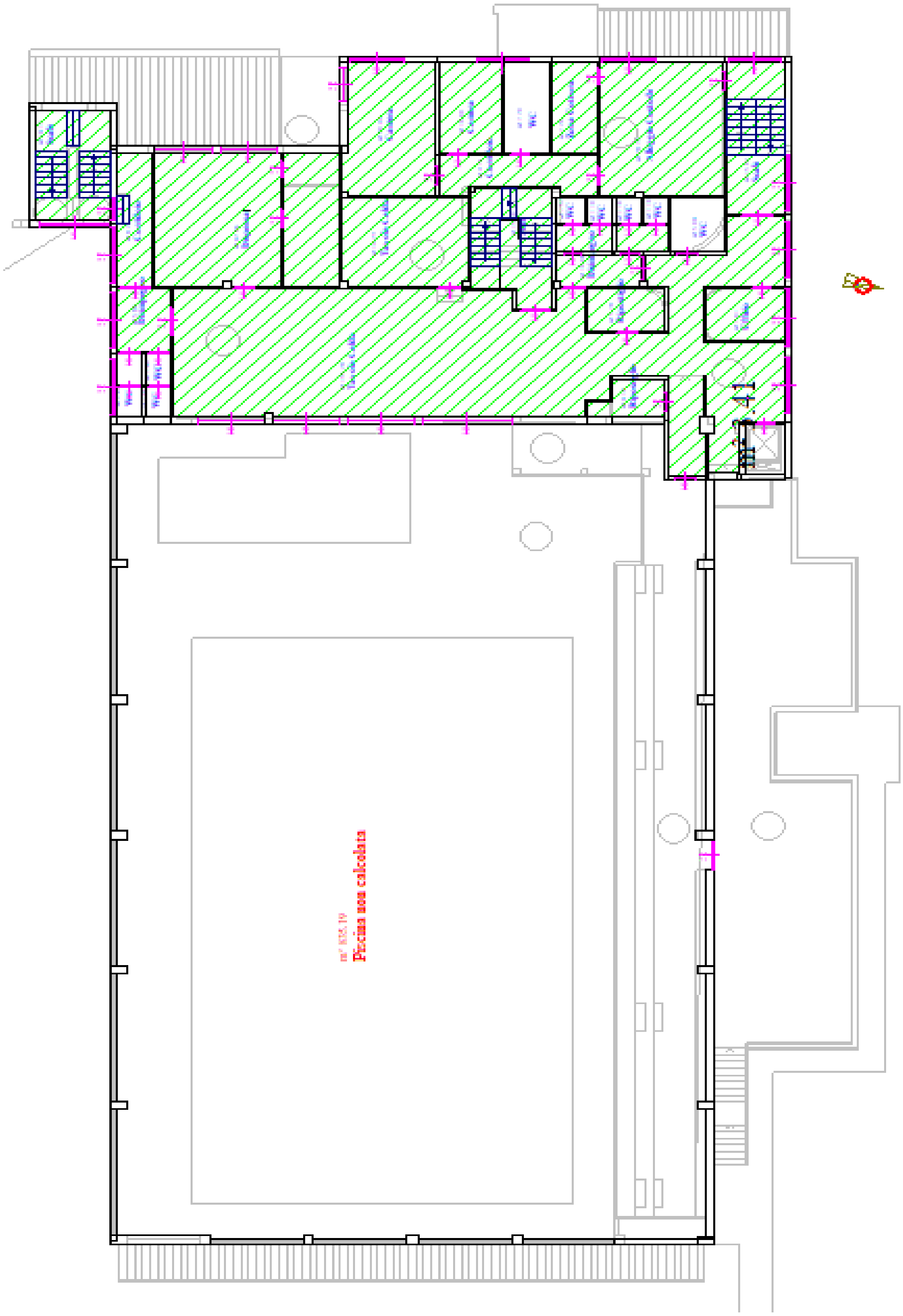


FIGURE 50: VINOVO'S POOL BASEMENT, OTHER ZONE

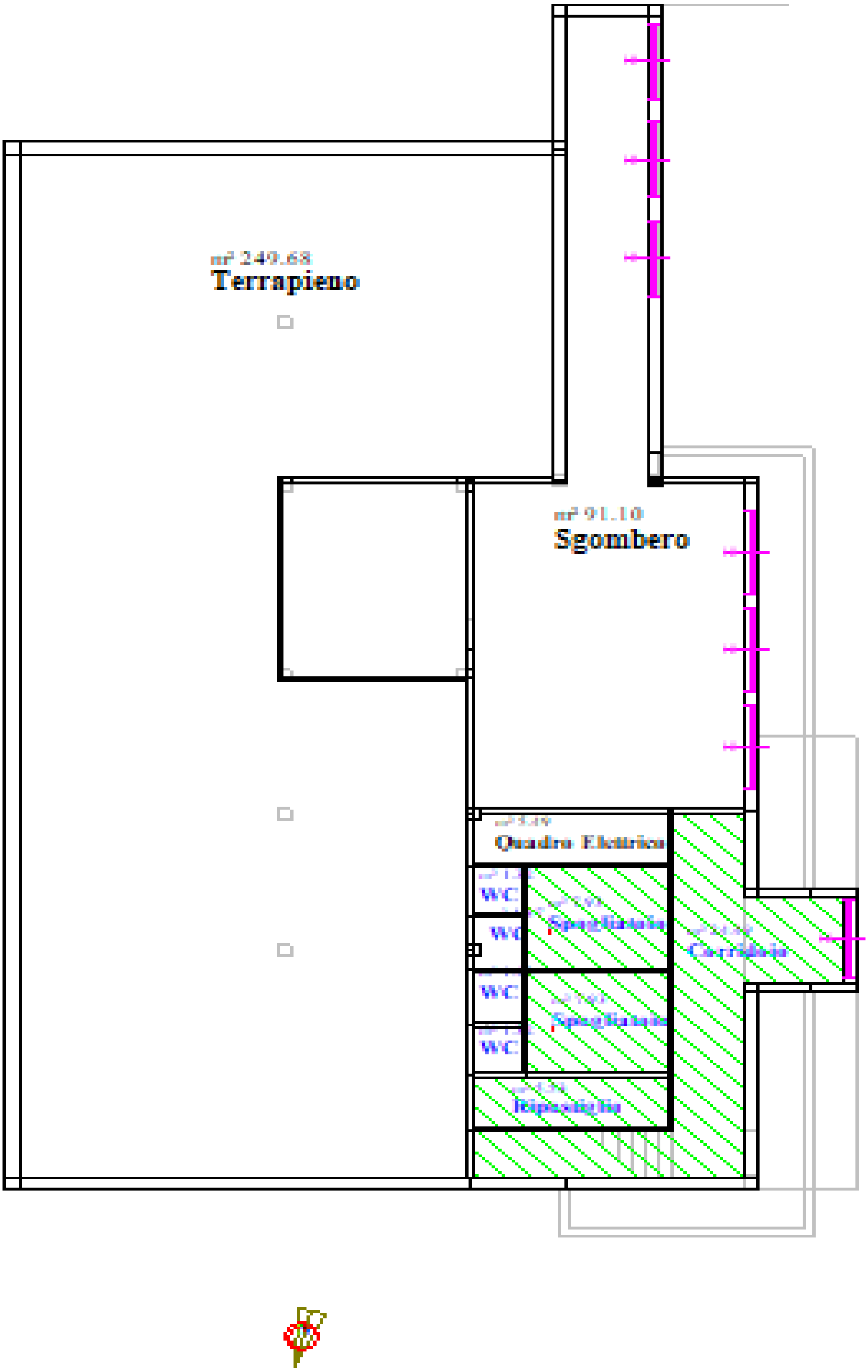
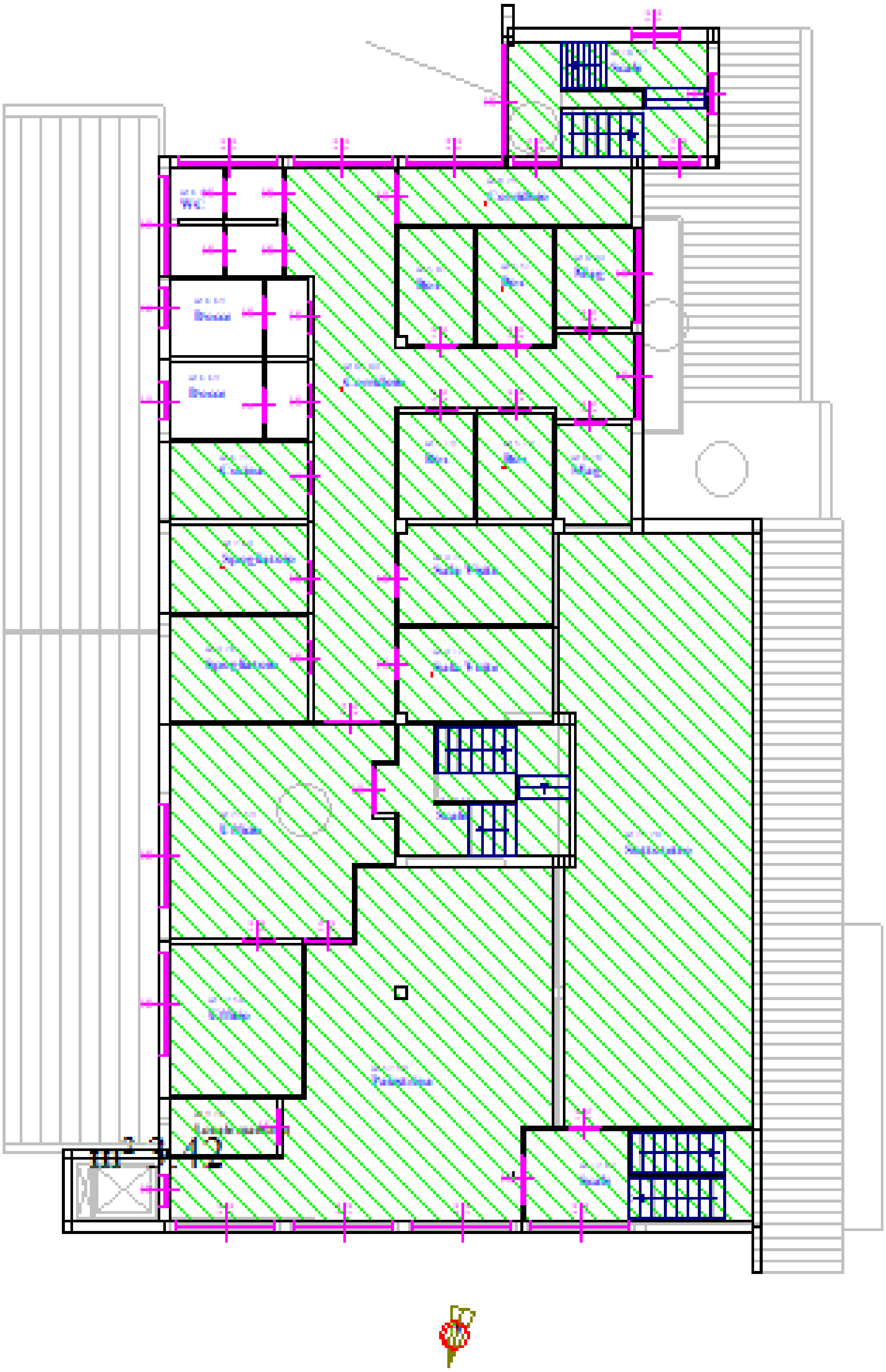


FIGURE 51: VINOVO'S POOL SECOND FLOOR, OTHER ZONE



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